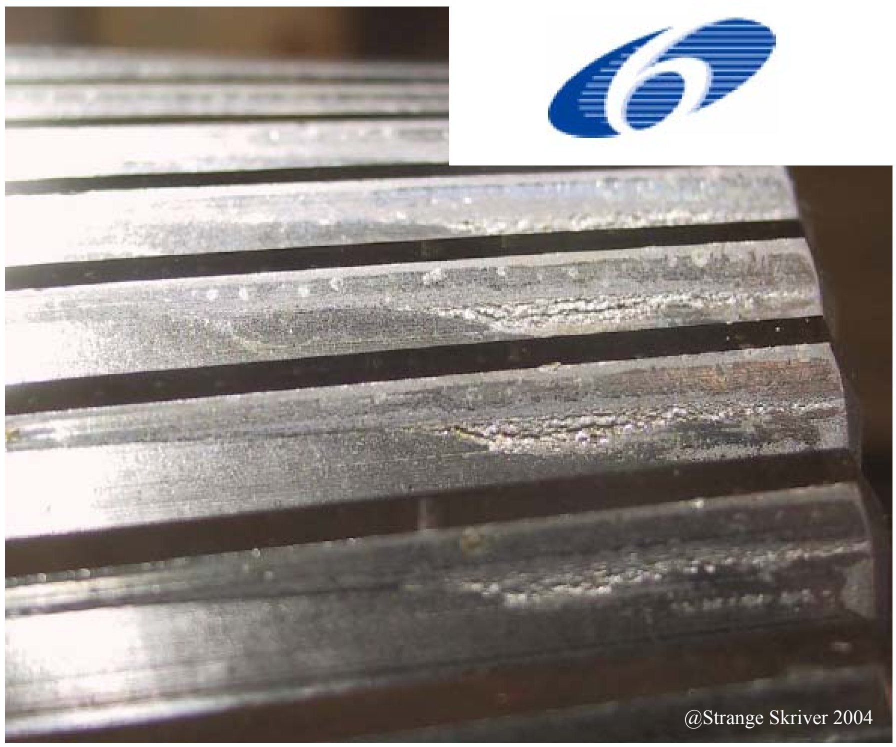
RISØ

Risø-R-Report

Risø-R-1593(EN)

Work Package 1B.2 under the European Commission, Integrated Wind Turbine Design (UPWIND): Specification of Long-Term Load Measurement Technique

Uwe Schmidt Paulsen, Nicolaos Cutululis, Poul Sørensen



Risø National Laboratory
Technical University of Denmark
Roskilde
Denmark
February 2007

DTU

Author: Uwe Schmidt Paulsen, Nicolaos Cutululis, Poul Sørensen
Title: Work Package 1B.2 under the European Commission, Integrated Wind Turbine Design (UPWIND): Specification of Long-Term Load Measurement Technique
Department: Wind Energy Department, Test and Measurement

Risø-R-1593(EN)
February 2007

Abstract (max. 2000 char.):

The present report is the 12 month intermediate report of the UPWIND WP1B2 transmission and conversion describes the developed measurement technique for long-term load measurement technique, presents the hardware details, type of sensors and location, data storage and data analysis technique to verify design load assumptions.

The work is carried out under Contract no 019945 (SES6) "UPWIND" within the European Commission

ISSN 0106-2840
ISBN 978-87-550-3579-9

Contract no.:

019945

Group's own reg. no.:
(Føniks PSP-element)
1125137-01

Sponsorship:

Cover :

Pages:25
Tables:2
References:26

Information Service Department
Risø National Laboratory
Technical University of Denmark
P.O.Box 49
DK-4000 Roskilde
Denmark
Telephone +45 46774004
bibl@risoe.dk
Fax +45 46774013

Contents

Preface

This work is part of the sixths framework programme on the integrated design for wind turbines within transmission/conversion with the acronym UPWIND[1], which in particular for the work package WP 1B2 transmission and conversion deals with "..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."[2].

The members of the working group under WP 1B2 are:

WP Member	Country	Name
Risoe National Laboratory	Denmark	RISOE
GE Global Research, a registered branch office of General Electric Deutschland Holding GmbH	Germany	GE
WZL der RWTH Aachen	Germany	WZL
Samtech s.a.	Belgium	SAMT
Lohmann und Stolterfoht GmbH	Germany	REXR
Aalborg University	Denmark	AAU
Delft University of Technology	Netherland	DUWIND
University of Edinburgh	UK	EDIN
ISET	Germany	ISET
Fundacion ROBOTIKER	Spain	ROBOT

This report is a part of the deliverables from Risoe National Laboratory on the contribution to the integrated project.

The work is carried out under Contract no 019945 (SES6) "UPWIND" within the European Commission

1 Introduction

It is further stated in the DOW[2] of the project, that the drive train in terms of reliability today is the most critical component of modern wind turbines, a statement which might be enhanced by looking at the picture provided in the front page, demonstrating *gear wheel pitting* observed on a Flender PEAC gearbox .

The typical drive train of modern wind turbines consists of an integrated serial approach where rotor shaft, main bearing, gearbox and generator are as close 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. The following different system parts need to be addressed within one coupled “integral” model: Wind field simulation; Aero-elastic interaction at blades; Nonlinear flexibilities of fibre blades; Linear flexibilities of metal components of e.g. drive train; Nonlinear behaviour of drive train components e.g. gears, bearings, bushings; Electro-mechanic behaviour of generator; Electrical behaviour of power electronic converter and grid.

Depending on the specific location of a wind turbine the actual loads on the components are quite different from the design loads, which for the reasons of the component level needs verification on a real wind turbine. The objective of this work is to participate within the work package with a set of specific information, which validates the design assumptions. Therefore a long-term measurement technique is the necessary tool to provide load cycle analysis for all turbine conditions. As a secondary effort on a technology driven approach, the same technology will be used for development of a low-cost drive train load monitoring system, which enables to down-count the proposed and designed lifetime according to the actual measured load cycles. The measured load cycles for specific conditions will be compared to simulation results performed within task 1B.2a.1. Thus the commonly used assumptions for component design can be verified and enhanced towards future large-scale wind turbines. Electromechanical models for wind turbines usually include the drive train components of the wind turbine, while aeroelastic models apply simplified generator models. However, preliminary simulations and measurements have indicated that there is a significant dynamic coupling between the generator and the wind turbine structure beyond the drive train, and that this coupling can cause oscillations in the drive train and tower. The interaction between the mechanical system and the generator will be studied further as explained in 4 Design tools.

Risø elaborates in the project on a drive train measurement system for long-time measurements, in particular generator power P and angular rotor speed Ω with high accuracy both in time resolution and with appropriate dynamical performance as in 3

Extended experimental approach. The aim is to demonstrate that the drive train conditions can be measured in a simple and robust way. In order to ensure sufficient bandwidth, the generator power is derived by measured 3-phase generator AC current I and –voltage V according to:

$$P(t) = \sum_{i=1}^{3} U_i(t) \cdot I_i(t)$$

The measurements are expected to be carried out on the 500 kWwind turbine online measurement laboratory (WTMLAB) facilities at the Risø Campus (http://www.winddata.com/nordtank/). Analysis of indicated electromagnetic generator torque (equal to $P \cdot \Omega^{-1}$) is provided with subsequent emphasis on describing the interaction between the mechanical and the electrical system under wind turbine operation. The method is tested for robustness by comparing with results of measured mechanical torque Q. Based on this comparison done in the time domain as well as frequency domain, the bandwidth with which the mechanical torque is close to the electrical is determined and compared to the free-free eigenfrequency for oscillation between generator and wind turbine rotor inertias. The possible benefit of including the generator inertia in a dynamic conversion of power and speed to mechanical torque is also investigated. The probability distribution of the indicated torque is calculated for the complete measurement period. Load cycles under specific wind turbine and - conditions are investigated. The measured load spectrum is compared to the compound design load spectrum. Elaboration on higher order excitations from primarily the indicated torque is performed. Simulations with and without interaction between the mechanical and electrical system and comparison with measurements are carried out.

