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UPWIND METROLOGY

Deliverable D 1A2.1
List of Measurement Parameters

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Abstract

The UPWIND project is a European research project that focuses on the necessary up-scaling of wind energy in 2020. Among the problems that hinder the development of wind energy are measurement problems. For example: to experimentally confirm a theoretical improvement in energy production of a new design by field experiments of around 5% is very hard to almost impossible. As long as convincing field tests have not confirmed the actual improvement, the industry will not invest much to change the turbine design. This is an example that clarifies why the development of wind energy is hindered by metrology problems (measurement problems). Other examples are in the fields of:

- Warranty performance measurements
- Improvement of aerodynamic codes
- Assessment of wind resources

In general terms the uncertainties of the testing techniques and methods are typically much higher than the requirements. Since this problem covers many areas of wind energy, the work package is defined as a crosscutting activity. The problem is especially relevant for the following areas:

Production related

- Power performance testing especially in wind farms
- Testing and verification of turbine improvements in the order of several percent
- Verification of aerodynamic codes
- Testing and verification of turbine response to effects such as turbulence and shear

Load related

- Mechanical load measurements in farms aimed at verification of aero elastic codes. (blade root moments, yaw moments, tower foot moments etc.)

Wind related

- Measurement of wake effects and wind resources inside wind farms
- Measurements of inter farm effects (regarding velocity profiles, turbulence, surface shear recovery distances etc)
- Measurements of the interaction wind farms and microclimate

The objectives of the metrology work package are to develop metrology tools in wind energy to significantly enhance the quality of measurement and testing techniques. The development of the basic metrology measures is done by

- Identifying all relevant measurands within the wind energy community
- Describing their definition in detail
- Identifying all relevant influence parameters
- Quantifying their systematic influence on measurements
- Specifying traceability and
- Applying advanced uncertainty analysis methods.

This report presents a state of the art assessment to identify all relevant measurands. The required accuracies and required sampling frequencies are stated from the perspective of the users of the data (the other work packages in UPWIND). The interaction with the other work packages has initiated internal debates which led to feedback to this list of measured parameters.

Contents

1. Introduction

The UpWind project

UpWind is a European project funded under the EU's Sixth Framework Programme (FP6). The project looks towards the wind power of tomorrow, more precisely towards the design of very large wind turbines (8-10MW), both onshore and offshore. Furthermore, the research also focuses on the requirements to the wind energy technology of 20MW wind turbines.

The challenges inherent to the creation of wind farms of several hundreds MW request the highest possible standards in design, complete understanding of external design conditions, the design of materials with extreme strength to mass ratios and advanced control and measuring systems geared towards the highest degree of reliability, and critically, reduced overall turbine mass.

The wind turbines of the future necessitate the re-evaluation of the turbine itself for its reconception to cope with future challenges. The aim of the project is to develop the accurate, verified tools and component concepts the industry needs to design and manufacture this new type of turbine. UpWind focuses on design tools for the complete range of turbine components. It addresses the aerodynamic, aero-elastic, structural and material design of rotors. Critical analyses of drive train components will be carried out in the search for breakthrough solutions.

The UpWind consortium, composed of 40 partners, brings together the most advanced European specialists of the wind industry.

Expected results

In the UpWind project research will lead to accurate, verified tools and some essential component concepts the industry needs to design and manufacture the new breed of very large wind turbines. Among others, UpWind will address the aerodynamic, aero-elastic, structural and material design aspects of rotors. Future wind turbine rotors may have diameters of over 150 meters. These dimensions are such that the flow in the rotor plane is non-uniform as a result of which the inflow may vary considerably over the rotor blade. Full blade pitch control would no longer be sufficient. That is why UpWind will investigate local flow control along the blades, for instance by varying the local profile shape. New control strategies and new control elements must be developed and critical analyses of drive train components must be carried out in the search for breakthrough solutions.

Furthermore, wind turbines are highly non-linear, reactive machines operating under stochastic external conditions. Extreme conditions may have an impact a thousand times more demanding on, for instance, the mechanical loading than average conditions require. Understanding profoundly these external conditions is of the utmost importance in the design of a wind turbine structure with safety margins as small as possible in order to realise maximum cost reductions.

A similar argument applies to the response of the structure to external excitations. In order to make significant progress in this field, more accurate, linearly responding measuring sensors and associated software are needed. Preferably the sensors should remain stable and accurate during a considerable part of the operational lifetime of a wind turbine. UpWind will explore measuring methods and will look more in detail into new remote sensing techniques for measuring wind velocities. The validation and verification of the analyses, tools and techniques depend on reliable and appropriate measurements. The task of the work package ‘Metrology’ is to identify the critical issues in measurement techniques and to find solutions for the most critical ones.

More information on the UpWind project is found on the website:
www.upwind.eu

1.1 Work Package 1A2 Metrology

As the project includes many scientific disciplines which need to be integrated in order to arrive at specific design methods, new materials, components and concepts, the project's organisation structure is based on work packages which variously deal with scientific research, the integration of scientific results, and their integration into technical solutions. Since the measurement problems are related to several areas in the wind energy, the work package Metrology is defined as an integrating work package.

The metrology problem around wind turbine technology is the focus of this work package since the development of wind energy is hindered by measurement problems. In particular the fluctuating wind speed introduces large uncertainties and these fluctuations in the wind are experienced throughout the entire wind turbine. An example of a problem through measurement uncertainties is that it is almost impossible to confirm anticipated small performance improvements resulting from design modifications by means of field tests. As long as convincing field tests have not confirmed the actual improvement, the industry will be hesitant in investing in turbine design improvements. Furthermore, the developments within the UpWind project will require validation that is based on reliable and appropriate measurements.

The objective of the metrology work package is to develop metrology tools in wind energy to significantly enhance the quality of measurement and testing techniques. The first deliverable is the first step to reach this objective and is the production of a list of parameters that should be measured in wind energy. The list has been developed in close collaboration with the work packages to which the intended results apply.

1.2 How to read this report

The development of metrology tools to significantly enhance the quality of measurement and testing techniques in wind energy is carried out in three steps. These steps are described in the work programme and are defined as deliverables. The three steps (deliverables) are

1. Problem identification: determination of the parameters that must be measured for the various problems encountered in wind energy and the required accuracies.
2. Available techniques and theoretical solutions: for the identified parameters the state-of-the-art measurement techniques are described, the problems that may be encountered are described and possible theoretical solutions are presented.
3. The practical value of the proposed solutions is demonstrated.

After finishing the second step where the theoretical solutions are presented, a work programme for the demonstration phase is defined.

This report presents lists of parameters that should be measured for the various subjects in wind energy. Since the work packages in the UpWind project are divided along these subjects, the lists are specified for the different work packages. The lists have the intention not only to include the present-day techniques, but rather describe required or desired measurement techniques for the future 20MW wind turbines. The list has been made after interaction with the work packages in the UpWind project. All members of these work packages did have the opportunity to comment on the list or add further required measurements.

When setting up the lists of parameters, it was found that the most valuable list limits itself to the following columns

Parameter / Signal	Unit	Desired accuracy	Traceable (Y/N)	Sampling frequency range [Hz]	Required / Optional	Measurement position

Where the columns are:

- **Parameter / Signal:** The name of the parameter or signal that must be measured.
- **Unit:** The unit in which the parameter should be measured.
- **Desired accuracy:** The desired accuracy with which the parameter should be determined for the specific task. This means that a single parameter could have quite different requirements for the different applications (work packages).
- **Traceability:** Whether or not the parameter should have a traceable value. In general all values that are measured should be traceable, otherwise you will have a 'floating' value. Although almost all values should be traceable, it is still included in the list to remind the experimenters and users of experimental data of the importance of traceability. Further information on traceability is presented in section 1.4.
- **Sampling frequency range:** The required frequency range for the specific purpose. For many parameters a minimum sampling frequency is provided. For some of the more general parameters, the reader is reminded that the sampling frequency should be eight times larger than the highest frequency to be studied.
- **Required or Optional:** indicate whether the parameter is required for the purpose or can be optional. Optional is also indicated when we expect that it will be required for future techniques but at the moment it is (only) optional. It must be noted that in many cases the optional measurements can improve the final accuracy and reliability of the measurements.
- **Measurement position:** the location where the parameter should be measured.

