ECN

Energy research Centre of the Netherlands

Fiber Optic Blade Monitoring

Final report / public part

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Abstract

Condition monitoring of wind turbine components is of growing importance. For bearings, gearboxes and other rotating equipment, techniques are available from other applications. For condition monitoring of rotor blades, no suitable techniques are available up to now. However the interest for it is increasing rapidly.
Three main reasons can be mentioned for the late development of blade condition monitoring systems.

- The sensors to be implemented in the blades were expensive and had a short lifetime expectation.
- A measurement system should be mounted in the hub and supplied with power. A data link between the rotor and the turbine that operates independent from the turbine communication system is necessary. Up to now, such a data link was expensive, and sensitive to failures.
- Algorithms to predict the remaining lifetime and trigger alarms are available only partly and still need to be validated.

With respect to the sensors, reliable sensors become more and more available, particularly the fibre optic sensors. At this moment, measurement instrumentation based on fibre optic sensors, is available but mostly for other branches of industry. Most instrumentation is tailor made for specific applications. The gained experience can be used for wind turbines, however there are several specific requirements that ask for additional developments.

With respect to the data link between the rotor and the turbine, more solutions become available. Wireless LAN is one very serious option, which ensures a fast and flexible data link, independent from the wind turbine design. Additionally, the possibility to install instrumentation in the rotor is more and more common practice.

Both the sensors and the data communication systems are being developed outside the wind energy community. The implementation of the systems in wind turbines and the development and use of algorithms are wind energy specific.

This document gives a summary of the activities as performed during the project as far as the public part is concerned. This includes the feasibility of the application of load measurements for load reducing control strategies for the complete turbine as well as for condition monitoring of the blades. For the condition monitoring application algorithms have been defined which can give the user insight in the loads encountered during operation and the remaining lifetime of the blades. The specifications for a baseline system were also derived which can be used for the development of a specific blade monitoring system for further experiments and algorithm development.

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Summary

This report gives a description of the public part of the project results. The relevant objectives are:

1. To give an indication of the possibilities of the Fiber Optic Measurement system and using the measured loads for blade condition monitoring and for turbine control.
2. To give an overview of optical sensors as promising candidates for the measurement system.
3. A summary of results of fatigue and static tests of the optical sensors on several laminates.
4. Determination of the requirement specifications for further development of the current measurement system to a condition monitoring system for rotor blades.

With respect to the experiments, the project was hindered by delays. This was to a large extend caused by start up problems, bankruptcy of one of the partners and malfunctioning of the measurement system. For these reasons, not all tasks were performed in accordance with the work plan.

The following conclusions were drawn from this project:

1. From a brief feasibility study, it has been concluded that the use of strain measurements for turbine control, resulting in load reduction is a serious option. Further developments are needed to specify additional technical requirements with respect to the measurement system.
2. For condition monitoring several signal analysis methods have been identified, which can be implemented as real time monitoring techniques. For the development of the appropriate analysis software, practical experiments are essential. These experiments should be performed on production turbines for a longer period, in order to be able to recognise trends in the blade behaviour. For the time being load counting seems to be the most promising options.
3. From the trade off study it was concluded that the Bragg-sensor could be considered as the most optimal choice for this moment. The temperature sensitivity is recognised as a serious problem. There are technical solutions for a temperature compensated sensor, which will become available at the longer term. An alternative solution has been identified, which might result in a robust and low cost sensor. The proof of concept of this sensor is outside the scope of this project.
4. Together with the project partners, the requirement specifications of a blade condition monitoring system has been defined. This base line concept is suitable for performing the test during tool development and for demonstration of the technique for customers.
5. The experiments showed that the Bragg sensors perform well for strain measurements when the temperature is constant. As long as the temperature is distributed equally over the blade, the temperature effect can be eliminated for determination of the bending moment, by using opposite sensors.
6. For the current situation, the retrofit sensor in accordance with the FOS-design, was considered as the most optimal solution. Integration of the sensor in the blade material might be an option for the longer term. It was recommended to integrate a strain sensitive and a temperature sensitive grating on one layer in order to simplify the installation. This can only be done if a good functioning temperature sensor is available.

1. Introduction

Condition monitoring of wind turbine components is more and more becoming daily practice with the ultimate goal to reduce maintenance costs by changing from preventive and corrective maintenance to condition based maintenance. Condition monitoring techniques for detecting failures of gearboxes, bearings and other rotating parts at an early stage are commonly used in various branches of industry. Sensors, hardware and software for data acquisition and diagnosis are widely available and can be applied to wind turbines.

For monitoring rotor blades, no suitable techniques have been developed up to now. Various techniques to assess the health of blades have been investigated but seem not feasible in practice on a large scale. One method is to install acceleration sensors in the blades and to perform frequency analysis for health monitoring. Changes in the frequency behaviour might give an indication for changing properties of the blades. Another promising method is to measure and to analyse the blade loads continuously. However, up to now only the classical copper strain gauges were economically feasible. A major disadvantage of this measurement technique is that copper strain gauges are unreliable over a long period and need to be calibrated periodically. Optical strain gauges based on Bragg grating techniques pretend not to have these disadvantages. However, the sensors in combination with read out units were too expensive for condition monitoring applications and were insufficiently tested on their suitability. Since a few years, the Bragg grating sensors show a significant decrease in price and also the read out units have the potential to become much cheaper.

The advantages of the Bragg grating sensors and the expected decrease in price were reasons for ECN, FOS, NGUp, Baas R&D, and NEG-Micon to look further into the possibilities of optical fibres and to initiate the project Fibre Optic Blade Monitoring (FOBM) in 2002. The measurement system, further on called the FOS system, has been developed by FOS WindPower in France (see Figure 1.1). This system was also tested in the DOWEC turbine at EWTW.

Figure 1.1: FOS system with Bragg sensors

The capabilities of the FOS system are limited to measure local strains only. Loads can be derived from these strains. Such a system will only have added value for condition monitoring and optimising maintenance strategies of rotor blades if the measured strains can be converted into key parameters that can be presented in plots providing information on the health of the blades, e.g.:

- what is the consumed (or remaining) lifetime,
- are the actual loads more benign than the design loads,
- or is one turbine degrading faster than another one.

A suitable format for presenting the measured data should be determined in order to make the FOS system suitable for condition monitoring.

Apart from the measurement system, there are several other questions to be answered such as:

- what type of optical sensors are available which might be attractive alternatives in future,
- can measured signals also be used as inputs for the control,
- how should the sensors be installed in the blades.

This report contains a brief description of the public part of the project results. This concern the application area's of this measurement techniques, being condition monitoring and control. This subject has been addressed in chapter 3.