Risø's aeroelastic model HawC and electromechanical wind turbine models build in DIgSILENT Power Factory software are combined for analysis of the interaction between the mechanical- and electrical system. This issue will be studied further, applying HawC model with generator dynamics and/or a Power Factory model with extended structural model beyond the drive train. The measurements will be applied to validate the simulations.

2 Description of the experimental facility

2.1 Site

The Wind turbine is geographically located at the Risø Campus, about 6 km North of Roskilde as shown on Figure 1. The wind turbine is placed on the foundation no 4, in a rather gentle sloping terrain towards the area 'Bløden' on the west side of the Roskilde firth. The free undisturbed inflow is from the dominant western wind sector.

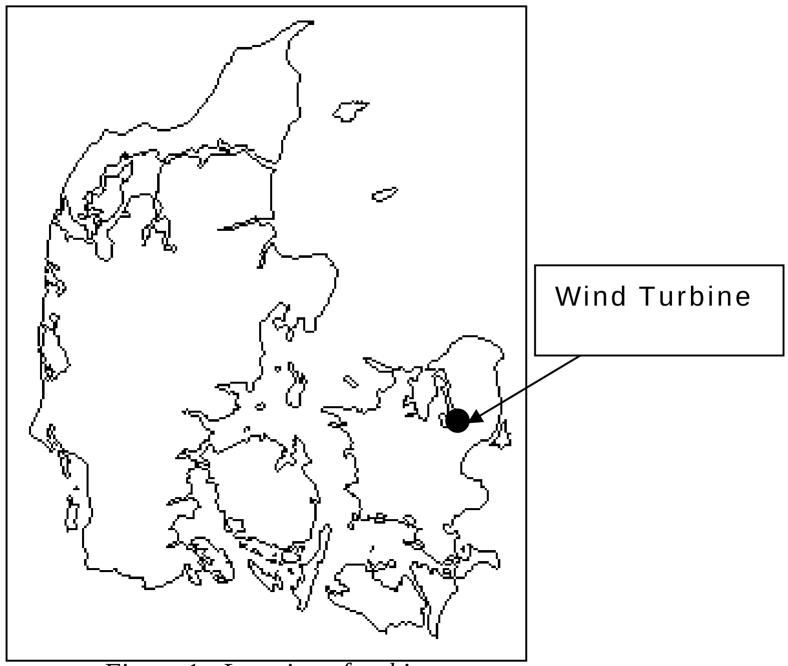


Figure 1: Location of turbine

2.2 Wind Turbine Description

The test wind turbine, which is located at Risø Campus, Roskilde, is a traditional Danish three-bladed stall regulated Nordtank, NTK 500/41 wind turbine – see specifications in table 1. The turbine is primarily used for energy production and tests and it is serviced on commercial conditions.

Table 1: Nordtank NTK 500/41 specifications.

Identification No.	92-500
Rotor	
Rotor Diameter	41.1m
Swept area	1320 m²
Rotational Speed:	27.1 rpm
Measured tip angle:	-0.2º±0.2º
Tilt	2º
Coning	0º
Blades	
Blade type:	LM 19.1
Blade profile[s]	NACA 63-4xx & NACA FF-W3, equipped with vortex generators.
Blade length:	19.04 m
Blade chord:	0.265 – 1.630 m
Blade twist:	0.02 – 20.00 degrees
Air brakes	Pivotal blade tips, operated in FS-mode
Drivetrain	

Mechanical brake	High speed shaft, operated in FS-mode
Power regulation	Passive aerodynamic stall
Gearbox	Flender; ratio 1:55.35
Generator	Siemens 500 kW, 4 poles, 690 V
Tower	
Type	Conical steel tube, h=33.8 m
Hub height	36.0 m
Masses:	
Blade weight:	1960 kg
Rotor incl. hub	9030 kg
Tower head mass	24430 kg
Tower mass	22500 kg

The turbine was installed in 1992 with a 37 m diameter rotor, which in 1994 was substituted with a 41 m diameter rotor in combination with a rotor speed reduction to limit the power output. The wind turbine has been subjected to tests and investigations during 1992- 1999 according to references [3,4,5,6,7,8,9]. There have been load measurements on the wind turbine drive train [16], and load simulations on a 600 kW gearbox design similar to the present wind turbine gearbox [17].

2.3 Grid connection

The wind turbine is connected to a local 400 V grid, designed for test of smaller wind turbines. The 400 V is supplied from the public 10 kV grid through a 1000 kVA, 10/ 0.4 kV transformer that is presently shared between the 500 kW Nordtank wind turbine and a 100 kW Tellus wind turbine.
The Nordtank wind turbine is rated to 690 V, and therefore an additional 800 kVA, 0.4 / 0.69 kV transformer is installed to increase the voltage. The principal electric connection diagram is shown in Figure 2.

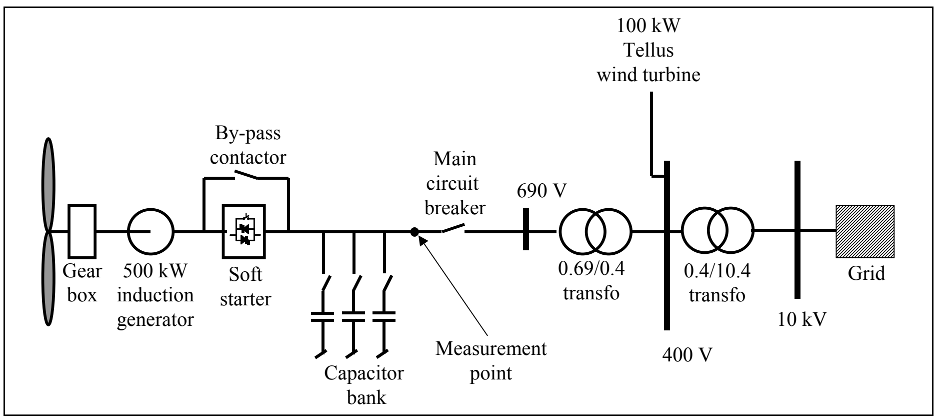


Figure 2: Connection diagram of 500 kW Nordtank in Risø.

A frequency converter system has been designed and implemented allowing the wind turbine to operate at variable grid frequency. This wind turbine operation mode can be switched to from stall regulated mode by means of a by-pass contactor as seen on Figure 2.

2.4 Instrumentation

Presently the experimental facility is instrumented as described in the following:
A meteorological mast is placed 2½ rotor diameters in westerly direction from the wind turbine. The mast is equipped for measurement of wind speed at hub height, wind direction, air temperature, air barometric pressure and air humidity. The installation is made in accordance with the recent IEC recommendations for both power performance [10]and structural load measurements[11] and [15].

The structural loads are monitored by strain gauges mounted at the blade root, on the main shaft, at the tower top and at the tower bottom. The instrumented locations are detailed below:

2.4.1 Blade

The load signals from the reference blade includes bending moments at the blade root, measured by strain gauges mounted on the blade root steel extenders, as shown on Figure 3. The gauge installation enables measurements of both flap-wise and edge-wise bending moments in a rotating reference system. During autumn 2005 the strain gauges installation has been extended with strain gauges on all three blades, both for measuring flap-wise and edge-wise bending moments in the blade root.