There are some remarks:

1. Measurands could be used for various applications. For the different applications, usually there are different requirements with respect to accuracy, sampling frequency or reliability.
2. For each measurand is indicated whether or not it is required. One should keep in mind that what is optional today might be required in the future because of for example advancements in turbine control or measurement techniques.
3. The measurement position does not include the mounting, since this is specific for each instrument and measurement technique. The mounting will be included in the list of measurement devices (deliverable D 1A2.2). In the list presented in this report is indicted the location in the turbine, or around the turbine where the measurement should be performed.
4. For offshore wind farms, it should be noted that the relative importance of certain parameters may differ from the onshore cases. For example, under low-turbulence ambient conditions, wake effects within wind farms are more pronounced. In addition, not only the single parameters are of relevance, but also the correlation with other parameters e.g. the correlation of wind and wave parameters. Another example is the description of the vertical wind speed profile. Thermal stratification of the atmosphere as well as the surface roughness has a major impact on the profile. While the surface roughness strongly depends on the actual sea state the thermal stratification is influenced by a number of conditions such as the ambient air and water temperature and the location of the site under consideration. This might require other methods to determine the vertical wind speed profile.
5. In the case of voltage measurements and current measurements, it is tempting to put the required class 0.5 (or other class) as desired accuracy. This is not done here: the total accuracy is indicated here, including the mounting, sampling etc., which is similar to the other measurands.
6. Controller signals may be measured in different ways. In some cases, a voltage signal representing the controller signal is measured. This should be traceable. In other cases, where the digital signal is ‘measured’ or obtained directly, this is considered traceable.

7. The accuracies of the derived parameters are not stated in the lists. The accuracies of the derived parameters are fully determined from the input parameters.
8. The time scale is an important parameter when analyzing and validating flow structures inside wind farms because of large transportation time and bad correlation.

This report describes the measured parameters and the required accuracies and required frequency range for measurements on wind turbines. The areas that are investigated are covered by the various other work packages in the UPWIND project. It is advantageous to combine the lists of parameters for some of the other work packages. The following subdivision is used throughout this report.

Work Packages	Parameter list
WP2 Aerodynamics & Aero elastics	Table A.1
WP3 Rotor structure and materials	Table A.1
WP4 Parameters Foundations	Table A.1
WP5 Control systems	Table B.1
WP7 Condition Monitoring	Table B.1
WP1B2 Transmission and conversion	Table C.1
WP9 Electrical Grid	Table C.1
WP8 Flow	Table D.1
WP6 Remote Sensing	Table D.1

From the many IEC documents, three have been selected to be included in the lists of parameters. These are:

IEC Documents		Parameter list
Noise Measurements	IEC 61400-11	Table F.1
Power Performance Measurements	IEC 61400-12-1	Table E.1
Power Quality Measurements	IEC 61400-21	Table C.1

For reference, the following IEC documents are indicated. The selection is quite arbitrary.

Design requirements	IEC 61400-1	
Measurement of mechanical loads	IEC 61400-13	
Wind turbine certification	IEC 61400-22	
Full scale blade testing	IEC 61400-23	
Lightning protection	IEC 61400-24	
Communications for monitoring and control of wind power plants	IEC 61400-25	

The tables in the Appendices of the lists of measurands also indicate a column with 'parameter number'. This parameter number is added for further analyses on the data. The parameter numbers indicate the following:

Parameter number	Indication
1	Structural parameters
2	Operational and control parameters
3	Meteorological parameters
4	Hydrological parameters
5	Geotechnical parameters
6	Acoustic parameters

1.3 Other areas of investigation

Other areas of investigation that are not included in the analyses of the Metrology work package are:

1. **Wind tunnel measurements**. Although for some measurands wind tunnel measurements could be a tool for the further improvement, the accuracies and measurement techniques connected to wind tunnel measurements is not included in the scope of this report.
2. **Material coupon testing**. The work package WP3 Rotor structures and Materials was one of the first work packages to send us the information required to build the lists of measurands. Despite the useful list, the UpWind work package leader meeting decided that coupon testing is not considered in the scope of WP1A2 Metrology.
3. **Blade testing** (although there is a common standard covering this subject) and requirements to the testing might need a revision, as the size of blades increases. Right now the increasing problems are subject for a discussion among the testing laboratories (outside the scope of Upwind WP1A2 Metrology).

1.3.1 Air Foil data

From the interaction with other work packages, the issue of air-foils did come up. The determination of the exact shape of the air foils is an issue not completely covered. The questions that did arise are:

- How to determine the outer shape of the blade
- How to determine the weight distribution in the blade
- How to determine the structural characteristics of the blade

Required accuracies should come from the aerodynamics work package (WP2).

1.4 Traceability in measurements

The definition of traceability as it appears in the ISO/IEC Guide 43-1:1997 is [VIM:1993, 6.10]**:**

> **“Traceability is the property of the results of the measurement or the value of a standard whereby it can be related to stated references, usually national or international standards through an unbroken chain of comparisons , all having stated uncertainties”**

This report includes a brief working analysis of this definition in this section. More details can be found in [1].

> **“Traceability is the property of the results of a measurement ...**
> **Whereby it can be <u>related to stated references</u> ...”**

ANY measurement result MUST BE TRACEABLE, in order to be comparable with values measured at different locations or different times.

> **“it can be related to stated references, usually <u>national or international standards</u> …”**

Traceability is assured by comparing the output of a “measurement system” to a globally accepted value and establishing a correction function (= calibration coefficients of the measurement system) connecting the measurement system output to the “real globally accepted value” of the measurand.

“ ….related to stated references, ….., through an unbroken chain of comparisons …”

It is not necessary to compare our measurement system (say a load cell) directly to the International Standard (for Mass) stored in Geneva. We can compare it to our reference load cell (Step 1) which was compared to the reference load cell of a calibration laboratory (Step 2) which was compared to the National Standard (Step 3) for Mass, which was compared to the International Standard (Step 4) in Geneva. In theory, unlimited number of in-between comparisons are accepted, provided that there is a continuous (unbroken) chain leading up to global values. However, the following comment should be taken into account:

“… all having stated uncertainties …”

For each comparison step made in the chain, an uncertainty factor should be included to the “calibration uncertainty” for our measurement system. This uncertainty relates to the limited accuracy of the “reference value” and to other uncertainty factors related to the comparison procedure (effect of ambient conditions, effects of mounting etc). In other words, the more steps in the comparison of our system to the globally recognised values, the greater the calibration uncertainty. The calibration certificate issued by the calibration laboratory must include an evaluation of the total uncertainty in the calibration step performed. It is assumed that the calibration uncertainties of all previous steps up to the Globally Accepted Value (International Standard) are included in the uncertainty evaluation of the calibration.

Important Note: The calibration uncertainty is only ONE of the uncertainty parameters that must be included in the measurement uncertainty analysis.
Other factors like

- limited resolution of the instrument,
- long term deviation,
- ambient conditions (e.g temperature, humidity) effects,
- mounting,
- and signal conditioning and transmission

just to name a few, should always be evaluated in the uncertainty analysis.

“A traceable calibration assures a globally accepted value for the results of the measurement but it cannot reduce uncertainty related to other factors”

2. Integration with other work packages in UpWind

In this Chapter the work packages are indicated for which lists of measured parameters are generated. Each section includes a short description of the work package and includes the relevance of Metrology for that work package. The lists of measured parameters are combined for several work packages.

2.1 WP2 Aerodynamics & Aero-elastics, WP3 Rotor structures and WP4 Turbine Foundations

The list of parameters for these work packages has been combined. The list is indicated in Appendix A. The four applications of the measured parameters in this list are

1. WP2 and WP3 Turbine Monitoring: measurements of a single turbine mainly intended for the verification of simulation codes
2. Farm Monitoring: Measurements to characterise the conditions within and around the wind farm
3. WP4 Design code verification: design code verification for offshore foundations
4. WP4 Advanced Control strategies: development of advances control strategies of single offshore wind turbines to reduce the loads on the structure (including foundations).

2.1.1 WP2 Aerodynamics & Aero-elastics

The objective of the work package “Aerodynamics & Aero-elastics” is to develop a basis for aerodynamic and aero-elastic design of large multi-MW turbines in order to ensure that the wind turbine industry will not be limited by insufficient models and tools in their future design of new turbines, including possible new and innovative concepts.

