REAL TIME LOADS MEASURED WITH FIBER OPTICAL SENSORS EMBEDDED IN ROTOR BLADES

J. Wernicke, J. Shadden, R. Byars (WindForce GmbH)

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1. Abstract

Multi Variable Turbine Controls (MVTC) presents the potential for significant improvements in cost, performance and reliability for future WTGs benefiting both the onshore and offshore markets. The use of MVTC requires a stable and cost effective measurement input from load sensors during operation of WTG. In addition to the performance requirements, the system must be reliable for the lifetime of the turbine, cost effective for volume deployment, and the system must not interfere or degrade the turbines' components or operation in any way.

In this paper we present an FOS load measurement system that meets these requirements and has been successfully demonstrated to fulfill the acceptance criteria for advanced control inputs. Fiber Optical Sensors (FOS) have been tested successfully in composite blades on wind turbine generators (WTG), showing their capability to perform under both laboratory and field conditions.

We present load data recorded from sensors in the turbine blade root and at critical blade cross sections. We discuss how the outputs of the system could be used for residual life expectancy calculations, black box functionality, turbine control input, overload detection, structural monitoring system, ice detection, frequency surveillance and temperature information. We discuss techniques that have been developed for deploying the systems in rotor blades during factory build and for retrofit of existing WTGs in the field. We share results from various installations including installation in 45-meter blades.

2. Introduction

Every day wind energy is being pushed to new limits; both in terms of operating conditions and in terms of size. To meet these challenges turbine designers and wind park developers need new tools to ensure their products will meet goals of operating cost and availability. Recent innovations in fiber optic load sensing have created such a tool, which will expand the options for advanced monitoring and control of turbines which are pushing the envelope, and open up possibilities for huge gains in availability and operating cost.

Today's turbines are being installed in more places, under more diverse conditions, than ever before. Most wind turbines are designed for a twenty year life. This life span is dependent on the cyclic load seen by the turbine's rotor, and as such, accurate assumptions and about the characteristics which influence this loading are critical to the design. However as the wind energy market expands and changes, many sites being used or considered for wind energy production present wind conditions which are further and further outside of well understood and defined wind regimes. There is a huge technical risk associated with putting even proven technology into poorly understood conditions.

FIBRADAPT™ uses new criteria and input from online load measurements during the turbine life time as innovative input into turbine logic controls and project management to significantly decrease operational cost as the main driver for profit across the investment time.

3. Technology of FIBRADAPT™

FIBRADAPT™ provides data from optical fiber sensors based on Fiber Bragg Gratings (FBG) which are commonly used in fiber optic communication systems. Unlike most fiber optical sensors, this system employs a "cold written" FBG, which allows the fiber to retain its structural integrity thus remaining robust for handling and installation.

Fiber optical sensors have wide a range of advantages in comparison to strain gauges, especially under severe environmental conditions such as those found during wind turbine operations. The benefits and main features of fiber optical sensors as they apply to wind turbines are as follows.

- Small cross section, low weight, very low heat conduction
- Long signal transmission lines, with very low or negligible losses
- Long term stability under operation in hostile environments (EMI, weather, chemicals, high/low temperatures)
- Remote, electrically passive sensors, ideal galvanic separation
- Ideal to embed in GRP structures
- Multiple sensors (up to 100) linked on a single conductor with only one mechanical connection point.