Although often Bragg gratings are used as well for wind turbines as for other applications, a trade-off study has been performed. Reason for this trade-off study was that other technologies than Bragg sensors are also in development. The telecom market has a strong influence on these developments, which might open new possibilities for alternative sensors. The results of this trade-off study is summarised in chapter 4.

Static and fatigue tests have been performed with optical sensors installed on test specimen. Due to very limited availability of the instrumentation, only a few experiments could be completed. The results of these tests are discussed in chapter 5.

For the further development of a condition monitoring system, based on Fiber Optic measurement technology, requirements with respect to the measurement system itself as well as with respect to the diagnostic software have been established, as reported in chapter 6.

2. Objectives

The objectives of the FOBM project as reported in the public part are:

1. To give an indication of the possibilities of the Fiber Optic Measurement system to use the measured loads for blade condition monitoring and for turbine control.
2. To give an overview of optical sensors as promising candidates for the measurement system.
3. To summarise the results of fatigue and static tests of the optical sensors on several laminates.
4. To determine the requirement specifications for further development of the current measurement system to a condition monitoring system for rotor blades.

The objectives 1 to 4 are treated in the chapters 3 to 6 of this report. Another objective in the original proposal was to gather user experience with the system for health monitoring. However this part of the proposal was left out by NOVEM and consequently not reported.

3. Load measurements and turbine control and condition monitoring

The two applications of Fiber Optic load measurements have been analysed in more detail during the project. The first application, load measurements for turbine control, has been evaluated with respect to the potential of load reduction and increase of energy yield.

With respect to the second application, Blade Condition Monitoring, some methods based on load measurements, have been identified. Based on a Failure Mode and Effect Analysis a selection has been made of methods, which are the most promising for early fault detection.

3.1 Load measurements for turbine control

The possibilities for using the fibre optic strain measurements for the wind turbine control system have been examined by theoretical models. Possible benefits are:

- Load reduction by means of individual blade pitching
- Increase of energy yield at low wind speeds
- Possibilities for drive train damping.

Load reduction
In order to quantify the potential improvements, the maximum load reduction for the individual blades and the tower, which could be achieved theoretically by individual pitching, have been estimated with time simulations [Ref. 2]. For the flap wise moments, a reduction of the equivalent 1 Hz load of 5 % is expected, while the lead-lag moments remain almost constant. This means that a a significant load reduction can be achieved. Whether this also results in a significant reduction of the weight and cost is not examined, because that requires a more detailed analysis, which could not be executed within the framework of this project.

Increase of energy yield
The increase of the energy yield by applying cyclic pitching at low wind speeds is very small. The limited contribution to the total production within the operational mode during which cyclic pitching can be applied and the small increase of the energy yield implies that the effect is very small.

Drive train damping
The effect on drive train damping can be examined by simulations, when the information from the strain measurements are used to estimate the rotor shaft torque. There are several possibilities for the torque estimation, however more detailed information should be available with respect to the properties of the optical measurements (accuracy, bandwidth and noise). The availability of more practical data is essential for further development.

Compared to the application of condition monitoring, most of the requirements for control are not much different from condition monitoring. However for control it is very important that the signal delay is very small and that the short-term accuracy is high (typically < 0.1%). Also the availability of correct measurements must be very high in case that lighter structures are being applied, based on the assumption that the loads can be reduced with the use of optical measurements.

Conclusions
There is certainly a potential for load reduction, although this cannot be quantified as a result of this project. Additional research on cost reduction of blades and reduction of drive train oscillations will give more insight. The control application sets some extra requirements to the

measurement, such as accuracy, reliability of data and the time delay. This application should be considered as an extra spin off of load monitoring of the blades.

3.2 Load measurements and condition monitoring

Based on ECN's experiences with mechanical load measurements in the past and on the possibilities of the FOS system, the project team has defined a number of formats to present the measurement results in such a way that they can assist operators in assessing the health of their rotor blades and prioritise and optimise the maintenance procedures. The following methods are worked out in detail [Ref. 1]:

- Blade load analysis
- Rotor shaft torque estimation
- Local strain analysis

3.2.1 Blade load analysis

The encountered loads during the lifetime of the turbine can be used for making accumulated load spectra. This spectrum can be extrapolated over the lifetime of the turbine. The spectrum is only relevant, if a reference is available, e.g. the spectrum in accordance with the IEC wind speed class, other turbines or a design spectrum (see Figure 3.1). The analytical results become available as graphs, which require background knowledge for further interpretation.

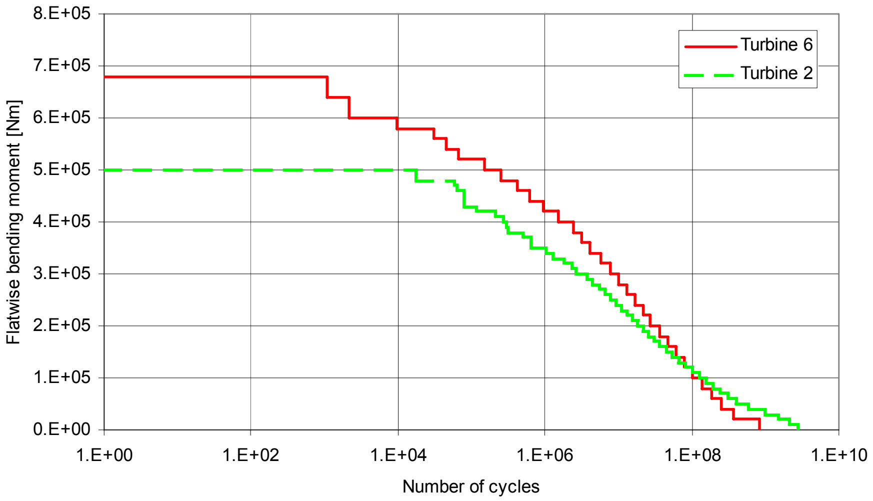

Figure 3.1: Example of comparison between the fatigue loads of two wind turbines within one wind farm

Another powerful concept is the equivalent load calculation. The equivalent load results in one value for a time series. Using a recursive algorithm for the calculation of the mean value of the equivalent load, gives an impression of the load encountered during the lifetime. Similar as for the load spectra, the equivalent load is only relevant if a reference is available, which might be a design value or data from other turbines (see Figure 3.2).

