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ABSTRACT

As part of the International Master of Science Program in Wind Energy at DTU, a complete interactive wind turbine measurement laboratory has been developed. A 500 kW stall regulated wind turbine has been instrumented with sensors for recording 1) turbine operational parameters, 2) meteorological conditions, 3) electrical quantities and 4) mechanical loads in terms of strain gauge signals.
The data acquisition system has been designed and implemented by Risø together with students and teachers from DTU. It is based on LabVIEW© combined with a MySQL database for data management. The system enables online access for real-time recordings, which are used both for demonstration purposes, in individual [student] exercises and in scientific investigations. Long-term registration of wind turbine loads results in a unique database of non-commercial time series, which are available for practicing fatigue calculations and extreme loads estimation in basic wind turbine courses.
Power quality analysis is carried out based on high speed sampled, three-phase voltage and current signals. The wide spectrum of sensors enables a detailed study of the correlation between meteorological, mechanical and electrical quantities.
Measurements are acquired by a PC placed at the wind turbine site near Risø National Laboratory. The PC can be remotely controlled from DTU, which gives the students the opportunity to work on an operating wind turbine. Furthermore, measurements are published on WindData.com, which facilitates cooperation with other Universities.

INTRODUCTION

To maintain the growth in the wind turbine industry, which has taken place during the latest 15 - 20 years, industry and research institutions require an increasing number of engineers. Since Denmark so far has been a leader in education, research, design, construction and manufacturing of wind turbines, DTU has implemented an international Wind Energy teaching Programme to educate highly qualified students.

The Wind Energy teaching programme focuses on skills, which qualifies for employment in the rapidly growing international wind energy sector, e.g. developers, wind turbine manufactures, utilities and research institutions. As part of the program a dedicated wind turbine measurement course has been formulated, which enables the students to design, implement and operate a complete measurement system on a wind turbine. The aim of the course is 1) to present and quantify the different standards used for documenting the behaviour of a wind turbine e.g. power curve determination, reporting of structural loads and electrical quantities and 2) to let the students practise the acquired knowledge on an online wind turbine measurement laboratory (WTMLAB), which is implemented on a commercial, operating 500 kW wind turbine.

The wind turbine is equipped with a data acquisition system for recording meteorological properties (wind speed, wind direction, air temperature, atmospheric pressure and rain), wind turbine operational properties (electric active power, nacelle position, rotor speed, rotor position, status signals) and structural loads in terms of strain gauge measurements from the blade root, the main shaft, tower top and tower bottom. Part of the data is uploaded to "Database on Wind Characteristics" [8], which is hosted at DTU.

WTMLAB enables development of new data acquisition utilities, enables hands-on experiences with wind turbine operations, enables design of new test procedures and algorithms and for collaboration with other universities and research institutions through the Internet.

WIND TURBINE DESCRIPTION

The test wind turbine is located at Risø Campus, Roskilde and is a traditional Danish three-bladed stall regulated Nordtank, NTK 500/41 wind turbine – see specifications in Table 1. The wind turbine is primarily used for energy production and is serviced on commercial conditions. It is located on the former Danish test station for wind turbines at Risø National Laboratory with free undisturbed inflow from the dominant Westerly wind sector.

Rotor Diameter	41.1m
Rotational Speed:	27.1 rpm
Measured tip angle:	-0.2º±0.2º
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	Pivot-able blade tips, operated in FS-mode
Mechanical brake	High speed shaft, operated in FS-mode
Power regulation	Passive aerodynamic stall
Gearbox	Flender; ratio 1:55.35
Generator	500 kW, 4 poles, 690 V
Tower	Conical steel tube, h=33.8 m
Hub height	36.0 m
Tilt	2º
Coning	0º
Masses:	
Blade weight:	1960 kg
Rotor incl. hub	9030 kg
Tower head mass	24430 kg
Tower mass	22500 kg

Table 1: Nordtank NTK 500/41 specifications - October 2005

The wind turbine was installed in 1992 for testing and has been subject to many tests and investigations during 1992-1999 according to references [1,2,3,4,5,6].
A frequency converter system has been designed and implemented, which enables an operation with variable frequency, but this feature has not been activated yet during the measurement period.
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, 10.4 / 0.4 kV transformer. Since the wind turbine is rated to 690 V an additional 800 kVA, 0.4 / 0.69 kV transformer is installed to step up the voltage from 400 V to the wind turbine level. The electric connection diagram is shown in Figure 1.