The specific objectives are:

- Development of structural dynamic models for the complete wind turbine or subcomponents that can handle highly non-linear effects e.g. from flexible blades with complex laminated composite and/ or composite sandwich skins and webs, spanning from micromechanics to structural scale.
- Development and application of advanced models on rotor and blade aerodynamics, covering full 3D CFD rotor models, free wake models and improved BEM type models.
- Aerodynamic and aero-elastic modelling of aerodynamic control features and devices. This represents the theoretical background for the smart rotor blades.
- Development of methods and models for analysis of aero-elastic stability and total damping including hydro-elastic interaction.
- Development of models for computation of aerodynamic noise in order to design new airfoils and rotors with less noise emission.

Relevance of Metrology: The verification of the simulation codes requires measurements that are reliable and accurate. The measurements should fit the requirements from the simulation codes verification process.

2.1.2 WP3 Rotor structures and materials

The objectives of the work package “Rotor structures and materials”: For larger wind turbines, the potential power yields scales with the square of the rotor diameter, but the blade mass scales to the third power of rotor diameter (square-cube law). With the gravity load induced by the dead weight of the blades, this increase of blade mass can even prevent successful and economical employment of larger wind turbines. In order to meet this challenge and allow for the next generation of larger wind turbines, higher demands are placed on materials and structures. This requires more thorough knowledge of materials and safety factors, as well as further investigation into new materials. Furthermore, a change in the whole concept of structural safety of the blade is required.

The specific objectives are:

- Improvement of both empirical and fundamental understanding of materials and extension of material database.
- Study on effective blade details.
- Establishment of tolerant design concepts and probabilistic strength analysis.
- Establishment of a material testing procedure and design recommendations.

Relevance of Metrology: The verification of the simulation codes requires measurements that are reliable and accurate. The measurements should fit the requirements from the simulation codes verification process. Coupon testing of materials is another issue, where measurement problems can be identified. Unless input was received from the work package regarding the requirements and problems encountered in measurement techniques, the subject of coupon testing is not included in this report (see also section 1.3).

2.1.3 WP4 Offshore Foundations and Support Structures

The objective of WP 4 “Offshore Foundations and Support Structures” is to develop innovative, cost-efficient wind turbine support structures to enable the large-scale implementation of offshore wind farms across Europe, from sheltered Baltic sites to deep-water Atlantic and Mediterranean locations, as well as other emerging markets worldwide. The work package will achieve this by seeking solutions which integrate the designs of the foundation, support structure and turbine machinery in order to optimise the structure as a whole. Particular emphasis will be placed on large wind turbines, deep water solutions and designs which are insensitive to site conditions, allowing cost-reduction through series production.

Relevance of Metrology to the work package Foundations is the determination and measurement of parameters that are relevant for offshore wind energy application in general and such that are directly related to future work of WP4. In this context the parameters are intended for a variety of purposes. These are:

- Design basis, site specific design of offshore wind farms.
- Advanced control & load mitigation concepts.

In addition, condition monitoring is important for the WP4 'Foundations'. This is taken into account when describing the list for WP7 “Condition Monitoring”. Another important aspect relates to the verification and further development of existing state-of-the-art simulation tools. Especially the measurement of the structural parameters becomes necessary as well as the environmental parameters and operational parameters. Due to the offshore specific environment, the hydrological and geological parameters are essential.

Here we elaborate a little on the **geotechnical parameters**. The range of demanded geotechnical parameters strongly depends on the actual foundation type and furthermore strongly depends on the modelling approach. Typically, the geotechnical investigations of a specific site comprise determination of the soil strata and their corresponding physical and engineering properties by in-situ tests and sample tests in the laboratory. Not only the initial values for these parameters are required, but also their variation over the lifetime due to the presence of the wind turbine. However, the sampling rate will not be high and these measurements will in most cases be performed by companies specialised in these geotechnical measurements.

2.2 WP5 Control systems and WP7 Condition Monitoring

The list of parameters for these work packages has been combined. The list is indicated in Appendix B. The applications of the measured parameters in this list are

1. WP5 Operational Control Systems; measurements needed for day-to-day control of the turbine. Main requirement is reliability.
2. WP5 Development of Control strategies; measurements needed for optimisation of control of the turbine and measurements to validate developments. Accuracy could be of more importance than reliability.
3. WP7 Condition Monitoring; measurements for condition monitoring. The condition monitoring is treated to focus primarily on the drive train. Main requirement is reliability.

2.2.1 WP5 Control systems

Further improvements in the cost-effectiveness of wind turbines drive designers towards larger, lighter, more flexible structures, in which more ‘intelligent’ control systems plays an important part in actively reducing the applied structural loads. This strategy of “brain over brawn” will therefore avoid the need for wind turbines to simply withstand the full force of the applied loads through the use of stronger, heavier and therefore more expensive structures. To reach this point it is necessary to demonstrate these load reductions in full-scale field tests on a well-instrumented turbine. **The objective of WP5 “Control Systems”** is to develop new control techniques can then be used with more confidence in the design of new, larger and innovative turbines.

As the penetration of wind energy increases, real issues are already arising relating to the control of the electrical network and its interaction with wind farms. These issues must be resolved before the penetration of wind power can increase further.

The specific objectives of this work package are:

- Further development of control algorithms for wind turbine load reduction, of the sensors and actuators which are required for the algorithms to be effective, of efficient methods of adjusting and testing controllers, and the application of these techniques to new larger and innovative turbines.
- Investigation and evaluation of different load estimation algorithms, using various sets of available sensor signals. Incorporation of promising structures to load reducing controller algorithms. Identification of potential problems to overcome when taking into account fault prediction information in controller dynamics.
- Field tests to demonstrate that the load reductions and estimated loads can be achieved reliably, so that future designs can take advantage of the implied reduction in capital costs.

Development of wind turbine and wind farm control techniques aimed at increasing the acceptable penetration of wind energy, by allowing wind turbines to ride through network disturbances, and to contribute to voltage and frequency stability and overall reliability of the network.

Relevance of Metrology to the work package “Control Systems” extends to two applications. The first application requires measurements for day-to-day control of the turbine. Apart from the accuracy of the measurements, the reliability shall be equally important. These measurements should extend at least 20 years. The second application requires measurement techniques to facilitate the development of new control strategies. These measurements are needed for optimisation of control of the turbine and measurements to validate new developments.

2.2.2 WP7 Condition Monitoring

The objective of work package “Condition Monitoring” is to support the integration of new approaches for condition monitoring, fault prediction and operation & maintenance (O&M) strategies into the next generation of wind turbines for offshore wind farms. Main aspects for these items are the cost effectiveness of the required condition monitoring hardware equipment, the introduction of optimised signal processing routines and the adaptation of fault prediction algorithms or O&M strategies. The results will be used in the educational part of the UpWind project and will have impact into the work packages dealing with material research and rotor blade sensor integration.

Relevance of Metrology to the work package “Condition Monitoring” are measurement techniques to measure during long periods the condition of the turbine, for example the drive train, and the analyses techniques required to obtain the required information from the large amount of vibration data.

From the work package it is stipulated that for condition monitoring purposes, most of the measured quantities are not evaluated according to their absolute values, but according to the deviation from a defined level (“base line”) as a trend analysis. This base line level can be derived, for example, from a measurement taken under a fault free condition of the component to be monitored. It can also be a component manufacturer’s recommendation. For the trend analysis, the absolute accuracy of the measured values is not that important. What is important for condition monitoring is the long term stability of the measured values to allow a reliable trend analysis.

2.3 WP1B2 Transmission and conversion and WP9 Electrical Grid

The list of parameters for these work packages has been combined. The list is indicated in Appendix C. The applications of the measured parameters in this list are

1. WP9 Electrical Grid, measurements needed for the work package electrical grid. Only a limited number of parameters could be identified. The assumption is that the work package limits itself to the components after the generator.
2. WP1B2 Transmission; measurements needed for the work package transmission and conversion. The parameters identified include the forces on the main shaft etc. Therefore also the bending moments on the blade root are the input for this work package.

The issue of Power Quality measurements (IEC 61400-21) is included in this table.

2.3.1 WP1B2 Transmission and conversion

This work package covers the entire drive train including mechanical and electrical components. The overall purpose is to develop the technology necessary to overcome the present limitations in turbine size, power, and effectiveness and to increase predictability and reliability. The work package is divided in three: Mechanical Transmission, Generators and Power Electronics. The interaction of Metrology primarily is with the Mechanical Transmission.