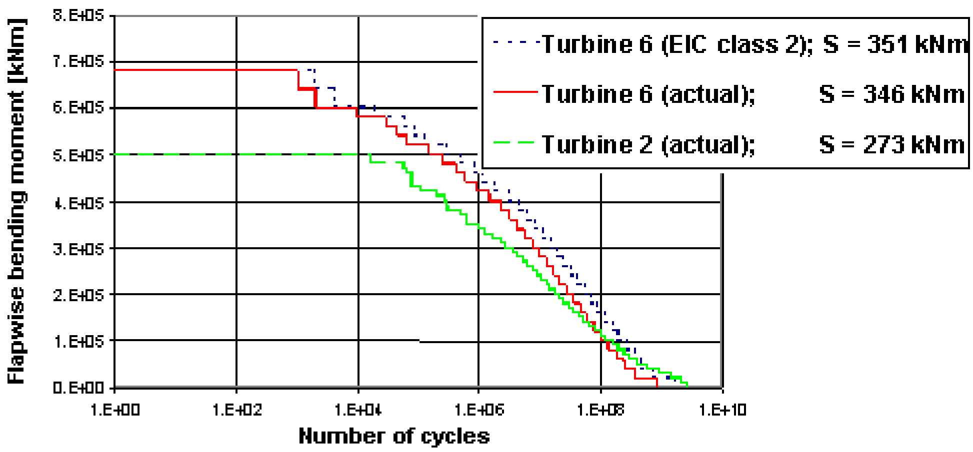

Figure 3.2: Three load spectra reduced to three equivalent loads by taking into account a simplified model of the fatigue material properties

Detection of extreme loads can be considered as a very direct method of safeguarding. If damage does not occur immediately, extreme loads may still cause damage over a longer period of time due to the so called "low cycle fatigue" (see Figure 3.3). For this reason, it is essential to monitor the occurrences of extreme loads and to generate a warning in case a certain threshold value is exceeded.

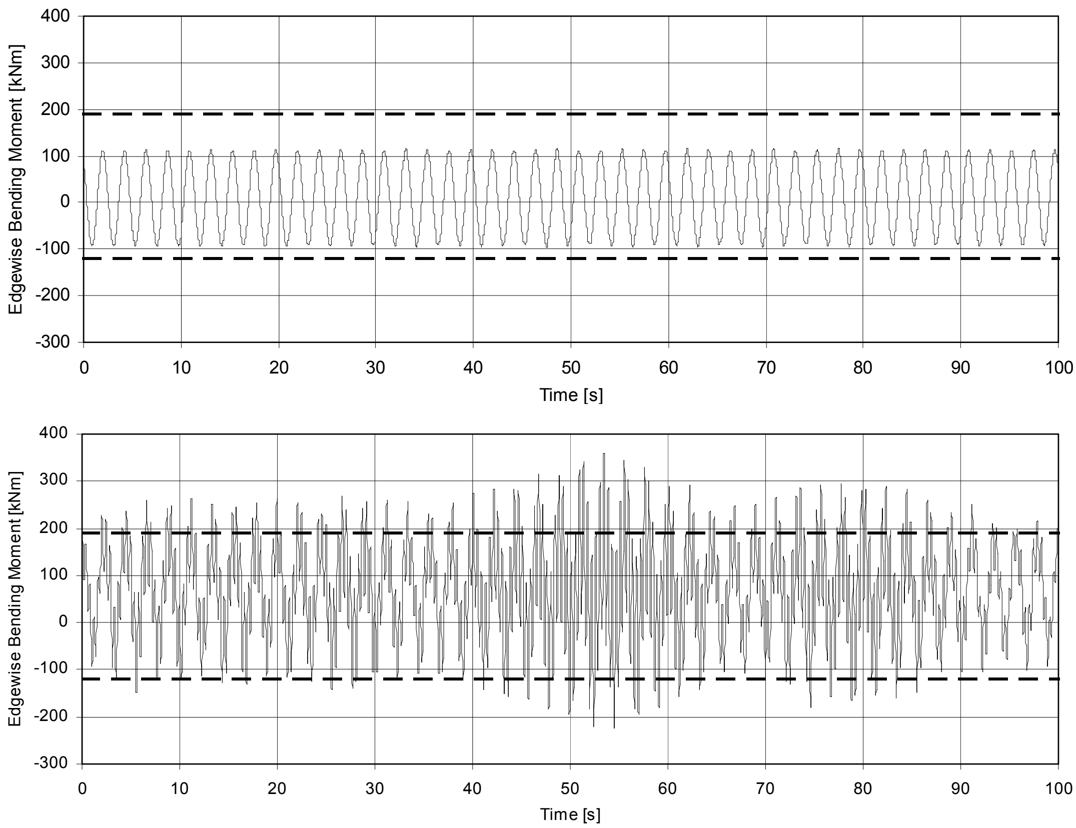

Figure 3.3: Edgewise bending moment exceeding threshold levels for certain amount of time at high wind speeds.

Instead of condition monitoring based on measured loads, health monitoring based on vibration analysis is another approach. FFT analysis results in frequency spectra, which gives information about the eigen-frequencies of the blades. The eigen-frequency spectrum can be used in several ways for early fault detection:

- Comparing natural frequencies (see Figure 3.4)
- Excessive vibrations and predefined envelopes (see Figure 3.5)

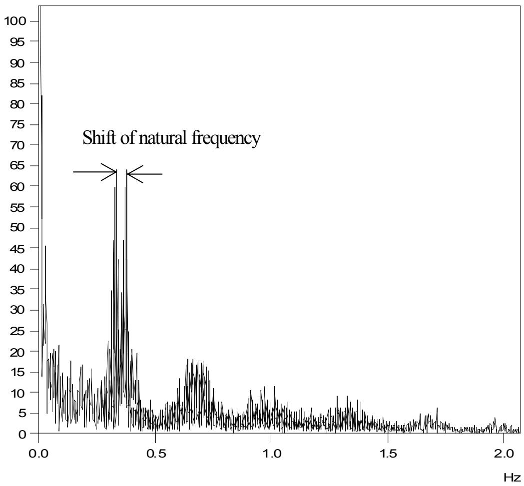

Figure 3.4: Shift of natural frequency

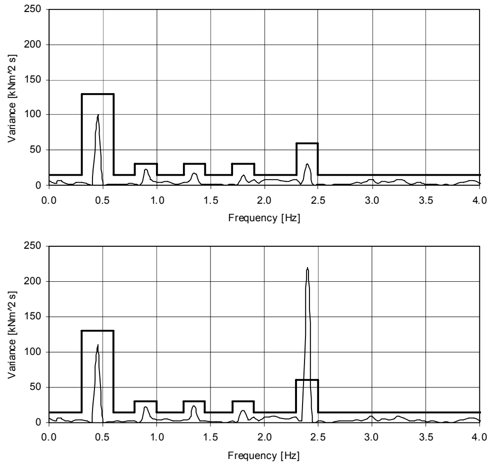

Figure 3.5: Variance spectrum showing excessive vibrations at 2.4 Hz

Another form of condition monitoring is to use the statistics of measured signals, such as mean, standard deviation, minimum and maximum values. The values are easy to determine and often provide relevant information in case of malfunctioning. For instance, the mean values of the edgewise-bending moment can be plotted as a function of the average wind speed (see Figure 3.6). The measured mean values should not exceed predefined values.