3.1. Structure of the Fiber Optical Sensor

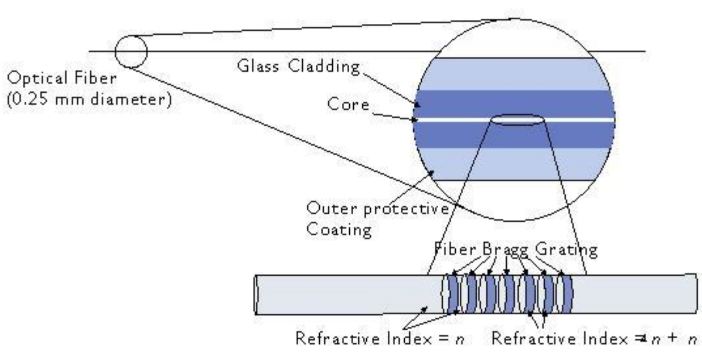

Figure 1: Structure of the fiber optical sensor

The optical fiber has a diameter of 0.25 mm which includes the core, the glass cladding and the coating. The FBG sensor consists of a small periodic variation in the refractive index of the optical fiber core. The periodic variation is made by a high powered ultraviolet laser. By irradiating the core material of photo sensitive quartz glass locally with UV-light, the refractive index is increased at certain locations along the fiber. These locations are spaced in equal distances, the entire sensor having a length of about 3 – 14 mm. [1]

3.2. Structure of the Measurement System

The main components are:

1. Fiber Sensor Interrogator (FSI) as source and receiver of light, data processor, communication interface, transformer, software
2. Interconnecting Fiber (IF) for data transfer between FSI and sensor arrays
3. Sensor Arrays embedded in the blade structure
4. Temperature compensation sensor
5. Support brackets (customized according to design requirements)

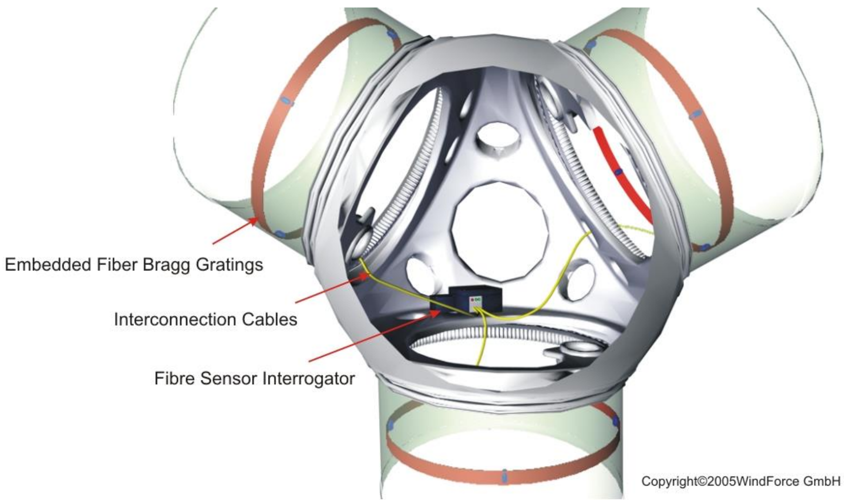

Figure 2: Structure of the Measurement System in a wind turbine

3.3. Function of the Fiber Optical Sensor

A light source provides a broadband input signal into the fiber. When passing an FBG, the light is reflected within the pre-selected narrow wavelength band around λ_B. When the sensor is exposed to a strain, the distances of the grating change, which also changes the wavelength of the reflected light. The analysis of the characteristic of the reflected light is used to measure the strain at the sensor location. Shifts in the reflected wavelength are proportional to change in elongation caused by temperature, or load induced strain which can be computed to stress based on the component geometry. [2]

Because the optical strain sensor is sensitive to temperature changes, the strain measurements must be temperature compensated.

One of the main advantages of the fiber optic sensor is the multiplexing feature using one single fiber with multiple FBGs without interference between the single measurement points. This system is based on time division multiplexing, which allows the interrogation unit to distinguish between individual strain sensors by using their physical position in the array as a reference. By measuring the time taken for the light to travel from the interrogation unit to the sensor and back, it is possible to calculate its physical distance from the interrogation unit, and therefore which sensor the signal originated at. [3]

4. FIBRADAPT™ Integration

The optical fiber sensors are embedded into the blade root as shown in figure 2. The measurement system can be independent for retrofit applications, or can be integrated into the wind turbine pitch system for production systems, as shown in Figure 3. The FSI acquires the sensor signals and processes these values. The bending moment Mb in flapwise and edgewise direction will be transferred with a frequency of 25 Hz to the Pitch System Control Unit or to the Turbine Controller.