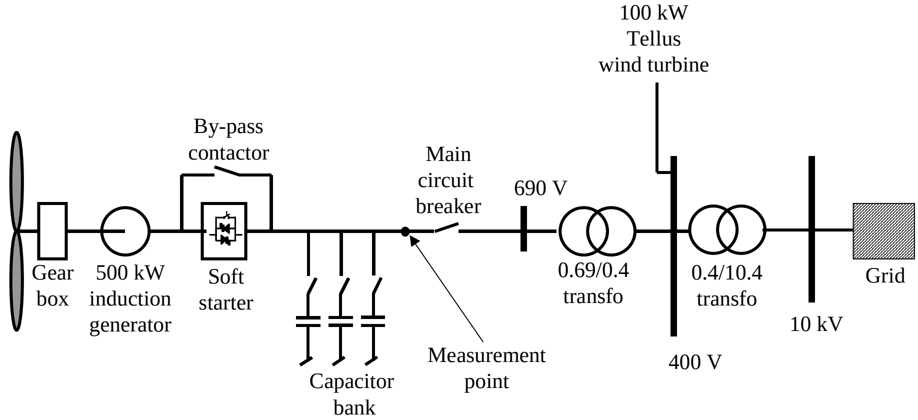

Figure 1: Connection diagram for NTK 500/41 wind turbine.

WIND TURBINE INSTRUMENTATION

The idea of establishing WTMLAB is to enable the students to explore experimentally the mechanical conversion of wind power to electric power on an operating wind turbine, with focus on four main areas:

1) Meteorological measurements to describe the inflow,
2) Structural measurements to analyze the dynamic response,
3) Control and power measurements to study the operational behavior.
4) Electrical measurements to examine the interaction between wind turbine and the electrical grid.

A meteorological mast is placed 2.5 rotor diameters in westerly direction from the wind turbine. The mast is equipped with standard instrumentation as listed in Table 2. The installation is made in accordance with the recent IEC recommendations for both power performance and structural load measurements.

Meteorological measurements	Wind speed, h=36m	m/s
	Wind direction, h=35 m	Deg
	Temperature, h=3 m	DegC
	Atmospheric pressure,h=3 m	mmBar
	Rain, h=3 m	mm/hour

Table 2: Meteorological sensors.

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 as listed in Table 3. The instrumented locations are described below:

Blade loads: The load signals from the reference blade includes bending moments at the blade root, measured as strain gauge signals located on the blade root steel extenders, as shown on Figure 2. The gauge installation enables measurements of both flap-wise and edge-wise bending moments in a rotating reference system.

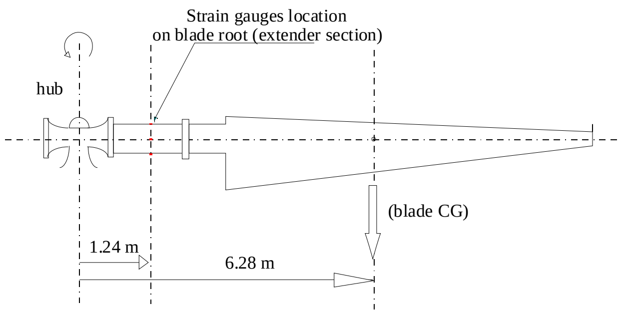

Figure 2: Structural load measurements in the blade root
at radius 1.24 m of the NTK 500/41 wind turbine

Rotor loads: The load measurement on the main shaft includes torque and bending moments at a position behind the hub/main shaft flange, as shown on Figure 3. The gauge location enables measurements of bending moments in two directions, perpendicular to each other. The bending moments in combination with the rotor position are used for calculation of the rotor bending moments in yaw and tilt direction with reference to the nacelle.