Objectives – Mechanical Transmission.

In terms of reliability the drive train today is the most critical component of modern wind turbines. Nowadays the typical design of the drive train of modern wind turbines consists of an integrated serial approach where the single components, such as rotor shaft, main bearing, gearbox and generator are as much closed together as possible with the aim of compactness and mass reduction. Field experiences throughout the entire wind industry show that this construction approach results in many types of failures (especially gearbox failures) of drive train components, although the components are well designed according to contemporary design methods and all known loads. It is assumed that the basic problem of all these unexpected failures is based on a principal misunderstanding of the dynamic behaviour of the complete system “wind turbine” due to the lack of an integral approach ready to use which at the same time integrates the structural nonlinear elastic behaviour with the coupled dynamic behaviour of multi body systems together with the properties of electrical components.

Beneath of the principal understanding of the actual loads within the gearboxes the turbine manufacturers increasingly request for a test to prove the reliability of the gearboxes. As the lifetime should be up to 20 years, the test has to be performed in a significantly reduced period of time. But within such test procedures the product needs to be stressed in the same way as if it has endured the designed lifetime. It is not sufficient to simply raise the load, but an intelligent combination of load cycles and speed is necessary. The theory for the layout of such accelerated lifetime tests up to now is still unclear and not state of the art.

Within this work package three main issues for the construction of future large scale wind turbines are addressed: 1st the in-depth and realistic simulation of the complete system behaviour for the design of reliable and cost effective components and 2nd the systematically analysis and test of gearboxes to ensure and verify a desired lifetime and at the same time reduce noise excitation. 3rd to verify common load assumptions for drive train design through long-term measurement technique and development of low-cost down counting technique of remaining drive train life-time due to actual measured stresses.

Relevance of Metrology to this work package is development of a measurement list required for the validation of models and the characterisation of the mechanical transmission.

2.3.2 WP9 Electrical Grid

The objective of work package “Electrical Grid” is to investigate the requirements to wind turbine design due to the need for reliability of wind farms in power systems, and to study possible solutions that can improve the reliability. The task is particularly important for large offshore wind farms because failure of a large wind farm will have significant influence on the power balance in the power system and because offshore wind farms are normally more difficult to access than land-sited wind farms.

The reliability of the power production from a wind farm depends on the wind turbine, the collecting grid of the wind farm including transformers, the power grid, and also the wind farm monitoring system can have an influence. However, critical situations are where the complete wind farm trips thus the influence of the grid is the most important, because grid abnormalities normally affect all the wind turbines in a large wind farm simultaneously. The consequences of grid abnormalities such as voltage dips, outages and unbalance, depend on the “ride-through” capability of the wind turbines. Finally, extreme wind conditions are important if all wind turbines are affected, i.e. if cut-out wind speed is reached or when the wind speed drops after a front passage.

The work package will investigate operational as well as statistical aspects of wind farm reliability. Investigating grid code requirements, extreme wind conditions and specific wind farm control options to cope with these requirements will cover the operational aspects. The statistical aspects will be covered by the development of a database and by statistical modelling of the reliability of wind energy.

The list of measurands for the work package “Electrical Grid” limits itself to the measurement of the electrical properties of the power evacuation system, some temperatures to monitor the system and the wind speed at the nacelle. Meteorological aspects are treated in connection to other work packages.

2.4 WP6 Remote Sensing and WP8 Flow

The list of parameters for these work packages has been combined. The list is indicated in Appendix D. The applications of the measured parameters in this list are

1. WP6 Remote Sensing. This is a specific work package where measurement techniques are being developed. The parameters to be determined from remote sensing devices are the wind speed and direction in the rotor plane including turbulence parameters with sufficiently high frequency.
2. WP8 Flow; Characterisation of the flow field within and around wind farm. For this work package, the wind conditions within and around the wind farm are important. Waves etc. are not included. Wake effects and validation of wakes is included, so that some turbine parameters are necessary to include.

2.4.1 WP6 Remote Sensing

The modern wind turbines are getting larger, requiring larger measuring heights. The instrumented mast installations of comparable height to these turbines are already more expensive than intelligent remote-sensing alternatives. Two such alternatives are SODAR (an acoustic version of a RADAR) and LIDAR (an optical version of a RADAR). The SODAR obtains reflections from atmospheric fluctuations and measures the mean horizontal speed of the turbulence. The LIDAR obtains reflections from atmospheric particles and measures their mean horizontal speed. The potential for remote sensing methods has been demonstrated, however, further research is required in a number of key areas. Recently new LIDAR technologies have arisen which are targeted toward wind measurements over a distance range appropriate to turbines, and which do not require the expense and logistic overheads of liquid nitrogen cooling or very stable optical platforms.

The objectives of WP6 “Remote Sensing” is to concentrate the research on LIDARs, the monostatic SODARs and the bistatic SODARs. There exist already examples of work on these instruments showing their capabilities (power curves using SODARs and LIDARs, site assessment and comparisons to cup anemometer measurements). It is the intention of this work package to mature the work, which has already taken place, on the LIDAR and the monostatic SODAR techniques, through a coordinated effort. By the end of this work the remote sensing methods will be introduced into the existing standards (the relevant IEC and MEASNET documents) as valid alternatives to the existing methods for wind speed and direction measurements which use mast-mounted instruments. For the bistatic SODAR the intention is to investigate further this technique, since the theory shows that it possesses large potential.

Relevance of Metrology to the work package “Remote Sensing” is the validation of the new remote sensing techniques against existing techniques. The differences mainly exist in the heights that could be measured and in the principle difference between point measurement of the wind speed and a volume measurement of the wind speed. Apart from measurement techniques, this will require analyses techniques and further refinement of standards and guidelines to include these techniques in the day-to-day operation of wind energy.

2.4.2 WP8 Flow

The objective of WP8 “Flow” is to provide input on free stream and wake (within wind farm) wind (shear) and turbulence. The research focuses on the interaction between wind turbines and the boundary-layer – including both the impact of the boundary layer on downwind wake propagation (affecting downwind turbines) and the impact of wakes on the boundary-layer affecting downwind free stream conditions. Each wind turbine generates a wake and a neighbouring wind turbine in that wake will be exposed to a lower wind speed and a higher turbulence than the unobstructed wind turbine and thus yield less energy but experience higher loads. In ideal circumstances, wind and turbulence on a fine mesh (horizontal and vertical) for the whole wind farm would be predicted. However, there is a gap between engineering solutions and CFD models and a bridge is needed for this prediction in order to provide more detailed information for modelling power losses, for better wind farm and turbine design, for more sophisticated control strategies and for load calculation.

Work package “Flow” focuses on individual wake model performance in the offshore environment and complex terrain and in further developing a whole wind farm model that can be used to evaluate impacts downwind for siting of multiple wind farm clusters. In large wind farms, other than accurate resource prediction, the largest impact on power output is losses through wind turbine wakes. Emphasis is placed on optimal performance of the wind farm as a unit through reduced wakes. Hence an additional task is to evaluate whether wake losses and turbulence can be minimized by close crosswind spacing, by better characterisation of the wake-induced loading, by controls on the turbines or by using turbine yawing to create enhanced farm level circulation. The specific objectives are:

- Further development of large wind farm models for offshore also incorporating downstream flow.
- Better prediction of flow and wakes in wind farms in complex terrain, taking into account flow turning and wind rose narrowing.
- Collection and dissemination of data sets (wind speed and power output, mainly for wake studies).
- Investigation of reduction of wake losses and turbulence by close crosswind spacing, by controls on the turbines or by using turbine yawing to create enhanced farm level circulation.
- Demonstration of the value of load-optimal layout design and wind farm operation in overall cost-effectiveness.

Relevance of Metrology to the work package Flow is the study of existing measurement techniques and analyses techniques. The integration will give better insight in the main uncertainties, their origin and if and how they can be reduced or removed. Furthermore, emphasis could be placed on the spatial and temporal correlation of the wind field across large offshore wind farms.

3. Discussion and Conclusions

The UpWind consortium research covers a wide area of expertise in wind energy. The required measurement and analysis techniques covering this wide range are identified after successful and extensive interaction between the various work packages of the UpWind project. The lists of measurands for a number of applications are added to the report. With this report the deliverable D 1A2.1 is presented. Further work within the work package 1A2 Metrology will concentrate on the further analyses and demonstration of the measurement techniques and analysis techniques.