An additional function in the FSI which is under development will include the reduction of data by load cycle counting and the record of trigger functions of single events. This reduced data will be transferred over the turbine control system to the remote control system where a load history for each individual turbine will be built up and the damage will be calculated. The real loads will be compared with the simulated design loads.

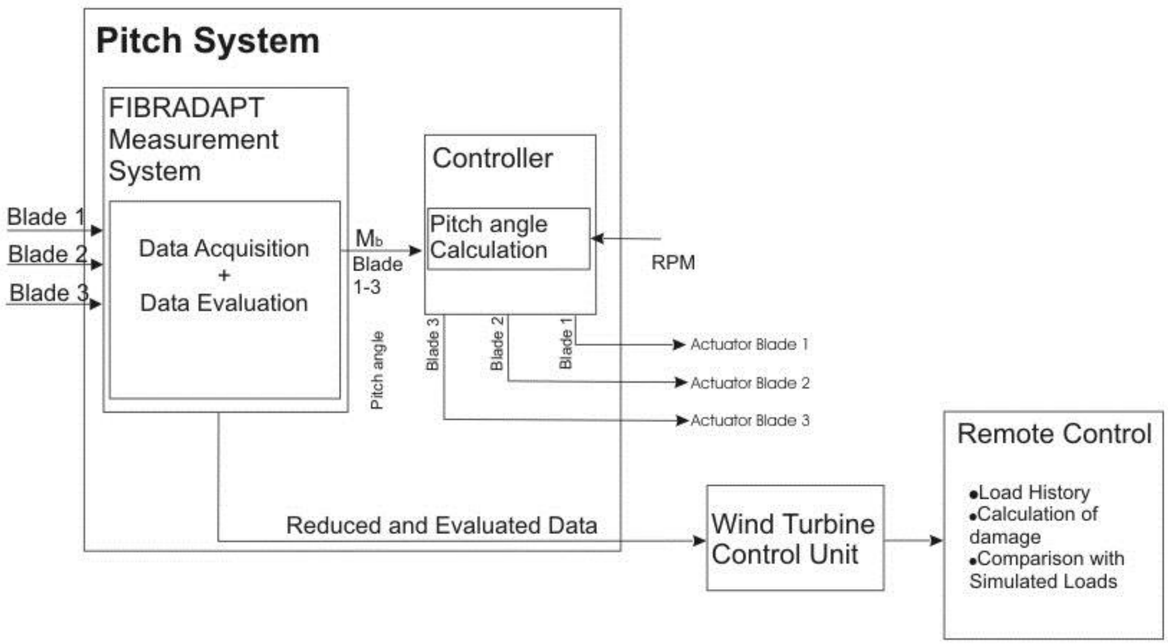

Figure 3: Integration into the Pitch System

5. FIBRADAPT™ Application

FIBRADAPT™ provides different functionality solutions with a focus on improvements in performance, reliability and availability of the wind turbine, some of them are described below:

5.1. Residual Lifetime Estimation

With the help of load cycles counting during a defined time interval, site specific and machine specific forecasts can be made for component repairs and replacements in order to prevent unexpected and lengthy downtimes. Residual lifetime estimation of wind turbine components allows an event based maintenance schedule. Knowledge of actual fatigue accumulated on the turbine in a specified amount of time can also be used to compare with and improve turbine modeling and fatigue loads analysis, as well as to compare with and improve predictions of site conditions.

Appropriate counting procedures (i.e. Rainflow-Count) of the recorded load time series determine the load spectrum of every single turbine, which includes the number of load cycles of all occurring amplitudes.