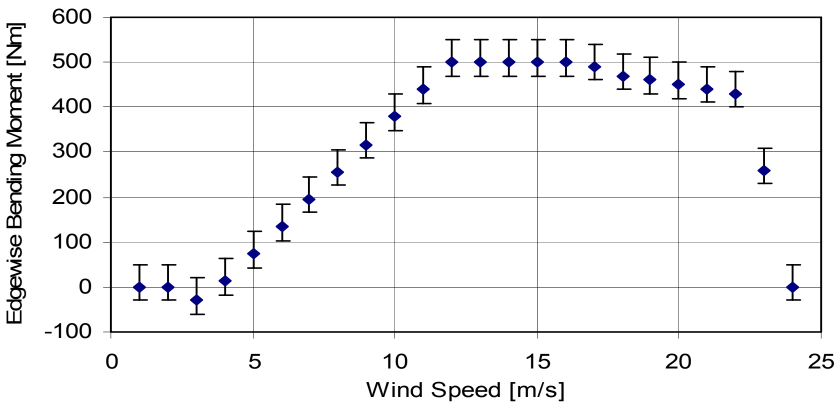

Figure 3.6: Mean values (or other statistic value) of edgewise bending moment should not exceed predefined values

3.2.2 Rotor shaft torque

The rotor torque can be derived by combining the individual blade loads and some other turbine parameters like the pitch angle and the azimuth angle. The blade loads should be converted from the blade co-ordinates to the hub co-ordinates. An example of constructing the rotor shaft torque from the individual edgewise moments is given in Figure 3.7. The sum of the three time series of the edgewise blade bending moment correspond fairly well with the torque measured on the main shaft, even if the blade loads suffer from excessive vibrations.

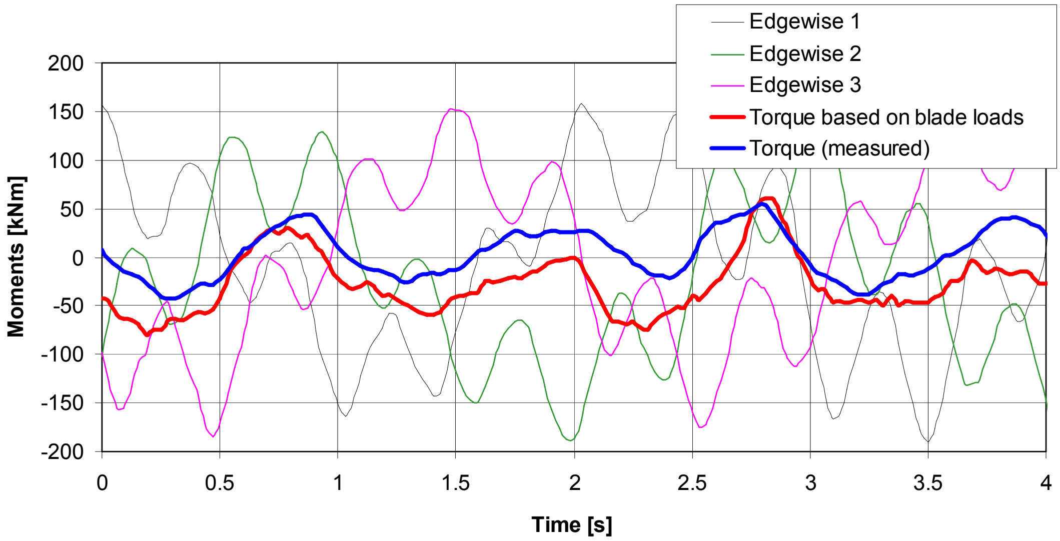

Figure 3.7: Sum of individual blade bending moments in edgewise direction

Worthwhile mentioning in this chapter is the analysis of mean values of the torque and the individual bending moments. All three edgewise bending moments should contribute equally to the rotor shaft torque. If from a certain time on one of the three blades starts contributing substantially more or less than 1/3 to the rotor torque, this may indicate that this blade is malfunctioning, e.g. damage from a lightning strike, or an incorrect pitch angle.

3.2.3 Local strain

The optical strain gauges in fact measure local strains. A large number of alternating strains may lead to fatigue damage whereas high strains may lead immediately to failure. The number of occurrences of the strain cycles can be counted with the rain flow count procedure and stored in a Markov matrix. The material data for fatigue are usually presented as S-N curves, showing the maximum allowable strain S to survive a certain number of cycles ($N=C.S^{-m}$).

Based on the material characteristics and the measured strains, the consumed fatigue damage can be calculated (see Figure 3.8)

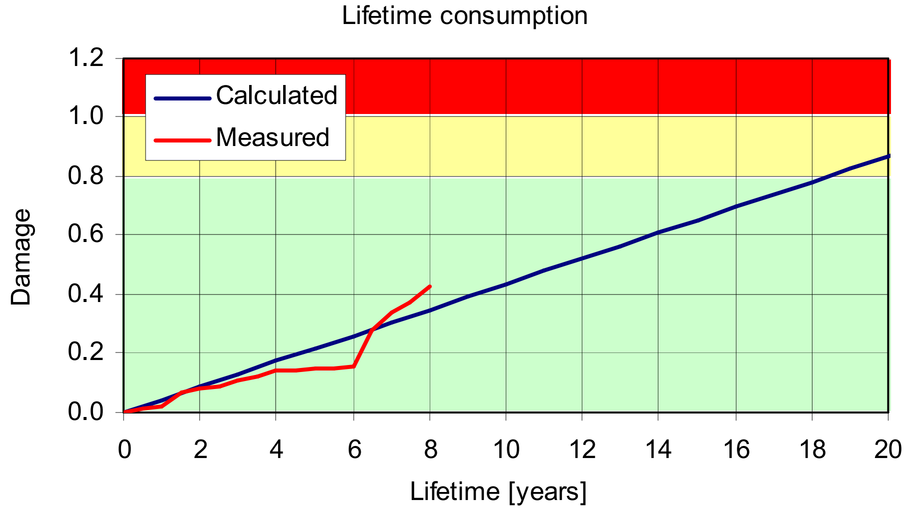

Figure 3.8: Consumed fatigue damage as function of the lifetime

3.2.4 Failure modes and ranking of formats

Based on a FMECA, the following failure modes have been identified:

1. Leading and trailing edge
   - *1.1 Longitudinal crack of adhesive joints*
   - *1.2 Transverse cracks in leading or trailing edge*
2. Suction and pressure side shells
   - *2.1 Transverse cracks over full profile depth*
   - *2.2 Debonding of gel coat*
   - *2.3 Buckling*
3. Shear Web
   - *3.1 Cracks in bonding line between shear web and girder*
   - *3.2 Damage / delamination / buckling in shear web*
4. Blade root flange
   - *4.1 Transverse cracks at blade root*
   - *4.2 Bonding failure of studs*
5. Bolt connection
   - *5.1 Loss of pretension*
   - *5.2 Operational failure*

The FMECA also includes the detection methods that can be used and the potential of these methods to be able to detect the failures in an early stage.
From this a priority list of most promising options have been determined that have the most added value for the operators.
This resulted in a priority list as given in Table 1.

Table 1: Priority list for implementation of detection mechanisms

	Detection method	Priority level [1]
	Blades (global)	
	Load spectrum analysis	1
	Equivalent load analysis	1
	Vibration analysis	2
	Ultimate load safeguarding	1
	Load statistics	1
	Blades (local)	
	Local strain / consumed fatigue damage	3
	Local strain / Ultimate strain safeguarding	3
	Local strain / statistics	3
	Rotor shaft	
	Load spectrum analysis	4
	Equivalent load analysis	4
	Vibration analysis	4
	Ultimate load safeguarding	1
	Statistics	4

Priority level:
1 Covers more failure modes, implementation realistic
2 Covers more failure modes, implementation/tuning complex
3 Specific failure modes, implementation/tuning complex
4 Of minor interest for condition monitoring

Based on this, it was decided to start the implementation with blade monitoring techniques based on blade load measurements. The local techniques for blade monitoring require more information about the blade design and material properties, which makes implementation more difficult and also more specific to the blade design.

Techniques, which are based on the rotor torque, derived from the blade loads require very accurate blade load measurements. This is considered as unrealistic at this moment.

4. Trade off study sensors and instrumentation

Within the framework of the project, a study has been performed on the various aspects of Fibre Optic Sensor Systems as possible candidates for load measurements of wind turbine blades. Different types of sensors and technologies have been reviewed and also alternatives have been considered [Ref. 4].

4.1 Sensors and technologies

The load on a wind turbine blade can be calculated from:

- Strain measurements at a limited number of strain-representative spots using a strain sensor at each spot. This method is normally referred to a "discrete distributed strain sensing".
- Strain measurement along a certain representative trajectory, distributed over the geometry of the blade, using a continuous sensitive strain sensor along the trajectory. This method is usually referred to as "continuous distributed strain sensing".

As a generic approach, both types of sensors can be figured for blade strain monitoring as shown in Figure 4.1.

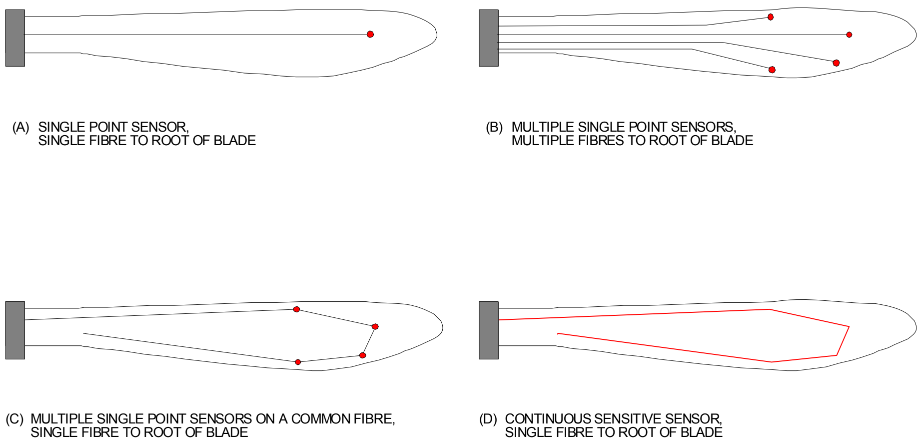

Figure 4.1: Generalised distribution of strain sensors over a wind turbine blade

For a distribution of strain sensors as shown in Figure 4.1(a,b,c) mostly Fibre Bragg Gratings based sensors (FBGs) are used as single point strain sensor. An FBG employs an optical grating written in the fibre core as strain sensitive element. Another well-known point-sensor for strain measurement is based on a Fabry-Perot Interferometer principle, with the Fabry-Perot etalon made up from optical fibre. In contrast with distributed point sensors, continuous distributed strain sensing employs in the most simple case a fibre "as is", i.e. without the introduction of special prepared strain sensitive regions or components. This approach is shown in Figure 4.1(d). One of the most common techniques for using a fibre "as is" for strain sensing is known as Brillouin Strain sensing.