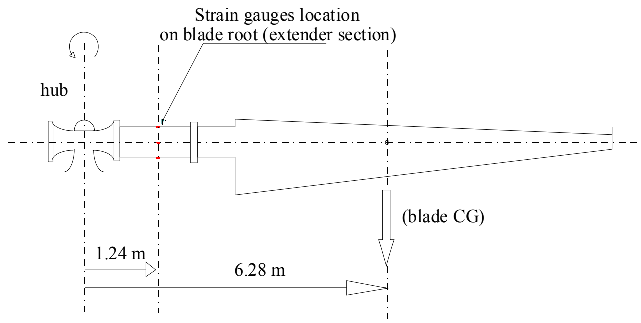


Figure 3: Structural load measurements in the blade root at radius 1.24 m.

2.4.2 Rotor

The load measurement on the main shaft includes torque and two bending moments at a position behind the hub/main shaft flange – in a rotating reference system, as shown on Figure 4 . The gauge location enables measurements of bending moments in two directions, perpendicular to each other in a rotating reference system. The two bending moments combined with the rotor position are used to determine the rotor bending moments in yaw and tilt direction - in a nacelle reference system.

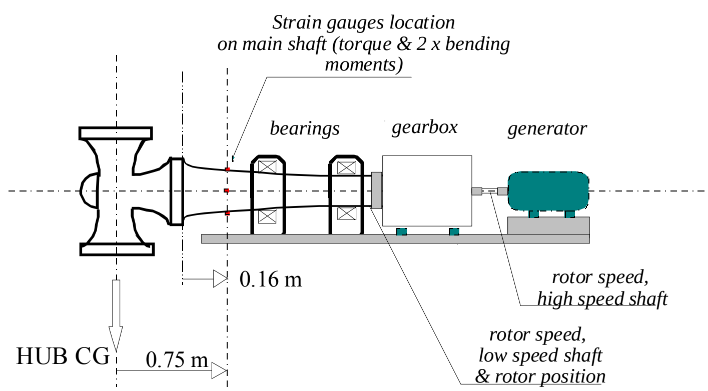


Figure 4: Structural load measurements on the main shaft.

2.4.3 Tower

The tower loads includes torque at the tower top and bending moments in two directions at the tower bottom, as shown on Figure 5 in a (fixed) tower reference system.

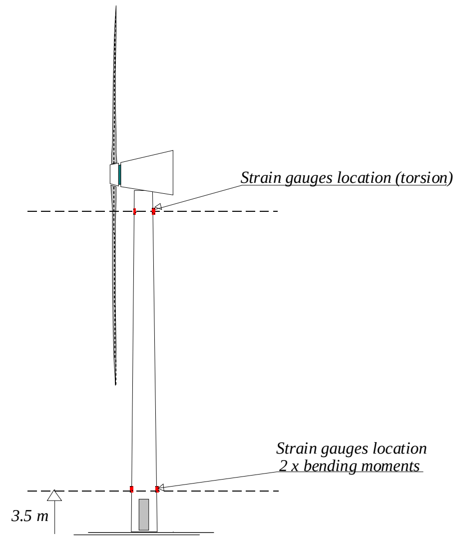


Figure 5: Structural load measurements on the welded tubular steel tower.

Various sensors are installed to measure the operational conditions of the wind turbine. The position of the nacelle, the wind direction and the wind speed on top of the nacelle are measured. Pulses from sensors placed on the fast rotating generator shaft and on the slow rotating main shaft are used to determine the rotational speeds. Status information on tip position, grid connection and shaft brake are registered. Finally, the electric power production is derived by integrating measurements of the 690 V line voltages and currents in the time domain using the Time Division Multiplication Principle.
An overview of the signals, the type and sensor conversion principle is given in Table 2.

Table 2: Sensor and transmitter description.

Measurement description	Sensor	Signal type	Conversion principle	Transmitter
Wind speed at hub height	Risø cup anemometer P2546A with Reed relay	Digital	2 magnets on turning shaft controls the contact closure timings of the relay per revolution	Risø P2858A DAU Configured to periodic time measurement
Wind Direction at hub height-1.5m	Wind vane P2021A with Cosine/Sine resolver	Analogue	2-phase transformer w. rotor mounted directly on turning shaft, attached to vane	Risø P2420 (DC to AC supply, 2 separate channels sin and cos)
Air temperature at hub height – 1.5m	Pt 100 thermistor and radiation shielding	Analogue	Metal Resistor response to heat	Risø P1867a (Wheatstone Bridge)
Air barometric pressure 1 m..a.g.l	Vaisala PTB100B Pressure sensitive vessel with position gauge	Analogue	Measuring of gauge position	
Precipitation	LED Light array	Digital	Blockage of light array path	LED circuit
Position of nacelle	Resistor with gearbox attached to yaw drive	Analogue	Measuring on resistive path	Voltage divider
Position of	Inductive sensor on low speed	Digital	Dampening of transistor	Risø P2858A DAU

rotor	shaft together with inductive sensor on high speed shaft with 6 holes		oscillations due to presence of metal provides pulse	Configured to position measurement
Rotor shaft speed low speed	Inductive sensor one pulse/rev	Digital	Dampening of transistor oscillations due to presence of metal provides pulse	Risø P2858A DAU Configured to periodic time measurement
Rotor shaft speed high speed	Inductive sensor with 6 pulses/rev	Digital	Dampening of transistor oscillations due to presence of metal provides pulse	Risø P2858A DAU Configured to periodic time measurement
Wind speed nacelle	Risø cup anemometer P2546A with Reed relay	Digital	2 magnets on turning shaft controls the contact closure timings of the relay per revolution	Risø P2858A DAU Configured to periodic time measurement
Wind Direction nacelle	Vector Wind vane F2819A	Analogue	Measuring on resistive viper path relative to one full turn	Voltage divider
Flap-wise bending root moment #1	Sokki TLM Strain Gauge WFLA-6-11	Analogue	Semiconductor foil subjected to resistive change due to bending	RisøP2912B SG amplifier
Edge-wise bending root moment #1	Sokki TLM Strain Gauge WFLA-6-11	Analogue	Semiconductor foil subjected to resistive change due to bending	Risø P2912B SG amplifier
Rotor shaft torque	Micro Measurement Strain Gauge CEA-06-W250C-350	Analogue	Semiconductor foil subjected to resistive change due to twisting	Risø P2912B SG amplifier
Main shaft bending moment X,	Micro Measurement Strain Gauge CEA-06-250A-350	Analogue	Semiconductor foil subjected to resistive change due to bending	Risø P2912B SG amplifier
Main shaft bending moment Y	Micro Measurement Strain Gauge CEA-06-250A-350	Analogue	Semiconductor foil subjected to resistive change due to bending	Risø P2912B SG amplifier
Tower top torsion,	Micro Measurement Strain Gauge CEA-06-W250C-350	Analogue	Semiconductor foil subjected to resistive change due to twisting	Risø P2912B SG amplifier
Tower bottom bending moment X	Micro Measurement Strain Gauge CEA-06-250C-350	Analogue	Semiconductor foil subjected to resistive change due to bending	Risø P2912B SG amplifier
Tower bottom bending moment Y	Micro Measurement Strain Gauge CEA-06-250UW-350	Analogue	Semiconductor foil subjected to resistive change due to bending	Risø P2912B SG amplifier
Electrical Power	Camille Bauer 502-34F1 Z291 0090 61 Watt converter, cl 05	Analogue	Time division multiplier principle of 3 voltage and 3 current signals	3 Garre G30/20 cl. 01 Current transformers 500/1
Tip deployment indicator	Via Controller electronics	Digital	Non-potential hazardous NPN signal amplifier	Risø P2858A DAU Configured to status measurement
Brake activation indicator	Via Controller electronics	Digital	Non-potential hazardous NPN signal amplifier	Risø P2858A DAU Configured to status measurement
Generator mode indicator	Via Controller electronics	Digital	Non-potential hazardous NPN signal amplifier	Risø P2858A DAU Configured to status measurement
Operations mode indicator	Via Controller electronics	Digital	Non-potential hazardous NPN signal amplifier	Risø P2858A DAU Configured to status measurement

Conventional measurement transformers are used to measure at the 690 V level at the generator terminals.
Three voltage transformers combined with differential 10:1 probes on the secondary side reduces the phase voltages to the 5 Volt level.
Three current transformers (ratio 500:1) followed by Hall elements convert the phase currents to voltage signals in the ratio 1A to 100 mV.