Due to the operating nature and lifetime of a wind turbine, fatigue failure is usually a dominant design criteria for structural integrity. IEC 61400-1 states that fatigue damage shall be estimated using an appropriate fatigue damage calculation. It goes on to suggest the use of a linear damage accumulation method. This method is also called the Palmgren - Miner rule. There are some deficiencies to this method but its simplicity and general industry wide acceptance make it the model of choice. [4]

IEC 61400-1 states that when using the Palmgren-Miner rule, the accumulated damage within the lifetime of the turbine shall be less than 1.

$$\mathrm{Damage} = \sum_i \frac{n_i}{N(\gamma_m \gamma_n \gamma_f s_{ki})} \leq 10$$

n_i Counted number of fatigue cycles in bin i of the characteristic load spectrum, including all relevant load cases

s_{ki} Stress or strain level associated with the counted cycles in bin i, including the effects of both mean and cyclic range

N( ) Number of cycles to failure as a function of the stress or strain indicated by the argument (i.e. the characteristic S-N curve)

By counting the number of cycles accumulated on the turbine in each bin in a specified period of time, and normalizing that number to the lifetime of the turbine, a calculation can be made of projected (based on measured loads) versus theoretical (based on simulations) lifetime damage.

For example, the damage accumulated during the test period would be represented by:

$$\text{Damage}_{\text{Actual}} = \sum_i \frac{n_{i\text{Measured}}}{N(\gamma_m \gamma_n \gamma_f s_{ki})}$$

And the projected lifetime damage would be represented by:

$$\text{Damage}_{\text{Projected}} = \sum_i \frac{n_{i\text{Measured}}\left(\frac{L}{t}\right)}{N(\gamma_m \gamma_n \gamma_f s_{ki})}$$

L Lifetime, defined as time turbine is expected to be in active service

t Period of time in which loads measurements are gathered

The benefits of Residual Lifetime Estimation are extension of economic lifetime and consequently cost reduction for wind projects. [5] This also gives information for financial project management within the operating time.

5.2. Structural Monitoring

Structural monitoring of the wind turbine blades is required for offshore wind turbines and recommended as well for use in onshore projects to improve reliability and reduce total project costs. The occurrence or cracks and defects can be detected at an early stage preventing catastrophic failures and lengthy downtimes. This type of system could also be useful as a 'black box', providing real time loads data leading up to an overload event or component failure.

The data is also been used as ice load monitoring system to prevent mass imbalance due to ice built up at the leading edge under certain weather condition.

Fiber Optic Sensors fit this requirement because unlike traditional sensor arrays they have little or no change or degradation in signal quality or accuracy over time, regardless of harsh environmental conditions and repeated strain cycles.

Project benefits are an increased reliability and insurability.

5.3. Active or Adaptive Control

With large wind turbines there is significant variation in load across the face of the rotor. This can be the result of wind variation including shear and upflow, or turbine design and control, including yaw misalignment or rotor imbalance. Active individual blade pitch control based on load feedback from the blades can result in drastic decreases in fatigue loads in the rotor, and in the entire wind turbine structure.

The wind speed variations across the rotor disc result in a large once-per-revolution, or 1*P*, component in the blade loads, together with harmonics of this frequency, i.e. 2*P*, 3*P*, 4*P*. [4] As shown in figure 4 the 1*P* frequencies are particularly significant and these can be reduced by individual blade pitch control at the 1*P* frequency, 120° out of phase at the three blades. [6,7]

To achieve active control, bending moment in the flapwise and edgewise directions from each blade are required at a scan frequency of 10 to 20 Hz. [8] FIBRADAPT™ provides this input by means of four blade root sensors in each blade (a pair of flapwise sensors and a pair of edgewise sensors), with a scan frequency of 25 Hz, which is more than adequate to perform the active control algorithms.