4. References

[1] EAL-G12: Traceability of Measuring and Test Equipment to National Standards. European cooperation for Accreditation of Laboratories, Ed. 1, November 1995 See in http://www.european-accreditation.org/

Appendix A Aerodynamics & Aero-elastics, Rotor structures Materials, and Turbine Foundations

Table A.1 *List of parameters for WP2 Aerodynamics & Aero-elastics, WP3 Rotor structures and materials and WP4 Turbine Foundations*

Param No	Parameter / Signal	Unit	Desired Accuracy (Uncertainty)	Traceable (Y/N)	Sampling frequency range [Hz] (1)	Required / Optional	Measurement position	WP2 and WP3 Turbine Monitoring	Farm Monitoring	WP4 Design code verification	WP4 Advanced Control strategies
1	Displacements (2)	m	To be determined	Y	It should be 8 times larger than the highest frequency to be studied	O	Blade, hub, tower, nacelle, substructure, foundation and individual components	X	X	X	X
1	Velocities (3)	m/s	To be determined	Y	It should be 8 times larger than the highest frequency to be studied	O	Blade, hub, tower, nacelle, substructure, foundation and individual components	X	X	X	X
1	Accelerations (4)	m/s2	To be determined	Y	It should be 8 times larger than the highest frequency to be studied	O	Blade, hub, tower, nacelle, substructure, foundation and individual components	X	X	X	X
1	Nacelle acceleration in three directions (5)	m/s2	0.05 m/s2	Y	It should be 8 times larger than the highest frequency to be studied	R	Nacelle, measurement in more locations to capture all degrees of freedom	X		X	X
1	Tower bending moment on different height levels (fore-aft, side-side and torsional)	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	R	Tower	X		X	X
1	Tower acceleration in three directions on different height levels	m/s2	0.05 m/s2	Y	It should be 8 times larger than the highest frequency to be studied	R	Tower	X		X	X
1	Substructure (monopile, tripod, floating) bending moment on different height levels above and below mudline (fore-aft, side-side and torsional if relevant)	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	R	Substructure	X		X	X
1	Yaw moment	kNm	Target 3%	Y	It should be 8 times larger than the highest frequency to be studied	R	Nacelle, it could be measured from the rotating structure, or from the fixed structure.	X		X	X
1	Tilt moment	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	R	Nacelle, it could be measured from the rotating structure, or from the fixed structure.	X		X	X
1	Main shaft bending (0° 90°)	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	R	Main shaft	X		X	X
1	Main shaft torsion	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	R	Main shaft	X		X	X
1	Strain distribution to determine local stress distributions and for instance shear (anywhere)	kN	3%	Y	It should be 8 times larger than the highest frequency to be studied	R	Blade, hub, tower, nacelle, substructure, foundation and individual components			X	
1	Blade bending moment along the blade length (flapwise and edgewise)	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	R	Blade			X	X
1	Blade root bending moment (in-plane and out-of-plane)	kNm	Derived from blade bending moments and pitch angles	-	-	-		X	X	X	X
1	Blade torsional moment along the blade	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	R	Blade			X	X

param No	Parameter / Signal	Unit	Desired Accuracy (Uncertainty)	Traceable (Y/N)	Sampling frequency range [Hz] (1)	Required / Optional	Measurement position	WP2 and WP3 Turbine Monitoring	Farm Monitoring	WP4 Design code verification	WP4 Advanced Control strategies
1	Blade deflection along the blade length (flapwise and edgewise)	m	1% of maximum deflection	Y	It should be 8 times larger than the highest frequency to be studied	O	Blade			X	
1	Blade twist along the blade length (flapwise and edgewise)	degree	0.01 degree from the mean value (wind still)	Y	It should be 8 times larger than the highest frequency to be studied	O	blade			X	X
1	Tower deflections on different height levels (fore-aft, side-side)	m	1% of maximum deflection	Y	It should be 8 times larger than the highest frequency to be studied	R	Tower			X	X
1	Tower torsional deflection on different height levels	degree	1% of maximum deflection	Y	It should be 8 times larger than the highest frequency to be studied	R	Tower			X	X
1	Tower torsional moment on different height levels	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	R	Tower	X		X	X
1	Substructure (monopile, tripod, floating) deflections on different height levels above and below mudline (fore-aft and side-side)	m	1% of maximum deflection	Y	It should be 8 times larger than the highest frequency to be studied	R	Substructure			X	X
1	Substructure (monopile, tripod, floating) torsional deflection on different height levels	degree	1% of maximum deflection	Y	It should be 8 times larger than the highest frequency to be studied	O	Substructure			X	X
1	Subtructure and tower forces, such as anchor, tripod etc.	N	1% of maximum force	Y	It should be 8 times larger than the highest frequency to be studied	O	Substructure, Tower			X	X
1	Support structure natural frequencies (fore-aft, side-side and torsional)	Hz	Derived parameter	-	-	-	-			X	X
1	Rotor blade natural frequency (edgewise, flapwise)	Hz	Derived parameter	-	-	-	-			X	
1	Drive train natural frequencies	Hz	Derived parameter	-	-	-	-			X	
1	Applied pitch torque	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	O	Hub			X	
2	Nacelle position (yaw)	degree	0.1 - 0.5 degrees	Y	>=1Hz	R	Nacelle	X	X	X	X
2	Rotor speed (low speed shaft)	rpm	0.1-1%	Y	It should be 8 times larger than the highest frequency to be studied	R	Nacelle	X	X	X	X
2	Rotor position (rotor azimuth)	degree	0.1 %	Y	It should be 8 times larger than the highest frequency to be studied	R	Nacelle	X	X	X	X
2	Generator speed (high speed shaft)	rpm	0.1-1%	Y	It should be 8 times larger than the highest frequency to be studied	R	Nacelle	X	X	X	X
2	Actual torque on high speed shaft	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	R	Nacelle			X	X
2	Demanded torque on high speed shaft	kNm	0.1%	-	It should be 8 times larger than the highest frequency to be studied	R	Control system			X	X
2	Pitch angle	degree	0.01 degree	Y	It should be 8 times larger than the highest frequency to be studied	R	Nacelle	X	X	X	X
2	Demanded pitch angle	degree	0.1%	-	It should be 8 times larger than the highest frequency to be studied	R	Control system	X		X	X

Param No	Parameter / Signal	Unit	Desired Accuracy (Uncertainty)	Traceable (Y/N)	Sampling frequency range [Hz] (1)	Required / Optional	Measurement position	WP2 and WP3 Turbine Monitoring	Farm Monitoring	WP4 Design code verification	WP4 Advanced Control strategies
2	Pitch rate	degree/s	Derived signal					X		X	X
2	Active electrical power	kW	0.5%	Y	It should be 8 times larger than the highest frequency to be studied	R	Between wind turbine and electrical connection; It could be at different locations, such as stator, rotor etc.	X	X	X	X
2	Reactive electrical power	kW	0.5%	Y	It should be 8 times larger than the highest frequency to be studied	O	Between wind turbine and electrical connection; It could be at different locations, such as stator, rotor etc.	X	X	X	X
2	Controller mode	-	Derived from controller	Y	It should be 8 times larger than the highest frequency to be studied	R	Control system	X	X	X	X
2	Availability	-	Derived from controller	Y	It should be 8 times larger than the highest frequency to be studied	O		X	X	X	X
2	Failure	-	Derived from controller	Y	It should be 8 times larger than the highest frequency to be studied	O		X		X	X
2	Status	-	Derived from controller	Y	It should be 8 times larger than the highest frequency to be studied	R	Control system	X		X	X
2	Wind speed measured at nacelle	m/s	0.1 m/s	Y	>=1Hz	R	Nacelle	X	X	X	X
2	Wind direction measured at nacelle	degree	1 degree	Y	>=1Hz	R	Nacelle	X	X	X	X
3	Wind speed at different positions in the rotor plane (longitudinal, lateral and vertical)	m/s	0.1 - 0.25 m/s at 10 m/s	Y	>=1Hz	R	Rotor plane, free sector	X	X	X	X
3	Wind direction at different positions in the rotor plane	degree	2-5 deg	Y	>=1Hz	R	Rotor plane, free sector			X	X
3	Air Temperature	^oC	0.5-3 ^oC	Y	>=1Hz	R	Hub height			X	
3	Atmospheric pressure	hPa	5 hPa	Y	>=1Hz	R	Hub height			X	
4	Sea surface elevation	m	0.1 m	Y	>=1Hz	R	Sea level			X	
4	Wave direction	degree	5 degree	Y	>=1Hz	R	Sea level			X	
4	Current speed profile	m/s	0.1 m/s	Y	>= 0.1Hz	R	From mudline til sea level			X	
4	Current direction	degree	5 degree	Y	>= 0.1Hz	R	From mudline til sea level			X	
4	Ice parameters (thickness)	m	0.01m	Y	daily, hourly values	O	Sea level	X		X	
4	Water temperature (6)	^oC	0.3 degree C	Y	>=1Hz	R	Surface temperature			X	
5	Soil strata - Soil description as function of depth	-	-	Y	once, or larger than 1/year	R	Soil			X	X
5	Internal friction angle of soil	degree	5 degree	Y	once, or larger than 1/year	R	Soil			X	X
5	Cohesive strength	kN/m^2	?	Y	once, or larger than 1/year	?	Soil			X	X
5	Unit weight	kN/m3	?	Y	once, or larger than 1/year	?	Soil			X	X
5	Scour	?	?	Y	once, or larger than 1/year	?	Soil			X	X
5	Sea bed movement	?	?	Y	> 8 times the highest frequency to be studied	?	Soil			X	X