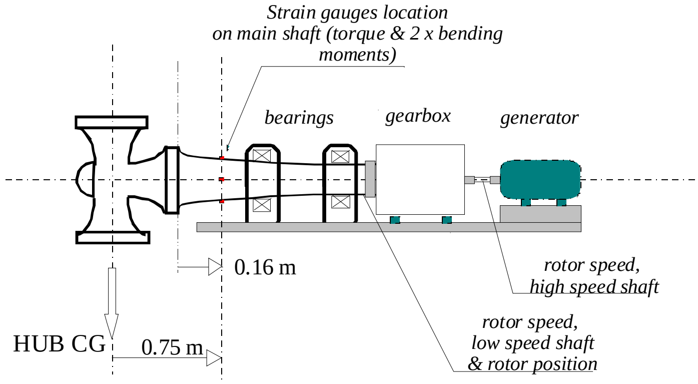

Figure 3: Structural load measurements
on the main shaft of the NTK 500/41 wind turbine**.**

Tower loads: The tower loads includes torque at the tower top and bending moments in two directions in the tower bottom, as shown on Figure 4.

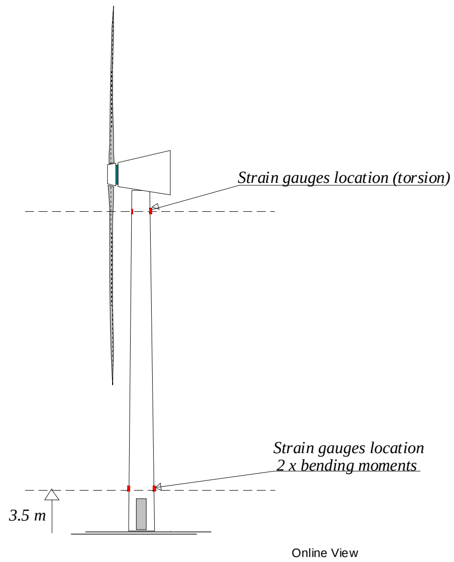

Figure 4: Structural load measurements
in the tower of NTK 500/41 wind turbine.

Structural loads blade #1	Flapwise bending moment in blade root	kNm
	Edgwise bending moments in blade root	kNm
Main shaft	Torsion in main shaft	kNm
	Bending moment 0-180 deg.	kNm
	Bending moment 90-270 deg.	kNm
Tower	Torsion in tower top	kNm
	Bending moment E-W in tower bottom	kNm
	Bending moment N-S in tower bottom	kNm

Table 3: Measured structural loads in wind turbine.

Calibration of the strain gauge instrumentations is performed on site. Both for rotor, main shaft and tower loads cyclic gravity loads or external loads are applied to the structure at the measurement sections.

The operational conditions of the wind turbine are logged with different sensors according to Table 4. Furthermore status information regarding tip position, grid connection and shaft brake are registered.

Operation params.	Nacelle position	deg
	Rotor speed slow shaft	Rpm
	Rotor speed high shaft	Rpm
	Rotor azimuth position	Deg
	Wind speed on nacelle	m/s
	Wind direction on nacelle	Deg
Output	Active power	kW

Table 4: Wind turbine operational parameters.

Risø National Laboratory has used most of the sensors and transmitters for many years in field experiments and the selected sensors have a documented high precision and good reliability - especially the Risø cup anemometer has demonstrated noteworthy performance.

Traditional voltage transformers (ratio 400:18) are used to measure the phase voltages. A differential 10:1 probe on the secondary side reduces the voltage to the 5 Volt level. Current transformers (ratio 500:1) are used for the current measurement. A Hall element converts the output to a voltage signal in the ratio 1A to 100 mV.