2.4.4 Data Acquisition

A PC-based data acquisition system has been designed to monitor and collect data from the wind turbine sensors – see Figure 6: Complete data acquisition system.

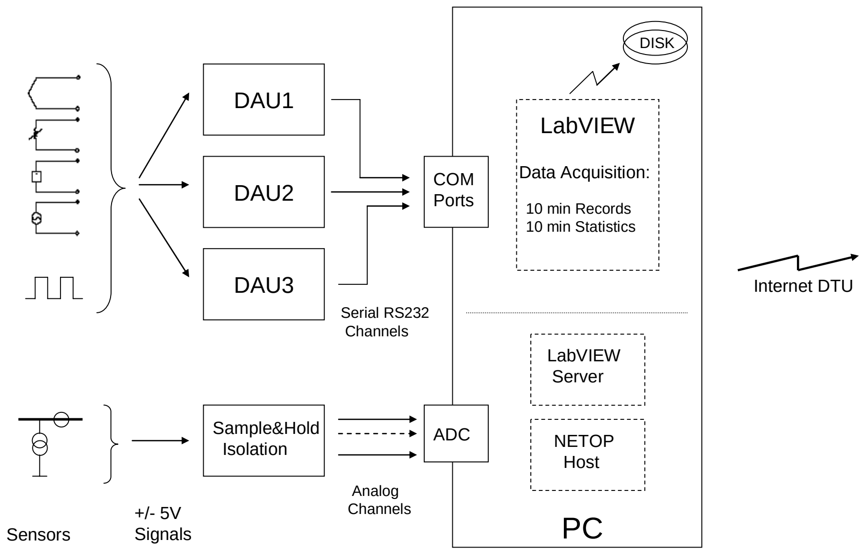


Figure 6: Complete data acquisition system

The output signals from all sensors are conditioned to the +/- 5 V range. Analogue signals are either continuously varying (strain gauges, temperature…), digital types such as train of pulses (rotational speed, anemometer…) or on/off levels (status signals for brake, blade tips and generator modes). All signals - except outputs from voltage and current transformers - are connected to one of three RISØ P2558A data acquisition units (DAU), each of which provides 16 analogue input channels and 6 general-purpose digital input channels [14]. The analogue inputs are converted into 16-bit quantities. Data from all channels are assembled in a binary telegram, each data occupying 16 bits. The telegram is preceded by two synchronization bytes and it is succeeded by two check-sum bytes. The whole telegram is transmitted to the PC over a RS232 serial channel at a rate of 38400 Baud. The sampling rate at the DAUs is set to 35 Hz so new telegrams are created and send 35 times per second per channel.

One DAU is installed in the bottom of the wind turbine tower, another in the nacelle and the last one is mounted on the hub – it is rotating and transmitting data over a RF-link. The serial channel from each DAU is connected to the PC over a multi-port serial plug-in board.

The 35 Hz scan rate is high when considering meteorological conditions, appropriate for mechanical phenomena, but it is far too slow when studying the impact of the wind turbine on the power grid or mechanical loading in the drive train. Thus, another part of the acquisition system works at a much higher sampling rate (12.8 kHz) on transducer signals originating from the 3 phase voltages and currents at the 690 V generator terminals – see Figure 1. The signals are fed to a signal-conditioning interface that performs sample and hold operation, scales down the signals to the ±5 V level and delivers the conditioned signals to a 12-bit multi-channel ADC plug-in board in the PC.

The data acquisition system is build up around a standard desktop PC. The PC is connected to the Internet and thereby to DTU from where it can be operated remotely.

An important aspect of WTMLAB is instant access to a real wind turbine, which are well documented at all possible operational situations. Besides being a test facility the wind turbine works as production unit creating revenue for Risø, so most of the time it is running on normal, commercial basis.
To build up complete documentation of the wind turbine behaviour, data acquisition is carried out constantly. Dedicated measurement software has been developed under LabVIEW©. The data streams received on the serial channels from the DAUs are read, error checked and the measured values are derived from the data telegrams. Data are assembled in 10-minutes time series and statistics such as mean, standard deviation, maximum and minimum values are calculated. The whole time series and the statistics – with a time stamp added – are stored on disk in ASCII-format.
The electric power signals are treated differently due to the fast sampling rate. The idea is to aggregate power quality parameters over 10 minutes' intervals – synchronous with the DAU intervals - so atmospheric, mechanical and electrical behaviour directly can be correlated. To diminish the amount of data, on-line data reduction is compulsory.
Another benefit of WTMLAB is that the students are able to develop data acquisition programs of their own, upload the programs to the PC at Risø and perform test directly on an operating wind turbine. In addition, due to the built-in server in LabVIEW©, the measurement application can be monitored and controlled across the Web.

3 Extended experimental approach

3.1 Methodology

The DOW of WP 1B2[2] provides a road map to issues on mechanical transmission systems which to be covered, and has been mentioned in the introduction to this report:
Firstly, a novel method of gathering an estimate for the mechanical torque is presented. The suggested method originates from using the AC measured power and converting this into a torque. The method is applicable to systems with a well defined power-outlet, which simply states that the energy produced or dissipated can be experimentally measured. For the actual wind turbine the asynchronous generator directly driven via the gearbox high speed shaft outlet and the power is easily measured at the nodal point within the controller shown in Figure 2. For the turbine there is additionally a practical point that the gearbox losses are quite moderate and constant and mostly concerned with friction in bearings and thermal influences on lubrication. To verify the method an independent measure of mechanical torque is necessary along with rotor shaft speed.
Secondly, the interaction is investigated between the impacts from mechanical substructures-primarily originating from the 1´st modal shape of the tower movement and the rotor stator relative movement in the generator, by monitoring the angular deflection of the tower and comparing this against the electrical power.
The signals are basis for statistical treatment in terms of parametric dependency rain flow counting and for test of robustness in a broader perspective in the wind energy industry. The signals of mechanical based torque and virtual torque derived from power and rotational speed are represented as an ensemble. The ensemble is processed according to standard time series analysis techniques. Analysis of data is carried out on duty cycles according to recommendations of IEC 61400-13[11] with respect to categorized conditions defining a capture matrix and recommended practices[14] with respect to load cycles and counting techniques.:

- normal power production
- normal power production plus occurrences of faults

- parked conditions
- normal transients events and
- other than normal transients events

In the analysis of gear loads [16] the components on the high speed section are primarily reported to deflect and independent observations as shown on the cover proof for faults. The gearbox analysis will be used as a basis of 'possible problem' for a state space analysis. Previous measurements on the wind turbine [17] conclude that much of the gearbox load is transferred in the lower frequency range up to 10 hz. This will be emphasized further.

Elaboration on higher order excitations from primarily the indicated torque is performed. The signals are monitored and conditioned on events determined by operational -and meteorological conditions in a standardized hierarchy developed at Risø. The measured load spectrum is compared to the compound design load spectrum for these load cycles. The data are stored as time series for analysis with Mathematica™ or similar products.