(1) For many parameters, it is noted that the sample frequency should be 8 times larger than the highest frequency to be studied. This is most practical, since the parameters could be used for more purposes with own requirements.
(2) Displacements. Examples are gearbox displacements, angular displacements of flexible coupling, etc
(3) Velocities. Examples are pitch piston velocities, main shaft velocities etc.
(4) Acceleration. Examples are accelerations in subcomponents etc.
(5) The accelerometer should be applicable also for the lower frequencies encountered in larger wind turbines
(6) Water temperature is included for stability of the atmospheric boundary layer
In the future, the calibration by means of adding force on the turbine can be impossible, so new calibration methods should be defined

Appendix B Control systems and Condition Monitoring

Table B.1 *List of parameters for WP5 Control systems and WP7 Condition Monitoring*

Param No	Parameter / Signal	Unit	Desired Accuracy (Uncertainty)	Traceable (Y/N)	Sampling frequency range [Hz] (1)	Required / Optional	Measurement position	WP5 Operational Control Systems	WP5 Development of Control strategies	WP7 Condition Monitoring
1	Displacements (2)	m	To be determined	Y	It should be 8 times larger than the highest frequency to be studied	O	Blade, hub, tower, nacelle, substructure, foundation and individual components. (8)	X	X	X
1	Velocities (3)	m/s	To be determined	Y	It should be 8 times larger than the highest frequency to be studied	O	Blade, hub, tower, nacelle, substructure, foundation and individual components	X	X	X
1	Accelerations (4)	m/s2	To be determined	Y	It should be 8 times larger than the highest frequency to be studied	O	Blade, hub, tower, nacelle, substructure, foundation and individual components (9)	X	X	X (7)
1	Temperatures	C	To be determined	Y	It should be 8 times larger than the highest frequency to be studied	O	Individual components	X	X	X
1	Pressure	Pa	To be determined	Y	It should be 8 times larger than the highest frequency to be studied	O	Individual components	X	X	X
1	Liquid levels	m	To be determined	Y	It should be 8 times larger than the highest frequency to be studied	O	Individual components	X	X	X
1	Strain	microstrain	To be determined	Y	It should be 8 times larger than the highest frequency to be studied	O	Individual components		X	X
1	Nacelle acceleration in three directions	m/s2	0.05 m/s2	Y	It should be 8 times larger than the highest frequency to be studied	R	Nacelle, measurement in more locations to capture all degrees of freedom	X	X	X
1	Tower acceleration in three directions on different height levels	m/s2	0.05 m/s2	Y	It should be 8 times larger than the highest frequency to be studied	R	Tower	X	X	X
1	Yaw moment	kNm	Target 3%	Y	It should be 8 times larger than the highest frequency to be studied	O	Nacelle, it could be measured from the rotating structure, or from the fixed structure.	X	X	X
1	Tilt moment	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	O	Nacelle, it could be measured from the rotating structure, or from the fixed structure.	X	X	X
1	Main shaft bending (0° 90°)	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	O	Main shaft	X	X	X
1	Main shaft torsion	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	O	Main shaft	X	X	X
1	Blade bending moment along the blade length (flapwise and edgewise)	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	O	Blade	X	X	X
1	Blade root bending moment (in-plane and out-of-plane)	kNm	Derived from blade bending moments and pitch angles	-	-	-	-	X	X	X
1	Blade torsional moment along the blade	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	O	Blade	X	X	
1	Blade deflection along the blade length (flapwise and edgewise)	m	1% of maximum deflection	Y	It should be 8 times larger than the highest frequency to be studied	O	Blade	X		X

param No	Parameter / Signal	Unit	Desired Accuracy (Uncertainty)	Traceable (Y/N)	Sampling frequency range [Hz] (1)	Required / Optional	Measurement position	WP5 Operational Control Systems	WP5 Development of Control strategies	WP7 Condition Monitoring
1	Blade twist along the blade length (flapwise and edgewise)	degree	0.01 degree from the mean value (wind still)	Y	It should be 8 times larger than the highest frequency to be studied	O	Blade	X	X	
1	Tower deflections on different height levels (fore-aft, side-side)	m	1% of maximum deflection	Y	It should be 8 times larger than the highest frequency to be studied	O	Tower	X	X	
1	Tower torsional deflection on different height levels	degree	1% of maximum deflection	Y	It should be 8 times larger than the highest frequency to be studied	O	Tower	X	X	
1	Tower-top accelerations (horizontal)	m/s2	to be determined	Y	It should be 8 times larger than the highest frequency to be studied	O	Tower	X	X	
1	Substructure and tower forces, such as anchor, tripod etc.	N	1% of maximum force	Y	It should be 8 times larger than the highest frequency to be studied	O	Substructure, Tower	X	X	
1	Support structure natural frequencies (fore-aft, side-side and torsional)	Hz	Derived parameter	-	-	O	-	X	X	X
1	Rotor blade natural frequency (edgewise, flapwise)	Hz	Derived parameter	-	-	O	-	X	X	X
1	Drive train natural frequencies	Hz	Derived parameter	-	-	O	-	X	X	X
2	Oil particle number	No.	10%	Y	<1Hz	R	Nacelle			X
2	Oil conductivity and pH value	S and PH	10%	Y	<1Hz	R	Nacelle			X
2	Nacelle position (yaw)	degree	0.1 - 0.5 degrees	Y	>=1Hz	R	Nacelle	X	X	X
2	Rotor speed (low speed shaft)	rpm	0.1-1%	Y	It should be 8 times larger than the highest frequency to be studied	R	Nacelle	X	X	
2	Rotor position (rotor azimuth)	degree	0.1 %	Y	It should be 8 times larger than the highest frequency to be studied	R	Nacelle	X	X	X
2	Generator speed (high speed shaft)	rpm	0.1-1%	Y	It should be 8 times larger than the highest frequency to be studied	R	Nacelle	X	X	X
2	Actual torque on high speed shaft	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	O	Nacelle	X	X	X
2	Demanded torque on high speed shaft	kNm	derived from controller	Y	It should be 8 times larger than the highest frequency to be studied	O	Control system	X	X	
2	Pitch angle	degree	0.01 degree	Y	It should be 8 times larger than the highest frequency to be studied	R	nacelle	X	X	X
2	Demanded pitch angle	degree	derived from controller	Y	It should be 8 times larger than the highest frequency to be studied	R	Control system	X	X	
2	Pitch rate	degree/s	Derived signal	-	-	O	-	X	X	X
2	Voltage	V	0.5%	Y	It should be 8 times larger than the highest frequency to be studied	R	At several locations; before and after the converter, at stator, etc. Also in case of DC-lines, several locations might be required	X	X	X
2	Current	A	0.5%	Y	It should be 8 times larger than the highest frequency to be studied	R	At several locations; before and after the converter, at stator, etc. Also in case of DC-lines, several locations might be required	X	X	X
2	Active electrical power	kW	Derived parameter	-	-	-	-	X	X	X (10)