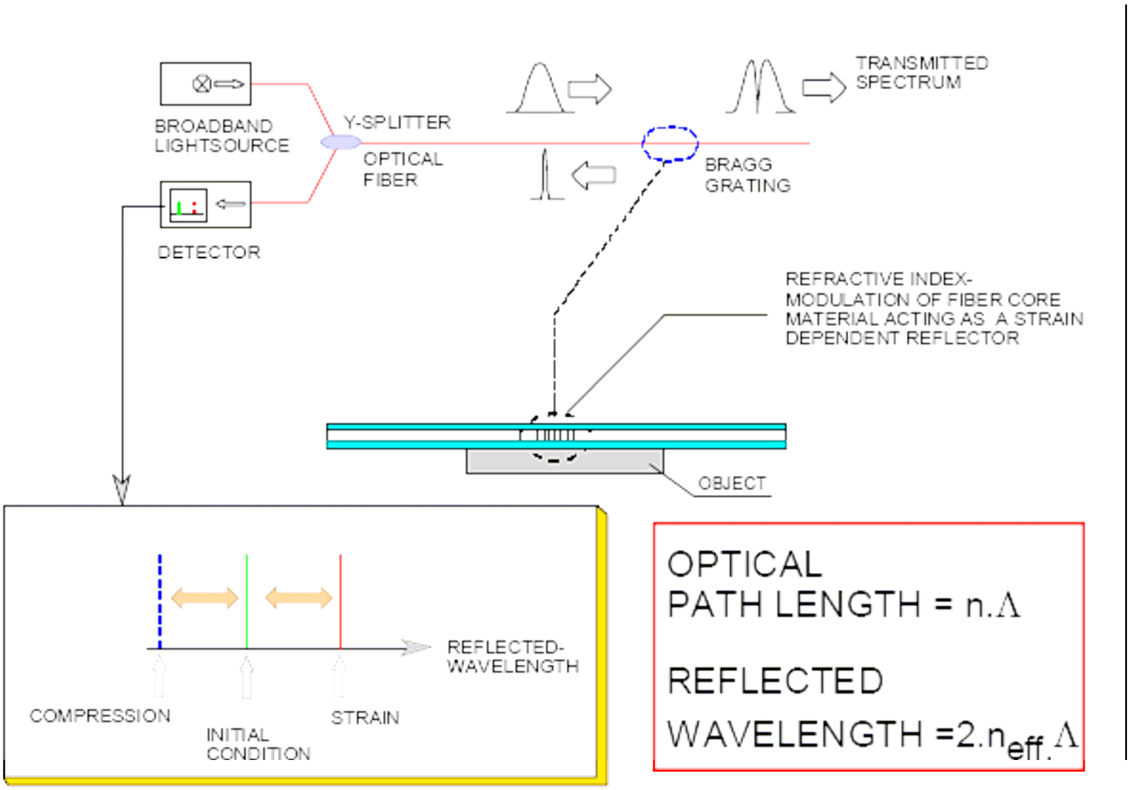

Figure 4.2: Fibre Bragg Grating read out unit and wavelength response to strain

The Fibre Bragg Grating (Figure 4.2) is considered as the most realistic option for the time being, although there are other strong candidates on the longer term. Especially with respect to the temperature compensation there are several possibilities identified, such as the use of a-thermal housings, use of elliptical core or long period gratings. Applications of these techniques are still hindered by costs. However given the demand in optical telecommunication networks for temperature insensitive optical filters based on Fibre Bragg Gratings will lower the price.

4.2 Sensor integration

With respect to embedding sensors in the blade, the following remarks can be made:

1. The long term reliability of a FBG based strain sensor is greatly determined by the handling of the bare fibre during the process of writing of the grating and the subsequent handling of the “bare quarts wire” containing the FBG.
2. The present mechanical strength of FBG based sensors and their handling precautions require very careful manipulation of the sensor and the connecting fibre. Therefore, integration of a FBG during production of a turbine blade requires extra attention of the production personnel and may even ask for a trained technician to perform this task. Furthermore, it would be efficient to monitor the integrity of the FBG directly after positioning in the blade, but before injection moulding. These requirements can be relaxed at the moment a FBG sensor can be recoated and covered with an extra coating to increase their strength and handling properties.
3. Embedding of a FBG into an intermediate carrier reduces the risk of damaging the sensor during integration into the turbine blade.
4. Embedding of a FBG into an intermediate carrier enables fatigue testing, performance testing and quality control on a relative easy basis.
5. Due to the protective character of the carrier, sensors have a much better chance will survive integration into the blade.
6. Surface mounting of the sensors allows replacement of defective ones or repair of fibre optic cabling more easily than in the case of embedded sensors.

7. Novel techniques to use a thin transparent coating around the fibre that can stay on during writing of the grating will increase the long term reliability of a FBG strain sensor considerably. Following this approach will require a separate development and verification program.
8. Non-FBG based strain sensors using the fibre “as is” do preserve the strength of the original fibre.

4.3 Conclusions

In the trade-off study, several techniques have been discussed, with their properties. From this the following conclusions are relevant for the project:

1. The Bragg gratings are at this moment still the most realistic option for application in wind turbines. However there are other technologies in development, which are less sensitive to temperature effects.
2. For the sensor installation, the retrofit option is considered as most realistic. Integration of sensors in the blade material requires long term development work with respect to production aspects. Also the state of the art with respect to sensor development and fibre protection is not yet in the stage that survival of the installation can be ensured. Repair of integrated sensors is impossible.

5. Static and fatigue tests of sensors on test specimen

One of the purposes of the project was to determine the suitability of Bragg sensors for condition monitoring. For this reason static as well as dynamic tests have been defined in an action plan. This included:

- Thin laminates under ambient conditions
- Thin laminates under hot and wet conditions
- Thick laminates under ambient conditions only.

However, the start of the test programme has been hindered seriously for several reasons, which implied that the programme has been delayed for one year. When all equipment for testing was available, execution of the test was severely hindered by failures of the FOS-measurement system. Especially tests with a long duration could not be completed. For this reason the test programme couldn't be executed completely. The following tests have been performed with usable results:

- Influence of cyclic loading on optical temperature sensors
- Creep at room temperature and at 60 ^{o}C
- Temperature influence on strain sensors
- Temperature influence on optical sensors.

5.1 Influence of cyclic loading on optical sensors

The tests have been executed on a 250 kN test rig. The test rig is operated with constant amplitude and the temperature of the test specimen can be controlled (Figure 5.1).

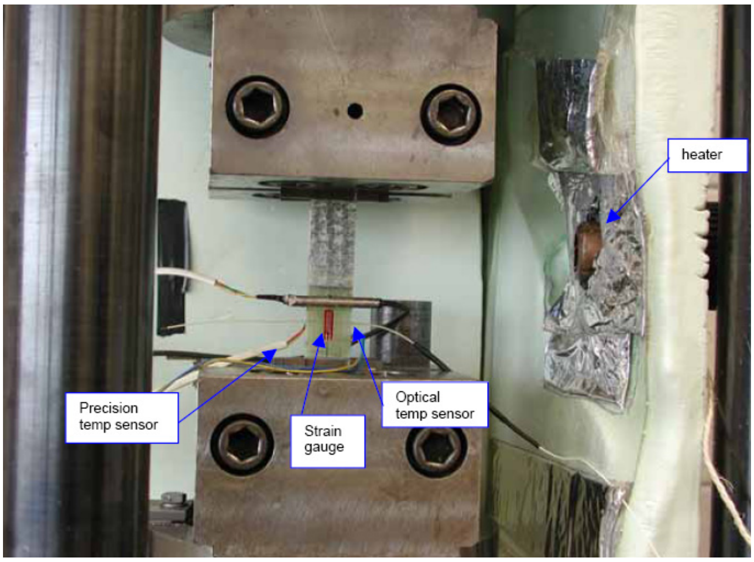

Figure 5.1: Test set up in bench

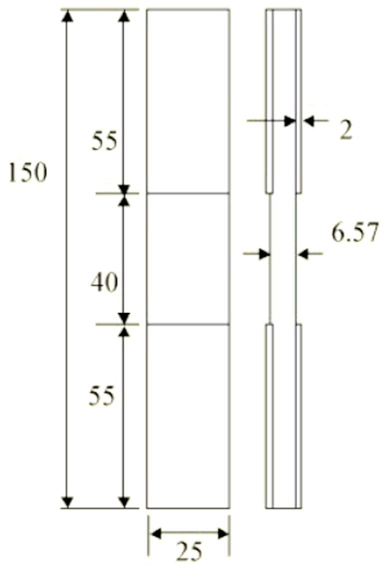

Figure 5.2: Thin test specimen lay-out (Optimat)

The tests have only been performed with the thin test specimen (Figure 5.2).