3.2 Supplemental equipment

The derived torque mentioned previously is provided by means of mounting a torque sensor along with a high precision counter for gathering rotational revolutions and variations, on the high speed shaft located between the gearbox and the generator. An experimental setup of a torque transducer is provided in Figure 7 showing the central part of the shaft suitable for the installation along with an adequately rpm sensor.

The torque transducer conditions and digitizes the strain gage signal within a miniature transmitter module right on the rotor. With precision signal conditioning circuitry, 16-bit digital resolution, and digital data transmission off of the rotor, the torque transducer provides extremely high precision torque measurement capability. This single-channel telemetry system is inductively powered, allowing long-term monitoring without the need for batteries. A built-in shunt calibration function insures the highest levels of accuracy and integrity. Analog output as well as Queued Serial Peripheral Interface (QSPI) high speed streaming digital data output are available. The signals are fed into the high-speed acquisition system as indicated- see *Figure 10*.

It is examined if it is possible within the project to monitor the low speed shaft with an approximately 1 kHz range torque transducer.

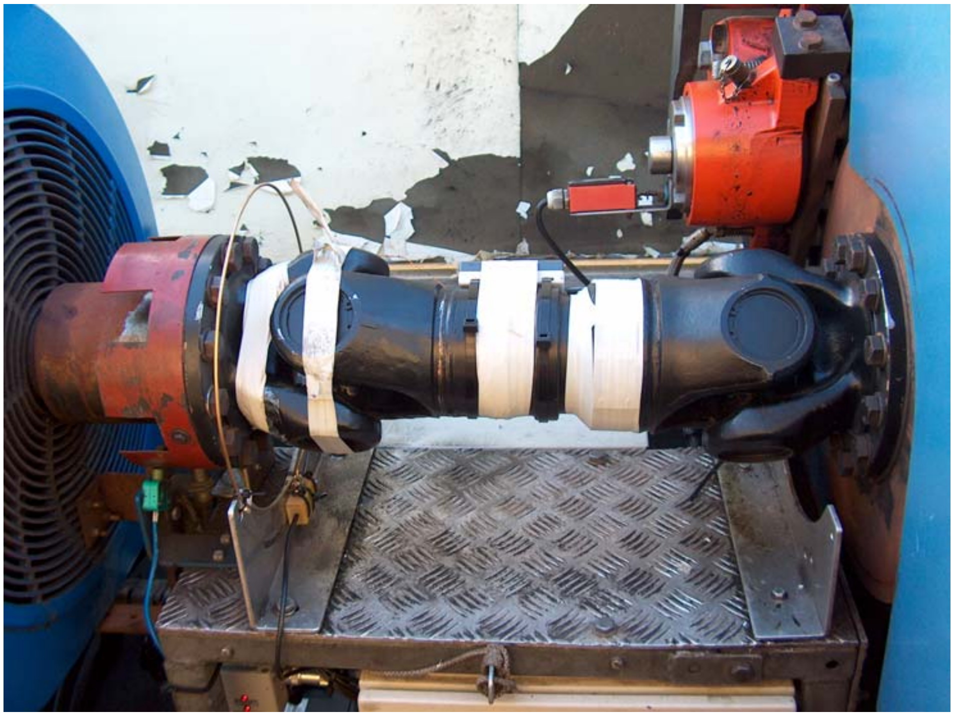


Figure 7: Drive train detail (generator-left, HSS shaft- central, brake and gearbox-right) with torque transducer, working by frequency modulation technique

AC 3-phase power is measured; to study these phenomena, voltage and current transformers have been installed at the common point of connection – see *Figure 8*. It is a 690 V 3-phase electrical power system. Measurements are taken in each of the three phases resulting in 3 phase voltages (V_R, V_S and V_T) and 3 phase currents (I_R, I_S and I_T) – see *Figure 8* and *Figure 9*.

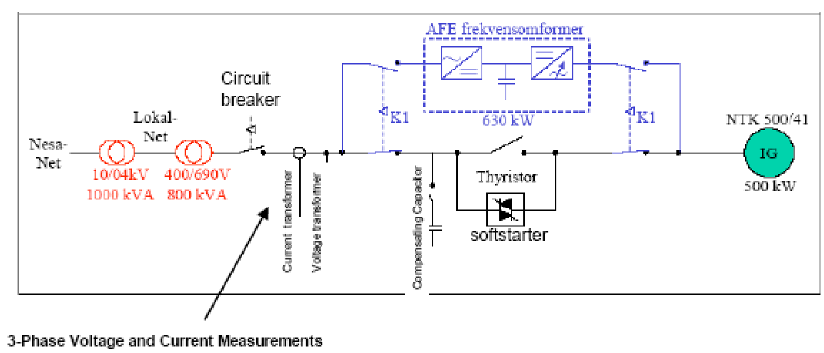


Figure 8: Electrical connection of Nordtank 500 kW induction generator - one phase representation.

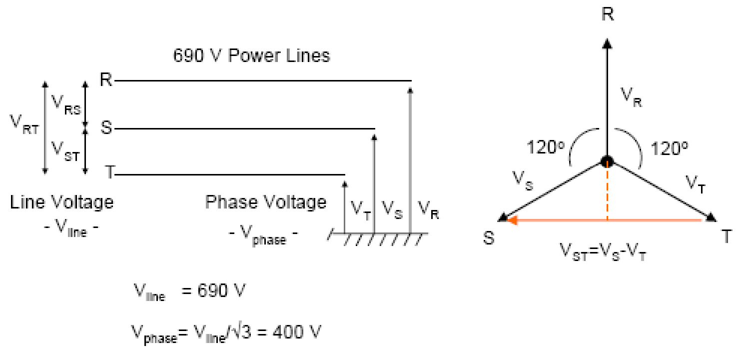


Figure 9: The 3-phase system

The signal path from the voltage and current transformers to the PC includes signal-conditioning equipment and an ADC-board-see *Figure 10* .

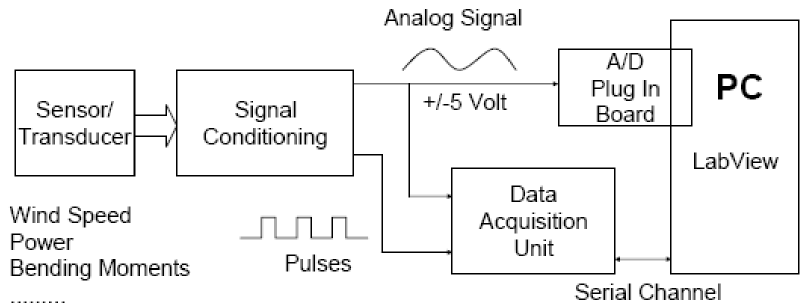


Figure 10: Overview of the high speed data acquisition system

The signal conditioning box performs 3 main functions:

1) Fitting the voltage to the PC level.
   The transformer signal are adjusted within the voltage range +/- 5 V
2) Anti-aliasing filtering.
   The input signals are filtered by a low-pass filter with a cut-off frequency of around 5 kHz. The cut-off frequency has been selected so that harmonics in the electric power signals at least to the 100th order –can be detected. This fulfils requirements set by the IEEE Electric Power Quality Standards[13].
3) Simultaneous sample and hold of the signal levels
   When receiving a trigger pulse from the outside the level of all 6 signals are kept at their present value until the value changes at receiving the next trigger pulse. This ensures simultaneous values of all the signals at the subsequent A/D conversion, carried out in a sequence channel by channel.