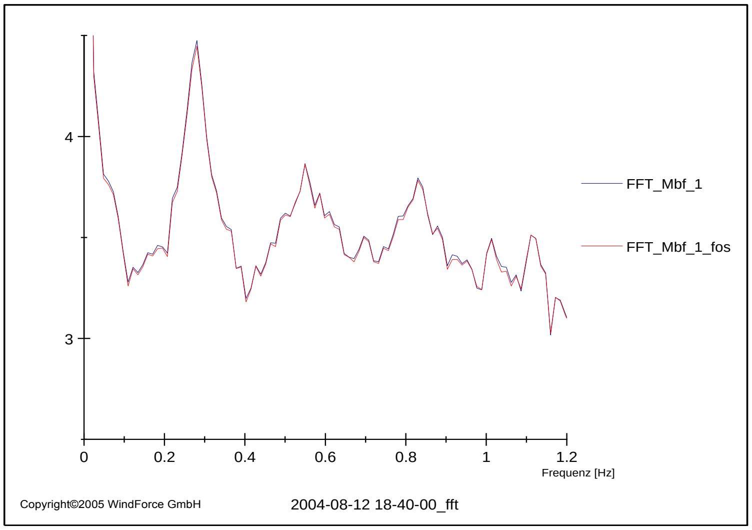

Figure 4: Frequency analysis from a 10 minute flapwise sensor signal

6. FIBRADAPT™ Test Structure

6.1. In Air Retrofit

The first test installation was a retrofit installation on a 1.5 MW prototype wind turbine. The selected turbine is located at a calibrated site with available wind data from a free stream met mast in wind direction of the turbine. A measurement system from the independent institution DEWI is installed for design verification of the wind turbine prototype according to IEC guidelines.

The whole system consists of 4 root sensors in each of two blades, with an additional 6 flapwise sensors on the pressure side and 6 edgewise sensors at the leading edge of one of the blades as shown in Figure 5.

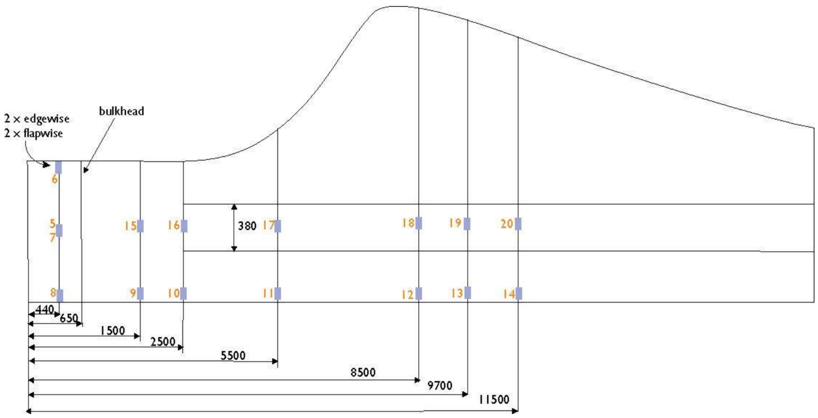

Figure 5: Sensor positions in the first test blade

The interrogation unit (FSI) is located in the hub. It is comprised of an integrated single board computer and in this application communicates over a CANBus system with an independent data collection system provided by DEWI.

The sensors at the root of the blade were installed next to existing strain gauges also monitored by the independent measurement system and comparison tests were made. The position of the edgewise and flapwise sensors were selected to match locations defined in the loads calculation tables for this particular wind turbine.

6.2. Surface Application during blade construction

The second test installation was performed in the blade manufacturing facility, after lay-up of separate blade components and before bonding of blade components. The sensor arrays were delivered as robust packages for easy installation. Sensors are embedded in composite patches for bonding to the interior surface of the blade. The remainder of the fiber optic cable is protected with a Kevlar cable. Splices within the arrays are protected by splice boxes. The system consists of a box beam array with sensors on the pressure side and on the suction side of the blade, an array for the leading and trailing edge of the blade and a root sensor array.