The test specimen have been equipped with:

1. Optical temperature sensor
2. Precision temperature sensor
3. Classic strain gauge

During the tests cyclic loading with a constant amplitude (±10 kN, R=-1) is applied. From Figure 5.3 has been concluded that the temperature sensors are not influenced by the strain. Even at high strain levels (amplitude of 9000 με), the temperature signal remains constant. This is not in line with experience of ECN. For the DOWEC-turbine, strain modulation has been observed for several temperature sensors. This is an important improvement of the sensor, however it must also be noticed that the design is completely different from earlier models and that there is always one sensor per optical line, which implies that the sensor is mechanically connected at only one side. In normal situations, when the sensor is part of a complete string, the sensor is connected with fibers at two sides.

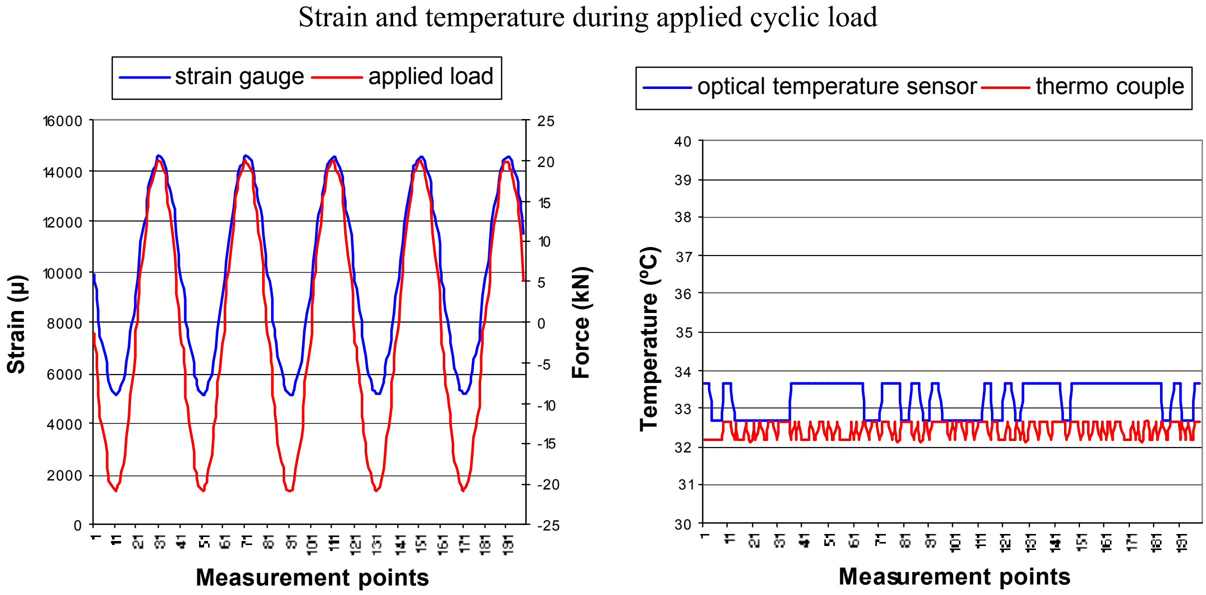

Figure 5.3: Influence of cyclic loading on optical sensors

Thermal cycling has been done by heating and cooling the test specimen (Figure 5.4). The absolute values lie in the same bandwidth. However the optical sensor seems to react quicker

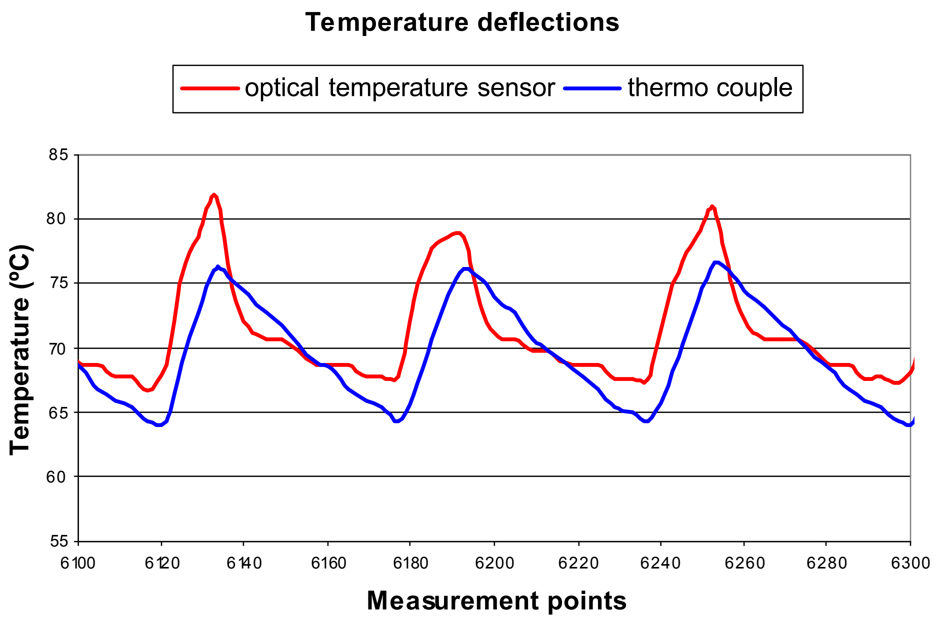

Figure 5.4: Temperatures during thermal cycling

on the starts and stops of the heater. This is probably caused by direct heating of the sensor by the air of the heater.

5.2 Creep at room temperature and at 60 ^{o}C

Creep tests have been performed at room temperature (30 ^{o}C) and at 60 ^{o}C. For the test, five sensors are installed on a standard Optimat specimen (Figure 5.5).