The ADC-board contains a multi-channel 12-bit A/D-converter, that translates the +/- 5V input signals into integer values in the range 0-4095. It is if possible planned in the project to replace the 12-Bit system with a 16-Bit A/D-converter.
An appropriate sampling rate has to be chosen. The rate must exceed the cut-off frequency of the anti-aliasing filter by at least a factor of 2 i.e. a sampling rate not less than 6 kHz. Derivation of power signal characteristics will be facilitated if an integer number of samples are acquired during the 20 msec period of the 50 Hz power system. Further facilitations will be obtained in e.g. frequency analysis using FFT algorithms if this number is a power of 2, which leaves (128 or) 256 samples

per period as good choices - corresponding to sampling rates of (6.4 kHz or) 12.8 kHz. Higher sampling rates might be a burden to the PC without giving extra information (as long as electrical power signal is considered, not mechanical).

Details on scaling of the physical voltage and power signals to the +/- 5 V computer level are shown in *Figure 11* . The phase-to-ground voltage and the phase current in the 3 phases are measured.
The power supply is 690 V phase-phase or 400 V phase-ground (note, it is RMS-values). Thus, the instantaneous voltage will cover the range +/- √2·400 V or +/- 550 V. The measurement range has been doubled i.e. +/- 1100 V to allow for spikes in the voltage.

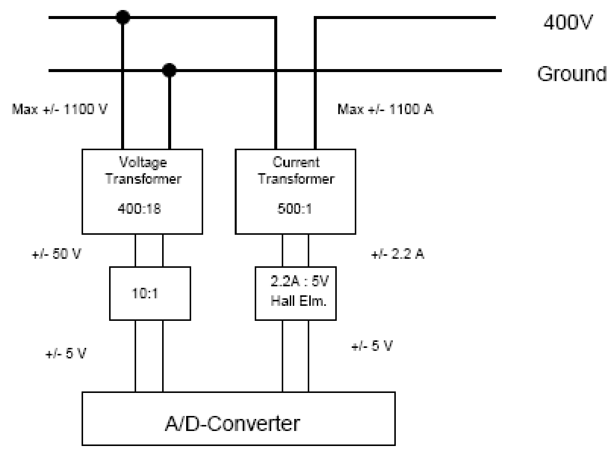


Figure 11: Overview of scaling the power signals

The power supply is 690 V phase-phase or 400 V phase-ground (note, it is RMS-values). Thus, the instantaneous voltage will cover the range +/- √2·400 V or +/- 550 V. The measurement range has been doubled i.e. +/- 1100 V to allow for spikes in the voltage.
The range of the current is determined by the power system voltage and by the production capacity of the generator, which is specified to a rated power of 500 kW. The relation between power, voltage and current is:

$$\text{Active Power: } P = 3 \cdot V_{Phase} \cdot I_{Phase} \text{ (W)}$$

This yields - at rated power 500 kW and at 400 V phase voltage - a phase current of about 400 A RMS or a current span of +/- 550 A. To take inrush currents at start-up into account this span is doubled - as seen in *Figure 12*.
The ADC-board can be governed from software through an instrument driver installed on the PC. Special LabVIEW VIs ©are meant for that purpose. One VI initialises the board and sets up sampling rate, number of channels etc. Another VI starts the measurements and writes the data into an internal buffer. A third VI reads a specified number of data from the buffer and delivers them in an array - the VI waits until the wanted number of data has arrived. In that way, it is possible - in one go - to read all samples covering one period of the 50 Hz power signal - as illustrated in *Figure 12* . However, a real-time requirement to the measurement program is that the

buffer is emptied faster then it is filled up, otherwise buffer overflow occurs.

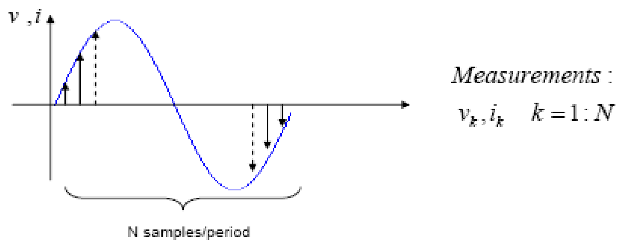


Figure 12: One period of samples

From the sampled values the following power signal parameters are calculated:

1) RMS values

$$V_{RMS} = \sqrt{\frac{\sum_{k=1}^{N} v_k^2}{N}} \qquad I_{RMS} = \sqrt{\frac{\sum_{k=1}^{N} i_k^2}{N}}$$

2) Active, Reactive and Apparent Power in one phase

   Active Power P in W:

$$P = \frac{\sum_{k=1}^{N} v_k \cdot i_k}{N}$$

3) Active and Reactive Power in 3 phases R-S-T – given as the sum of powers in each phase

$$P = \frac{1}{N} \sum_{k=1}^{N} (v_{R,k} \cdot i_{R,k} + v_{S,k} \cdot i_{S,k} + v_{T,k} \cdot i_{T,k})$$

$$Q = \frac{1}{\sqrt{3} \cdot N} \sum_{k=1}^{N} ((v_{S,k} - v_{T,k}) \cdot i_{R,k} + (v_{T,k} - v_{R,k}) \cdot i_{S,k} + (v_{R,k} - v_{S,k}) \cdot i_{T,k})$$

4) Harmonics

   Typically the 50 Hz voltage is superimposed with uneven harmonics of rather low order, such as 3rd (150 Hz), 5th (250 Hz), 7th (350 Hz) etc, but power electronic equipment can introduce harmonics of higher order - and even inter- harmonics are created. However, in all parts of the grid the voltage will be dominated by a clear 50 Hz component and harmonics just account for a minor part - less than 10% of the total signal energy. It is otherwise for the current that can appear in the most peculiar forms.

   If the time series covers exactly one period of the fundamental 50 Hz then the frequency resolution in the spectral analysis is also 50 Hz and the output from the VI contains RMS-values at DC, 50 Hz, 100 Hz, 150 Hz,.... up to N/2*50 Hz, where N is the number of samples in the time series.

5) Torque

   The torque is represented as a 16-Bit signal for comparison with the derived (virtual) torque. The signal is treated like the other signals by means of simultaneous sample and hold triggering-with shaft rotational power it is a basis for loads during one revolution, which can be analyzed further on harmonics.

6) Seismic accelerometers

Angular accelerometers provide signals for estimation of the rotational influence on the generator during operation.

7) Load spectra :

A statistical description of the torque width is described in a frequency distribution diagram for long term operation with emphasis on start/stop normal operation and shut down sequences.

8) Calibration

Careful calibration is carried out on transducers where accurate performance is expected down to DC-level. In general for AC signals, this is carried out.

3.3 Analysis

The mechanical drive train loads are compared with the virtual torque with the basis of statistical methods and time series analysis methods. Within statistical methods are parametric fit of data, load cycle analysis, peak detection and for frequency analysis processing of load cycle dependent time series. Literature dealing with machine vibration is reviewed for potential use within analysis of higher order frequency dynamics.

4 Design tools

4.1 General

The purpose of the planned analyses is to study the interaction between the mechanical system and the electric system of a wind turbine, to provide a better understanding of the mutual influence of those systems on the design. It has been common practice to analyse and design those systems independently, but lately studies have indicated that the dynamic coupling between the mechanical and electrical systems interferes more than it is expected in the design of wind turbines.

Aeroelastic codes like HAWC [18] or Flex are applied to simulate the structural design loads on a wind turbine. It is common practice to use very simple, steady state models of the wind turbine generator systems to define the link to the grid in these codes.

For electric design, many different tools are applied. For detailed electric design with power electronic drives, SABER is often applied [19]. For interaction with the power grid, power system stability simulation tools are applied. PSS/E is widely used in the power system sector for stability studies, and EMTDC is often the reference for transient studies. In the planned study, Power Factory from DIgSILENT will be used. Power Factory can represent the generator by the rotor flux transients only like PSS/E, or it can include the faster stator flux transients as well like EMTDC.