Param No	Parameter / Signal	Unit	Desired Accuracy (Uncertainty)	Traceable (Y/N)	Sampling frequency range [Hz] (1)	Required / Optional	Measurement position	WP5 Operational Control Systems	WP5 Development of Control strategies	WP7 Condition Monitoring
2	Reactive electrical power	kW	Derived parameter	-	-	-	-	X	X	X
2	Grid frequency	Hz	Derived parameter	-	-	-	-	X	X	
2	Controller mode (5)	-	derived from controller	Y	It should be 8 times larger than the highest frequency to be studied	R	Control system	X	X	X
2	Availability (5)	-	derived from controller	Y	It should be 8 times larger than the highest frequency to be studied	O	-	X	X	X
2	Failure (5)	-	derived from controller	Y	It should be 8 times larger than the highest frequency to be studied	O	-	X	X	X
2	Other parameters used in the controller	-	derived from controller	Y	It should be 8 times larger than the highest frequency to be studied	O	-	X	X	X
2	Wind speed measured at nacelle	m/s	0.1 m/s	Y	>=1Hz	R	Nacelle	X	X	X
2	Wind direction measured at nacelle	degree	1 degree	Y	>=1Hz	R	Nacelle	X	X	X
3	Wind speed at different positions in the rotor plane (longitudinal, lateral and vertical) (6)	m/s	0.1 - 0.25 m/s at 10 m/s	Y	>=1Hz	O (6)	Rotor plane	X	X	
3	Wind direction at different positions in the rotor plane	degree	2-5 deg	Y	>=1Hz	O	Rotor plane	X	X	
3	Air Temperature	C	0.5-3 °C	Y	>=1Hz	R	Hub height	X		X
4	Ice detection	-	-	-	-	O	Structure	X		X
6	Acoustic pressure measurements (11)	Pa	<0.1dB	Y	>22.4kHz	O	Individual components			X

Comments:
(1) For many parameters, it is noted that the sample frequency should be 8 times larger than the highest frequency to be studied.
This is most practical, since the parameters could be used for more purposes with own requirements.
(2) Displacements. Examples are gearbox displacements, angular displacements of flexible coupling, etc.
(3) Velocities. Examples are pitch piston velocities, main shaft velocities etc.
(4) Acceleration. Examples are accelerations in subcomponents etc.
(5) The controller should provide an output to monitor the state of the controller. It is not an input for the controller.
(6) If methods are developed to determine the wind characteristics in the rotor area in front of the turbine, this would be used.
(7) Cross sectional accelerations are required at each cross section in order to resolve flapwise as well as torsional vibrations.
(8) Main purpose for CM is monitoring of the main bearing.
(9) CM focuses on vibration analyses on all bearings, the gearbox as well as the blades.
(10) Is a requirement for CM. May be derived form turbine controller (IEC61400-25).
(11) Acoustic pressure measurements with the intention to early detect structural faults.

Analysis
1. We assume that vibrations or accelerations in the tower are used for the control, the tower bending moments are not applied.
2. We assume that strain distributions are not included for control or condition monitoring.
3. Condition monitoring tends to have the same signals as the control system.
Note that this is a consequence of the fact that when condition monitoring is a useful contribution to the turbine, it is advantageous to include it in the control itself.
4. Insurance regulations have to be considered; If the CM is integrated in the controller, it requires a certificate, at least for the German market.

Appendix C Transmission and conversion and Electrical Grid

Table C.1 *List of parameters for WP1B2 Transmission and conversion and WP9 Electrical Grid*

Param No	Parameter / Signal	Unit	Desired Accuracy (Uncertainty)	Traceable (Y/N)	Sampling frequency range [Hz]	Required / Optional	Measurement position	WP9 Electrical Grid	WP1B2 Transmission and conversion	Power Quality Measurements
1	Displacements (1)	m	To be determined	Y	It should be 8 times larger than the highest frequency to be studied	O	Individual components		X	
1	Velocities (2)	m/s	To be determined	Y	It should be 8 times larger than the highest frequency to be studied	O	Individual components		X	
1	Accelerations (3)	m/s2	To be determined	Y	It should be 8 times larger than the highest frequency to be studied	O	Individual components		X	
1	Temperatures	C	To be determined	Y	It should be 8 times larger than the highest frequency to be studied	O	Individual components	X	X	
1	Pressure	Pa	To be determined	Y	It should be 8 times larger than the highest frequency to be studied	O	Individual components		X	
1	Yaw moment	kNm	Target 3%	Y	It should be 8 times larger than the highest frequency to be studied	R	Nacelle, it could be measured from the rotating structure, or from the fixed structure.		X	
1	Tilt moment	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	R	Nacelle, it could be measured from the rotating structure, or from the fixed structure.		X	
1	Main shaft bending (0° 90°)	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	R	Main shaft		X	
1	Main shaft torsion	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	R	Main shaft		X	
1	Strain distribution to determine local stress distributions and for instance shear (anywhere)	kN	3%	Y	It should be 8 times larger than the highest frequency to be studied	R	Blade, hub, tower, nacelle, substructure, foundation and individual components		X	
1	Blade bending moment at the root of the blade (flapwise and edgewise)	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	R	Blade		X	
1	Blade root bending moment (in-plane and out-of-plane)	kNm	Derived from blade bending moments and pitch angles	-	-	-	-		X	
1	Rotor blade natural frequency (edgewise, flapwise)	Hz	Derived parameter	-	-	-	-		X	
1	Drive train natural frequencies	Hz	Derived parameter	-	-	-	-		X	
2	Nacelle position (yaw) (4)	degree	0.1 - 0.5 degrees	Y	>=1Hz	R	Nacelle		X	
2	Rotor speed (low speed shaft)	rpm	0.1-1%	Y	It should be 8 times larger than the highest frequency to be studied	R	Nacelle		X	
2	Rotor position (rotor azimuth)	degree	0.1 %	Y	It should be 8 times larger than the highest frequency to be studied	R	Nacelle		X	
2	Generator speed (high speed shaft)	rpm	0.1-1%	Y	It should be 8 times larger than the highest frequency to be studied	R	Nacelle		X	X
2	Actual torque on high speed shaft	kNm	3%	Y	It should be 8 times larger than the highest frequency to be studied	R	Nacelle		X	

param No	Parameter / Signal	Unit	Desired Accuracy (Uncertainty)	Traceable (Y/N)	Sampling frequency range [Hz]	Required / Optional	Measurement position	WP9 Electrical Grid	WP1B2 Transmission and conversion	Power Quality Measurements
2	Demanded torque on high speed shaft	kNm	Derived from controller	Y	It should be 8 times larger than the highest frequency to be studied	R	Control system		X	
2	Voltage AC	V	0.5%	Y	It should be 8 times larger than the highest frequency to be studied, typically >= 2048Hz. Power Quality: sampling frequency >= 5kHz and harmonics with >=20kHz.	R	At several locations;before and after the convertor, at stator, etc. Power Quality: Measurement on MV side (10 to 20kV) may be required for (very large) wind farms.	X (4)	X	X
2	Current AC	A	0.5%	Y	It should be 8 times larger than the highest frequency to be studied, typically >= 2048Hz. Power Quality: sampling frequency >= 5kHz and harmonics with >=20kHz.	R	At several locations;before and after the convertor, at stator, etc. Power Quality: Measurement on MV side (10 to 20kV) may be required for (very large) wind farms.	X (4)	X	X
2	RMS values for voltage	V	Derived parameter	-	-	-	-	X	X	X
2	RMS values for current	A	Derived parameter	-	-	-	-	X	X	X
2	Absolute time (e.g. for assessing response to voltage drops)	sec	1microsec	Y	It should be 8 times larger than the highest frequency to be studied, typically >=10Hz	R	-			X
2	Grid Frequency	Hz	0.2% (may also be a derived parameter)	Y	It should be 8 times larger than the highest frequency to be studied, typically >=10Hz	R	-			X
2	Voltage DC	V	0.5%	Y	It should be 8 times larger than the highest frequency to be studied, typically >=10Hz	R	At several locations;before and after the convertor, at stator, etc. In case of DC-lines, several locations might be required	X (4)	X	X
2	Current DC	A	0.5%	Y	It should be 8 times larger than the highest frequency to be studied, typically >=10Hz	R	At several locations;before and after the convertor, at stator, etc. In case of DC-lines, several locations might be required	X (4)	X	X
2	Active electrical power	kW	Derived parameter	-	-	-	-	X	X	X
2	Reactive electrical power	kVAr	Derived parameter	-	-	-	-	X	X	X
2	Phases	-	Derived parameter	-	-	-	-	X	X	X
2	Controller mode	-	Derived from controller	Y	It should be 8 times larger than the highest frequency to be studied	R	Control system	X	X	X
2	Status	-	Derived from controller	Y	It should be 8 times larger than the highest frequency to be studied	R	Control system	X	X	X
3	Wind speed measured at nacelle	m/s	0.1 m/s	Y	>=1Hz	R	Nacelle	X	X	X
3	Wind direction measured at nacelle	degree	1 degree	Y	>=1Hz	R	Nacelle	X	X	
6	Acoustic pressure measurements	Pa	<0.1dB	Y	>22.4kHz	O	Individual components		X	