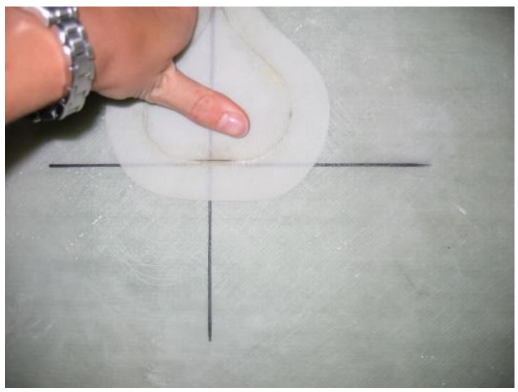

Figure 6: Alignment of sensor onto blade surface

Sensor patches were placed onto the blade surface in predetermined locations, taped down, and laminated onto the surface using vacuum infusion techniques.

In place repair procedures were also successfully demonstrated.

7. Test Results

7.1. Comparison to Strain Gauges

After calibrating the sensors in the wind turbine and combining the flapwise and the edgewise root sensors to a bending moment signal, the signals from the fiber optic sensors were compared to the signals from the strain gauges.

Figure 7 shows a comparison between FOS and strain gauges during the calibration turn and during the operation of the wind turbine.

The results show a maximum 6.5% deviation in absolute bending moment between the strain gauge output and the FIBRADAPT™ output during the idle calibration procedure.

During operation, the maximum deviation in absolute bending moment is 9% with a time delay of 0.07 s. The deviation in amplitude of the cyclic load is on the order of 1%.

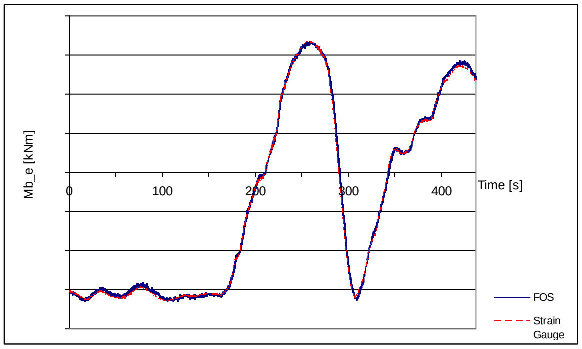

Figure 7: Comparison between strain gauge and FOS during calibration, edgewise bending moment

7.2. Sensor signals during operation

Figure 8 shows the flapwise sensor signals during the operation of the turbine in low turbulent wind at the rated wind speed. The sensors are installed along the blade, whereas Sensor 20 is at approx. 30% of the radius.

Review of the data from the fiber optic sensors during operation verifies that the data can be used as input into an active control algorithm.

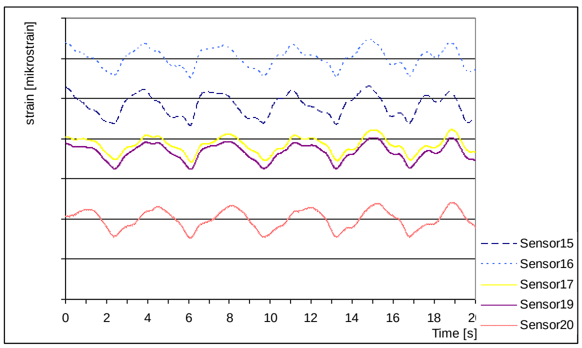

Figure 8: Flapwise sensor signals during operation

7.3. Static Test

Bending moment data during the static bending test of the blade was collected using fiber optic sensors and strain gages in parallel. Due to difficulties with the data collection system, separate data loggers had to be used for the fiber optic sensor output and for the strain gage output. Therefore the data is not directly comparable.