DATA ACQUISITION

A PC-based data acquisition system has been designed to monitor and collect data from the wind turbine sensors as illustrated on Figure 5.

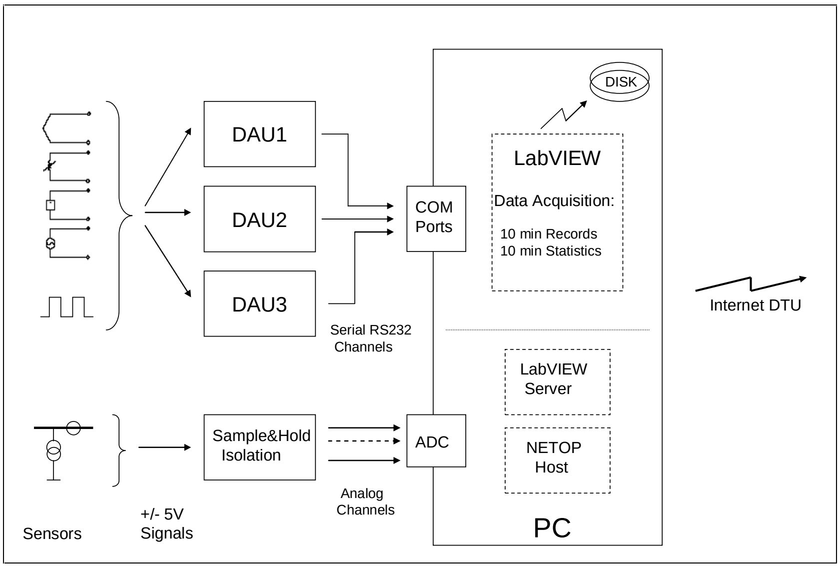

Figure 5: Data acquisition system implemented on the NTK 500/41 wind turbine.

The output signals from all sensors are conditioned to the +/- 5 V range. The signals are either continuously varying (strain gauges, temperature…) or of digital types such as train of pulses (rotational speed, anemometer…) or on/off levels (status of brake, blade tips and generator).

All signals - except outputs from voltage and current transformers - are connected to one of three RISØ P2558A data acquisition units (DAU). One DAU unit is located in the bottom of the wind turbine tower, another in the nacelle and the third 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 selected scan rate of 35 Hz is sufficient for meteorological properties and structural load measurements, but it is far too slow when studying the impact of the wind turbine on the power grid. Thus, another part of the acquisition system works at a 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 connected to a signal-conditioning interface that performs sample and hold operation, scales 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.

A standard desktop PC is used as the central component of the data acquisition system. The PC is connected to the Internet and thereby to DTU from where it can be operated remotely. Dedicated measurement software has been developed under LabVIEW©. Data are collected in 10 minutes intervals and the complete time series plus statistics derived from this series are saved on disk ready for later treatment.

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.

DATA MANAGEMENT

The data files with 10-minute statistics are uploaded every 10 minutes to an internal MySQL "NORDTANK" database located at DTU, using FTP as indicated in Figure 6.

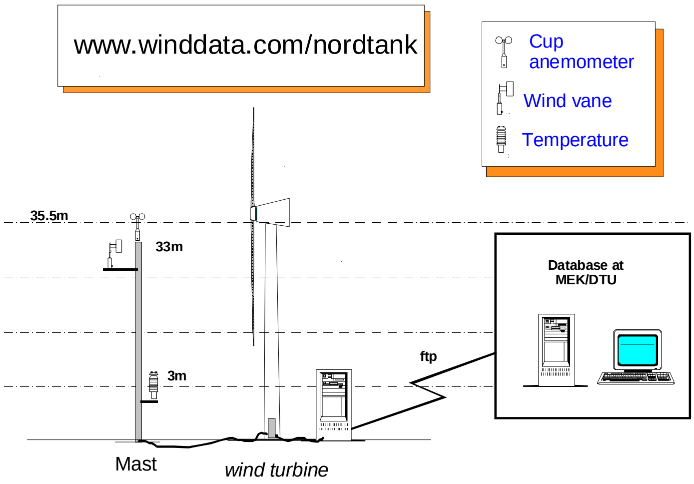

Figure 6: Data transfer to database at DTU - once every 10 minutes.