Comments:
(1) Displacements. Examples are gearbox displacements, angular displacements of flexible coupling, etc
(2) Velocities. Examples are pitch piston velocities, main shaft velocities etc.
(3) Acceleration. Examples are accelerations in subcomponents etc.
(4) In addition to these measurements, also high-frequency measurement campaigns might be required with sample frequencies >10kHz

Appendix D Flow and Remote Sensing

Table D.1 *List of parameters for WP8 Flow and WP6 Remote Sensing*

Param No	Parameter / Signal	Unit	Desired Accuracy (Uncertainty)	Traceable (Y/N)	Sampling frequency range [Hz]	Required / Optional	Measurement position	WP6 Remote Sensing	WP8 Flow Characterisation within and around wind farm
3	Wind speed (longitudinal, lateral and vertical) covering the rotor plane, below and above	m/s	0.1m/s	Y	>=1Hz	R	From 10m to one and a half times tip height; at several distances before and behind the turbine	X	X
3	Wind direction (longitudinal, lateral and vertical) covering the rotor plane, below and above	degree	1 degree	Y	>=1Hz	R	From 10m to one and a half times tip height; at several distances before and behind the turbine	X	X
3	Turbulence in the wind	%	derived parameter from horizontal wind speed	-	-	O	Rotor plane, free sector	X	X
3	Air Temperature	°C	0.5-3 °C	Y	>=1Hz	R	Hub height, ground level	X	X
3	Temperature difference	°C	0.01-0.1 °C	Y	>=1Hz	O	Rotor plane; offshore the difference between air temperature and sea water temperature may be dominating	X	X
3	Air relative humidity	%	3%	Y	>=1Hz	O	Hub height, ground level	X	X
3	Atmospheric pressure	hPa	5 hPa	Y	>=1Hz	R	Hub height, ground level	X	X
2	WT status signal	-	derived from controller	Y	>=1Hz	R	Control system		X
2	WT Grid Connected signal	-	derived from controller	Y	>=1Hz	O	Control system		X
2	Blade condition - icing, dust, insects	-	-	-	-	O	Blades		X
2	Rotor speed (low speed shaft)	RPM	0.1-1%	Y	1-10Hz	O	-		X
2	Pitch angle	degree	0.1-0.5 degree	Y	1-10Hz	R	-		X
2	Control Settings	-	derived from controller	Y	>=1Hz	O	-		X
2	Nacelle position (yaw)	degree	0.1-0.5 degree	Y	>=1Hz	R	Nacelle		X
2	Nacelle anemometer	m/s	0.1m/s	Y	>=1Hz	R	Nacelle		X
2	Active electrical power	kW	0.5%	Y	>=1Hz	R	Between wind turbine and electrical connection		X

Comments:
Remote sensing is performed from the ground, or could be performed from the wind turbine or mast.
Remote sensing from the nacelle could be

1. pointed to the front (inflow wind field),
2. pointed to the back (wake), pointed up (flow above wind farm).

Remote sensing from a mast could for instance assist the (complex terrain) power performance analysis.

Appendix EPower Performance analysis (IEC 61400-12-1)

Table E.1 *List of parameters for Power Performance analysis according IEC 61400-12-1.*

Param No	Parameter / Signal	Unit	Desired Accuracy (Uncertainty)	Traceable (Y/N)	Sampling frequency range [Hz]	Required / Optional	Measurement position	Power Performance	Site Calibration
2	Active electrical power	kW	0.5%	Y	>=1Hz	R	Between wind turbine and electrical connection	X	
2	Reactive electrical Power	kVAr	0.5%	Y	>=1Hz	O	Between wind turbine and electrical connection	X	
2	WT Availability Status signal	-	derived from controller	Y	>=1Hz	R	Control system	X	
2	WT Grid Connected signal	-	derived from controller	Y	>=1Hz	O	Control system	X	
2	Blade condition - icing, dust, insects	(1)	-	-	-	O	Blades	X	
2	Rotor speed (low speed shaft)	rpm	0.1-1%	Y	>=1Hz	O	-	X	
2	Pitch angle	degree	0.1-0.5 degree	Y	>=1Hz	O	-	X	
2	Control Settings	-	derived from controller	Y	>=1Hz	O	Control system	X	
2	Nacelle position (yaw)	degree	0.1-0.5 degree	Y	>=1Hz	O	-	X	
2	Yaw misalignment	degree	Derived parameter from nacelle position and wind direction	-	-	O	-	X	
3	Wind speed, horizontal component	m/s	0.1 - 0.25 m/s at 10 m/s	Y	>=1Hz	R	Hub height, free sector	X	X
3	Wind speed, horizontal component	m/s	0.1 - 0.25 m/s at 10 m/s	Y	>=1Hz	R	Hub height on a mast at the turbine location		X
3	Wind speed measured at other heights	m/s	0.1-0.25 m/s at 10 m/s	Y	>=1Hz	O	Rotor plane, free sector	X	X
3	Wind speed, vertical component	m/s	0.1 - 0.25 m/s	Y	>=1Hz	O	Rotor plane, free sector	X	X
3	Turbulence in the wind	%	Derived parameter from horizontal wind speed	-	-	O	Rotor plane, free sector	X	X
3	Wind direction	degree	2-5 deg	Y	>=1Hz	R	Rotor plane, free sector	X	X
3	Air Temperature	°C	0.5-3 °C	Y	>=1Hz	Power performance: R Site calibration: O	Hub height	X	X
3	Temperature difference	°C	0.01-0.1 °C	Y	>=1Hz	O	Rotor plane	X	X
3	Air relative humidity	%	3%	Y	>=1Hz	O	Hub height	X	X
3	Atmospheric pressure	hPa	5 hPa	Y	>=1Hz	Power performance: R Site calibration: O	Hub height	X	X
3	Atmospheric Stability	[-]	Derived from wind speed measurements in the rotor plane and temperature difference	-	-	O	-	X	X

Appendix F Noise Measurements (IEC 61400-11)

Table F.1 *List of parameters for Noise measurements according IEC 61400-11.*

Param No	Parameter / Signal	Unit	Desired Accuracy (Uncertainty)	Traceable (Y/N)	Sampling frequency range [Hz]	Required / Optional	Measurement position	Noise Measurements
2	Active electrical power	kW	0.5%	Y	>=1Hz	R	Between wind turbine and electrical connection	X
2	Rotor speed (low speed shaft)	rpm	0.1-1%	Y	>=1Hz	R	-	X
2	Pitch angle	deg	0.1-0.5 degree	Y	>=1Hz	R	-	X
2	Control Settings	-	Derived from controller	Y	>=1Hz	R	Control system	X
3	Wind speed horizontal	m/s	0.1 - 0.25 m/s at 10 m/s	Y	>=1Hz	R	Rotor plane, free sector	X
3	Wind speed horizontal	m/s	0.1 - 0.25 m/s at 10 m/s	Y	>=1Hz	R	Nacelle wind speed	X
3	Turbulence in the wind	%	Derived parameter from horizontal wind speed			R	Rotor plane, free sector	X
3	Wind direction	deg	2-5 deg	Y	>=1Hz	O	Rotor plane, free sector	X
3	Air Temperature	°C	0.5-3 °C	Y	>=1Hz	R	Hub height	X
3	Air relative humidity	%	3%	Y	>=1Hz	O	Hub height	X
3	Atmospheric pressure	hPa	5 hPa	Y	>=1Hz	R	Hub height	X
3	Atmospheric Stability	[-]	Derived from wind speed measurements in the rotor plane and temperature difference			O	-	X
6	Acoustic pressure	Pa	<0.1dB	Y	>22.4kHz	R	On a ground plate behind the turbine	X