4.2 Aeroelastic design – HAWC

The aero elastic simulation tool HAWC (***H****orizontal* ***A****xis* ***W****ind turbine simulation* ***C****ode*) is a code designed for calculating wind turbine response in time domain. It has been developed at the aeroelastic design research programme in the Wind Energy Department of the Risø National Laboratory.

Larsen et. al. [20] extended the HAWC code with generator dynamics including stator as well as rotor flux transients. The new code can also simulate with the traditional steady state generator model, and with rotor flux transients only. Larsen's simulations with the complete structural model combined with full generator dynamics of a SCIG indicate that there is a risk for coupling between the generator eigenfrequency and structural modes of the wind turbine. Thus, it is confirmed that generator dynamics can be essential, even in normal operation of the wind turbine,

assuming an ideal power system with constant grid voltage on the generator terminals.
Currently, a new version of HAWC, namely HAWC2 has been developed. The new HAWC2 code is based on a multibody formulation where the turbine is subdivided into to a number of bodies interconnected by constraint equations. Within a body the calculations are linear, which is valid as long as deflections and rotations are small, whereas large deflections and rotations are accounted for through the coupling of bodies. Using too few bodies will therefore result in a reduction of non-linear problems into a linear.
The main parts of HAWC2 are the structural part, the external loading part, and the control part. The structural model of HAWC2 is based on flexible multibody dynamics. The wind turbine structure is modelled by a number of bodies, e.g. a tower or a blade, and these bodies are then connected by a set of constraint equations. Normally, the tower and shaft are modelled by a single body each, while the blades are divided into several bodies in order to capture geometric non-linear effects. Further, all inertia forces and external loading are based on the deformed shape of the structure.
The aerodynamic part is based on the blade element momentum (BEM) principle with input data from 2D lift, drag and moment table values. The aerodynamic calculation points on the blades are positioned independently of the structural node/element discretization to provide an optimal distribution of these points, which normally differs from the optimal structural discretization. The spacing between aerodynamic calculation points are closest at the tip and root where the largest aerodynamic force gradients normally occur. The BEM method used for calculation of the induced velocities is modified to handle dynamic inflow, large yaw errors and dynamic stall effects. Since the code is especially intended to handle large deflections also influences in the BEM due to large deflections e.g. reduction in the effective rotor area is considered.
In HAWC2 the electrical components (generator) and the control are implemented as external DLL (***D**ynamic **L**ink **L**ibrary*) [21]. Thus, the induction generator coupled to a fixed speed wind turbine will be implemented as a DLL, as presented in Figure 13.

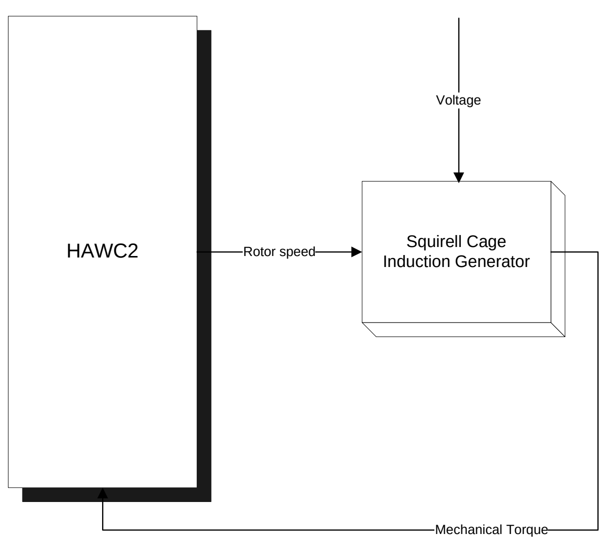


Figure 13 Fixed speed wind turbine with SCIG block diagram

Cutululis et.al [22]. extended HAWC2 with SCIG dynamics including the rotor flux transients only. The simulations conducted so far aimed at validating the SCIG model and its operation with the complete structural model of the wind turbine.

4.3 Electric design - Power Factory

In studies of power system stability and power quality, wind turbines and other generators are normally represented by the dynamics of the rotating system, i.e. the drive train.
The simplest representation of the drive train is by a lumped inertia, representing the wind turbine rotor, hub, shaft, gearbox and generator inertias as it appears from the generator shaft if this structure was stiff and the gearbox was ideal. Akhmatov [23] showed that the shaft flexibility of wind turbines has a significant influence in dynamic power system stability studies with wind power.
The most commonly used mechanical model for wind turbine drive trains in power system studies is the two-mass model shown in Figure 14. It lumps the inertias on the generator on one side and on wind turbine rotor on the other side. Between those two inertias, the flexibility is represented by stiffness and damper. The gear box is assumed ideal.

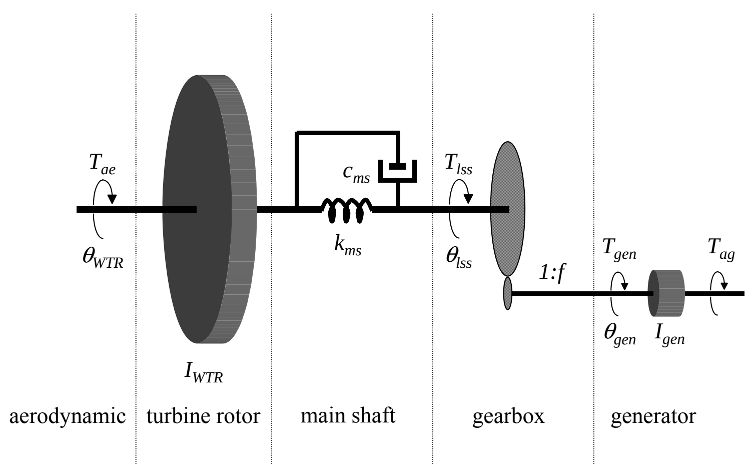


Figure 14: Two mass model of wind turbine drive train.

A significant advantage of the two-mass model is that the stiffness and damping parameters can be estimated by a torque measurement on the shaft. Normally, the inertias are known relatively well from the component data, but the stiffness and damping can vary significantly from values obtained by calculations based on data for material. The torque is measured right after the generator is disconnected from the grid. In that case, the torque will start oscillating because the generator air gab torque T_{ag} becomes zero, and the generator inertia I_{gen} can oscillate freely over spring and damper with the rotor inertia I_{WTR}. Then the stiffness is given by the frequency of the measured torque oscillation and the damping is given by the logarithmic decrement from one oscillation period to the next.
Sørensen et.al. [24] have used the two-mass model to simulate power output fluctuations from a wind turbine during normal operation. This model was implemented in Power Factory, and included the dynamics of the generator corresponding to rotor flux transients, which is the standard in power system stability

studies. Comparisons of simulations to measurements showed a distinct fluctuation around 5 Hz on the simulations, which was not present in the simulations.
The 5 Hz component corresponds to the generator frequency described by Thiringer [25]. It surprised in the first place that this frequency did not appear in the Power Factory simulations, because the generator dynamic is represented in Power Factory's standard model for the induction generator. The correct representation of the generator dynamics in Power Factory has also been confirmed by simulations of transients by Sørensen et.al. [26], where the response to short circuits in the grid has been simulated. When the voltage returns after a short circuit is cleared, the generator oscillates with 5 Hz corresponding to the generator frequency, see Figure 15.