Online operational wind turbine statistics are available through the database together with long-term statistics from Nov. 2003 until end of 2005. During the monitored period, that exceeds 16.700 operational hours, more than 1.5 GWh of energy has been produced and more than 8.000 start/stop sequences has taken place together with different types of events e.g. emergency stops.

The primary structure of the NORDTANK database, which is defined on Figure 7, enables an easy data access from standard software packages like Matlab© through SQL. The students can directly access the database and in that way, realistic exercises can be shaped.

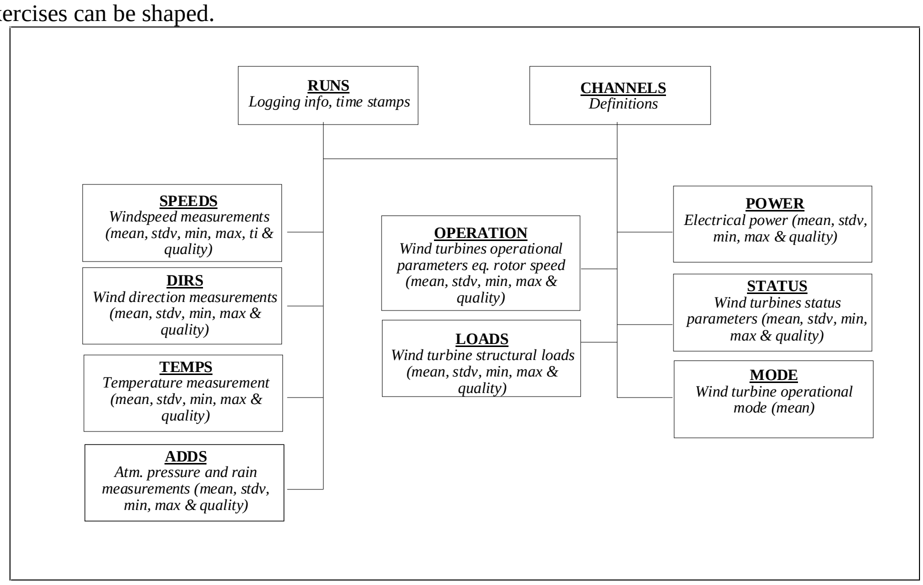

Figure 7: Structure of the database.

A parameter is associated with each scan, which represents the quality of the actual measurement according to the definition given in Table 5.

qa=0	Measurement is not validated
qa=1	Measurement is validated and ok.
qa=2	Measurement is validated and ok, but with spikes.
qa=3	Measurement is validated and ok, but with dropouts or constant periods.
qa=9	Measurement is faulty.

Table 5: Definition of signal quality.

E.g. determination of power curve requires that all signals (wind speed, wind direction, temperature, pressure and electric power) are of high quality (=1) and it is important to validate the signal quality with regular intervals.

Besides the 10-minutes statistics, also entire time series with wind and structural load measurements are uploaded to DTU every night - each time series contains 150 MB of 35 Hz data. Representative series are selected and inserted into WindData.com, where they have been indexed and made searchable for the student exercises. Furthermore tools have been developed to organize the time series in a database, which enables online plots and analysis with Matlab©.

WIND TURBINE EVENTS

A number of special wind turbine events have been logged and identified during the recent 2 years. One major event has been a short-circuit failure on the generator when operating at rated power (500 kW). The accident required a repair of the generator before restart of the wind turbine. The event - see Figure 8 below - demonstrates how an emergency stop sequence activates both tip brakes and the mechanical brake and how the wind turbine handles a rotor over-speed situation. Furthermore, the gearbox is heavily loaded due to the reversing torque in the main shaft during the stop sequence.