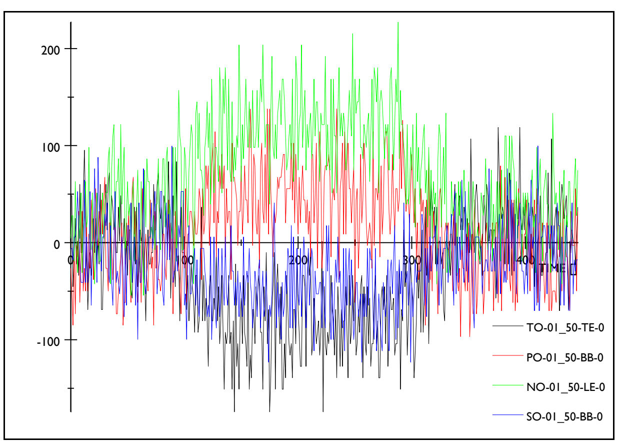

Figure 9: Strain Gage output during static bending test

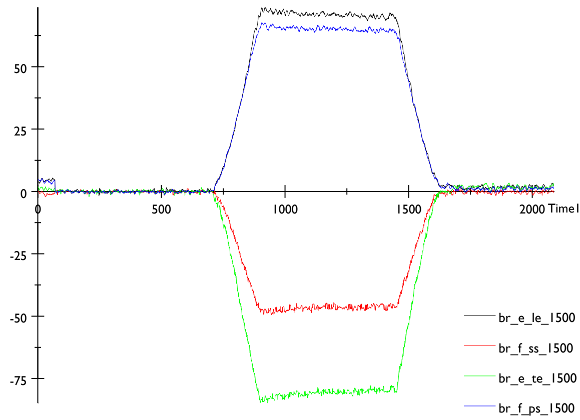

Figure 10: Fiber Optic Sensor Output during static bending test

8. Further Developments

The following advances are scheduled to be completed by the end of 2006.

Active control
Development and testing in simulation of active control algorithms using FIBRADAPT™ input for individual blade pitch will be conducted this year.

Integration of FIBRADAPT™ into standard electromechanical pitch systems
Two pitch system manufacturers have integrated the FIBRADAPT™ system into their products. Two additional suppliers are in the process of integrating the system.

Residual lifetime estimation
Software to perform continuous rainflow counting of load cycles for comparison to design equivalent loads for verification of simulations and residual lifetime estimation will be developed this year.

Serial production
The first production installation of 100 blade sets is schedule to be completed by the end of 2006.

9. Conclusions

The data from the first test installation proves the data reliability and repeatability over one year and provides data during a high amount of wind turbulence classes and wind speeds. This allows the development of algorithms for different wind turbine applications, such as Residual Lifetime Estimation, Structural Monitoring and Active Control.

Difficulties with the field calibration procedure for both the strain gages and fiber optic sensors result in larger than desired uncertainty in absolute bending moment measurements. Calibration methods for all load sensor installations should be reconsidered, and calibrations should be repeated periodically, preferably by automatic control system routine.

The test installations have been used to develop packaging for the measurement system for serial supply as an embedded solution to reduce the investment costs.

Complete hardware and software solutions providing residual lifetime estimation and active control are being developed and will be available for integration into wind turbines and parks in the near future.

10. References

[1] *Fiber Bragg Gratings*, R. Kashyap, March 1999

[2] *Fiber Bragg Gratings Fundamentals and Applications in telecommunications and sensing,* A. Othonos, K. Kalli, June 1999

[3] *Novel resonant cavity TDM demodulation scheme for FBG sensing,* G.D. Lloyd and I. Bennion, L.A. Everall, K. Sugden

[4] *GUIDELINE DG02, Wind Turbine Design Strength Analysis,* NREL, National Renewable Energy Laboratory, NWTC – Certification Team, June 1999

[5] *Cost Reduction of offshore wind parks by low cost load monitoring of pile foundations*, ir. J. Hessels, ir. J. van Rooij, ir. J.H. den Boon

[6] *Developments in Individual Blade Pitch Control*, E.A. Bossanyi, Garrad Hassan, April 2004

[7] Dynamic and design optimisation of offshore wind energy conversion systems, M.J. Kühn, June 2001

[8] *Wind Turbine Control for Load Reduction*, E.A.Bossanyi