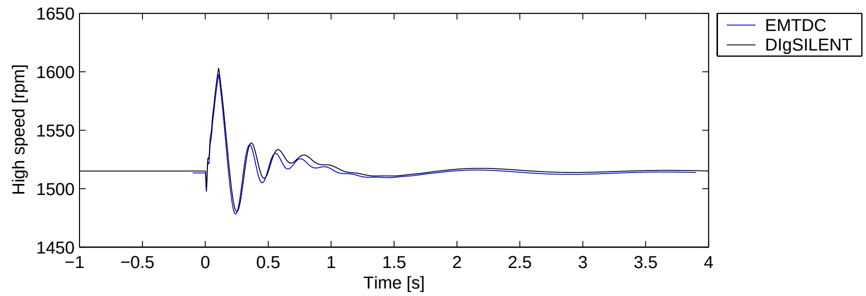


Figure 15: Generator rotor speed response to a short circuit from t=0 tot t=0.1 s.

The reason why the generator frequency then does not appear in the simulations of normal operation, i.e. without grid disturbances, is still not clear. However, the HAWC simulations strongly indicate that it could be due to the dynamic interaction with the remaining wind turbine structure, particularly the tower. This interaction is not included in the Power Factory simulations, since it is assumed that the generator stator is fixed.

4.4 Planned analyses

The analysis will be based on the measurements on the 500 kW Nordtank wind turbine. Since the scope is to analyse the impact of electrical system on structural design as well as the impact of structural system on electrical design, the analysis will be performed in HAWC2 as well as DIgSILENT.
The planned analyses will require models for the structural components as well as the electrical (read generator) in the Nordtank wind turbines. The models are neither available in HAWC2 nor in DIgSILENT.
HAWC2 simulations will be performed with three different assumptions:

1. The traditional structural design approach: a detailed representation of the structural flexibility combined with a simple steady state model of the generator.
2. The extended structural design approach: a detailed representation of the structural flexibility combined with a standard dynamic model of the generator representing the rotor flux transients.
3. The equivalent electric design approach: a stiff structure combined with the standard dynamic model of the generator representing the rotor flux transients.

This selection corresponds to the studies done by Larsen et.al. [20], but in the planned analyses, the three simulations will be compared to measurements as well. Besides, it will be done with HAWC2 instead of HAWC.

The Power Factory model will be extended to include tower top rotation as well. It is anticipated that a single degree of freedom is sufficient to represent the rotation of the generator stator. Then Power Factory simulations will be done with

1. The acknowledged electric design approach: a two-mass model of the drive train, combined with the build-in generator model assuming fixed stator.
2. The extended electric design approach: the two-mass model of the drive train, combined with the build-in generator model with modelling of the stator rotation with the tower top.

For completeness, it would be logical to perform Power Factory a simulation with an equivalent structural design, but it would not make much sense to simulate with only the tower top flexibility and no generator dynamics.

The comparison of the simulations will mainly be done on power spectral densities, i.e. statistically in the frequency domain, because different time series are expected in measurements, HAWC2 and Power Factory due to the stochastic wind input. Thus it will be possible to compare aeroelastic design simulations and electric design simulations to each other and to measurements. In the time domain, it will also be possible to compare the three HAWC2 simulations to each other and the two Power Factory simulations to each other, because the same random seeds will be used.

5 Conclusion

The present report describes the deliverable within "Drive train load analysis and lifetime prediction" the Specification of long-term load measurement technique under the sixth framework programme on the integrated design for wind turbines UPWIND (SES6) within WP 1B2, transmission and conversion.

The intermediate report describes the developed measurement technique, presents the hardware details, type of sensors and location, data storage and data analysis technique necessary to verify design load assumptions.

The interaction between the mechanical and electrical generator subsystems are described through a design tool which support studies of the interaction problem.

References.

[1] *Sixth framework programme priority 6 Sustainable development, global change and ecosystems*, Call ID: FP6-2004-Energy-3, October 2006.

[2] *Workpackage 1B2: Transmission and conversion (month 13 - 30) Work document* WP 1B2 January 2007

[3] *K.O. Helgesen, LabVIEW Data Acquisition exercise from 500 kW Wind Turbine*, DTU-Oersted 2005

[4] *Vindmølleafprøvning Nordtank NTK 500/37, Måling af Effektkurve*, Risø-I-731, September 1993.

[5] *Wind turbine Test, NORDTANK NTK 500/37, Risø-R-714*, December 1994

[6] *Vindmølleafprøvning Nordtank NTK 500/41, Måling af Effektkurve*, Risø-I-889, Maj 1995.

[7] *Power curve measurements, Measurement Summary, No. 12.2*, June 1995, NTK 500/41

[8] *Validation of Aeroelastic Model of Nordtank 500/37*, Risø-R-1006, November 1997

[9] *Accelerated Fatigue Testing of LM 19.1 Blades,* Risø-R-1358, May 2003

[10] *INTERNATIONAL STANDARD IEC 61400-12, Wind turbine generator systems – Part 12: Wind turbine power performance testing*

[11]. *Technical specification IEC TS 61400-13, Wind turbine generator systems – Part 13: Measurements of mechanical loads*.

[12] *INTERNATIONAL STANDARD IEC 61400-21, Wind turbine generator systems – Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines*

[13]. *INTERNATIONAL STANDARD IEC 61000-4-7, Testing and measurement techniques –General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto*

[14] *IEA Recommended Practices for wind turbine testing and evaluation; 3. FATIGUE CHARACTERISTICS.*

[15] *DAU P2858 Data Acquisition Unit description, User manual*. Risø 17-12-2001

[16] *Larsen, T.J et al, Dynamics of a Wind Turbine Planetary Gear Stage* paper presented at the European Wind Energy Conference EWEC 2003, Madrid 16-19 June 2003

[17] *Thomsen, K. et al*, *Experimental investigation of wind turbine- and gear dynamics for Nordtank 550 kW*, Risø-I-2123(DA), December 2003

[18] *Larsen TJ. How 2 HAWC2, the user manual – version 1.4* Risø-R-report(EN), Risø National Laboratory, April 2006.

[19] *Iov, F.; Timbus, A.V.; Hansen, A.D.; Sørensen, P.; Blaabjerg, F.*, Wind turbine blockset in Saber. General overview and description of the models. (2004) 41 p.

[20] *Larsen T.J.; Hansen, M.H.; Iov, F.*, Generator dynamics in aeroelastic analysis and simulations. Risø-R-1395(EN) (2003) 45 p.

[21] *Larsen T.J.*, Description of the DLL regulation interface in HAWC. Risø-R-1290(EN), Risø National Laboratory, 2001.

[22] *Cutululis, N.A.; Larsen, T.J., Sørensen, P.; Iov, F.; Hansen, A.D.; Blaabjerg, F.*, Electrical Components Library for HAWC2. Risø-R-1587(EN), Risø National Laboratory, 2007.

[23] V. Akhmatov. Analysis of Dynamic Behaviour of Electric Power System with Large Amount of Wind Power, PhD Thesis. Technical University of Denmark.2003

[24] *Sørensen, P.; Hansen, A.D.; Janosi, L.; Bech, J.; Bak-Jensen, B.*, Simulation of interaction between wind farm and power system. Risø-R-1281(EN) (2001) 65 p

[25] *T. Thiringer*, Measurement and modeling of low-frequency disturbances in induction machines, Ph.D. dissertation, Chalmers University of Technology, Göteborg, Sweden, 1996.

[26] *Sørensen, P.; Hansen, A.D.; Christensen, P.; Mieritz, M.; Bech, J.; Bak-Jensen, B.; Nielsen, H.*, Simulation and verification of transient events in large wind power installations. Risø-R-1331(EN) (2003) 80 p.

Risø's research is aimed at solving concrete problems in the society.

Research targets are set through continuous dialogue with business, the political system and researchers.

The effects of our research are sustainable energy supply and new technology for the health sector.

www.risoe.dk