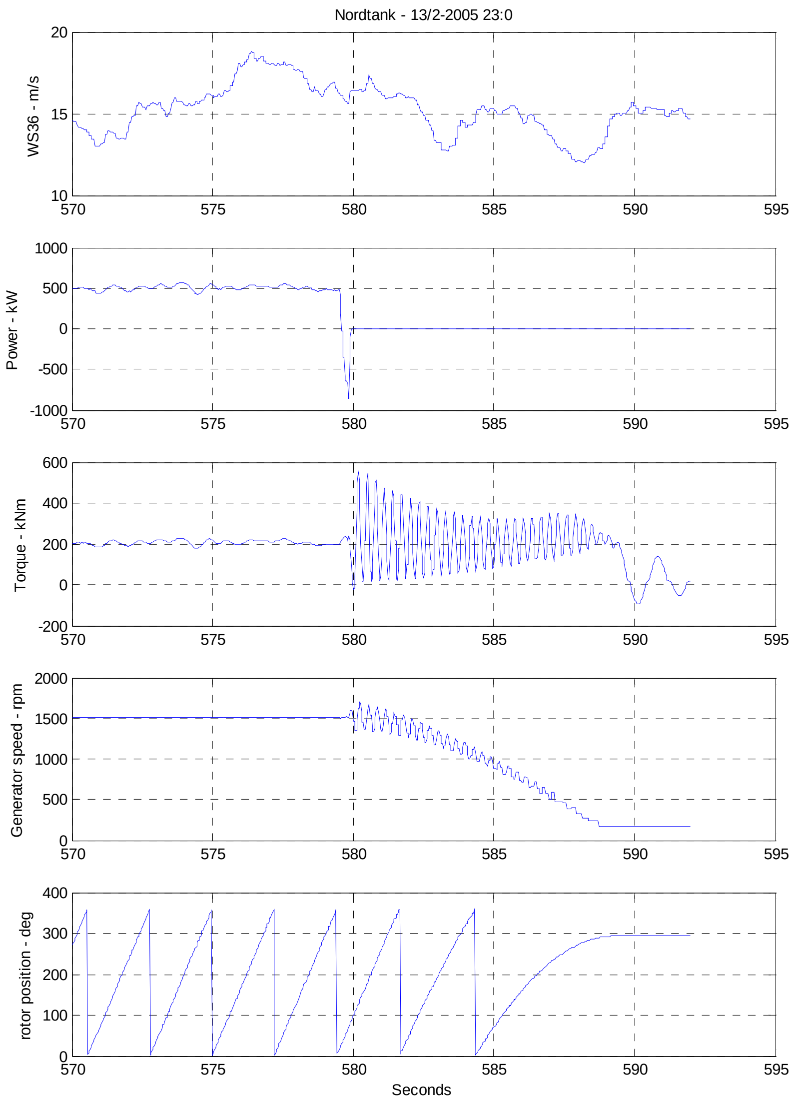

Figure 8: Example of recorded emergency stop.

CONCLUSION

An on-line wind turbine laboratory has been established in a joint project between DTU and Risø National Laboratory. The measurement laboratory is installed on a 500 kW Nordtank wind turbine that runs in daily operation.

The wind turbine has been fully equipped with sensors and an Internet accessible data acquisition system has been set-up. The on-line laboratory has been in operation for more than two years.
The main purpose is to give the students hands-on insight in methods for obtaining measurements from a operational wind turbine and for assessing the properties of such a wind turbine. Experiences up to now have proven that it is a pedagogical and motivating way of teaching students wind turbine techniques.

Since the data acquisition system constantly is collecting data and saving them systematically in a database the knowledge to the wind turbine behavior becomes more and more detailed which opens new prospects for future activities – both in education and in research.

The database is open and published on the Internet. Thus, co-operation with other Institutions and Universities is possible – and welcome.

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