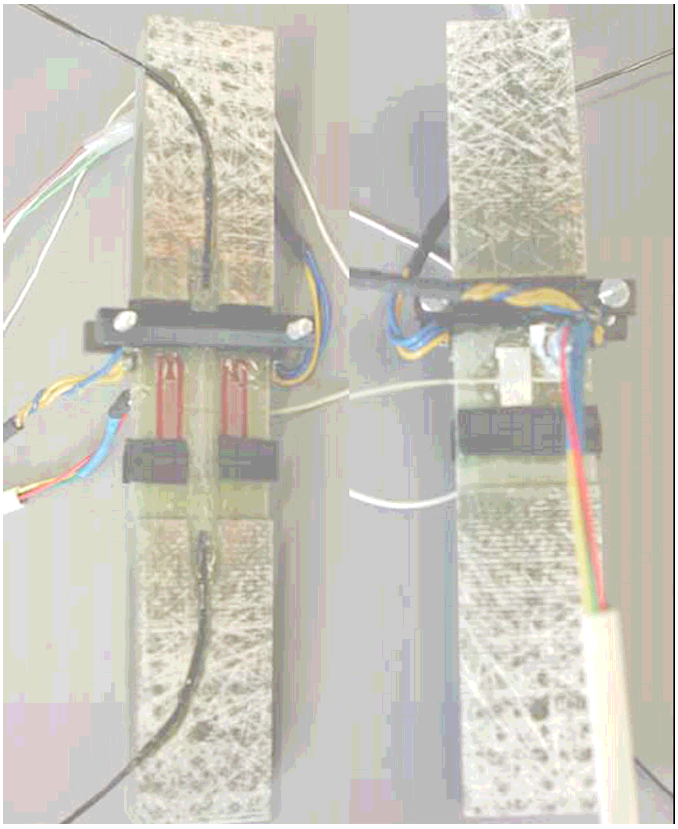
Figure 5.5: Front and backside of the test specimen

The following sensors are installed:
1. Two classic strain gauges
2. One thermo couple
3. One optical temperature sensor
4. One optical strain sensor.

For the test, the test specimen was clamped in the testing machine (Figure 5.1) and two test have been perfomed:
1. The first creep test was done at room temperature, starting with a tension of 5 kN, which has been changed to 22,1 kN tension.
2. The second test was done at 60 ^{o}C, starting with 22,1 kN tension, which was changes to 22,1 kN pressure.

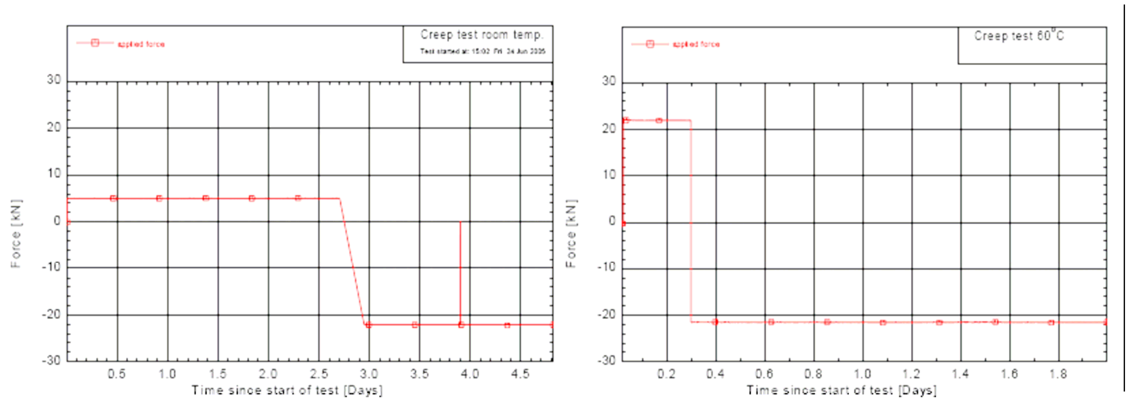

Figure 5.6: Applied forces during creep tests

The metallic strain gauges, which are used as a reference, show a mutual difference in the order of 5%. The differences between the optical and the metallic strain gauges are in the same order (see Figure 5.7). The optical strain gauges show the same behaviour as the reference strain gauges over the test duration. Apart from that, the optical strain gauges are very sensitive for the temperature, so that compensation is very important (see Figure 5.7, right detail: the dip in fibre optic signal is caused by temperature change). From the registrations can be learned that the temperature compensation is not functioning properly. For these reasons, no conclusions can be drawn with respect to the absolute values. Only with respect to the long term behaviour can be concluded that the optical strain sensors provide stable values. At 60 °C, the test results are the same.

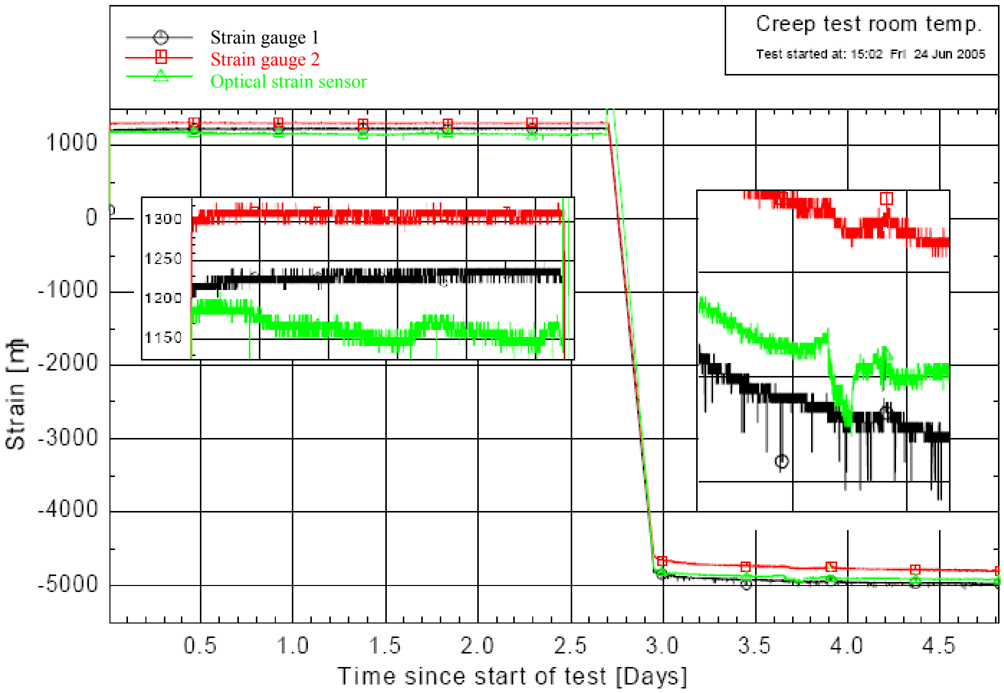

Figure 5.7: Strain during creep test at room temperature

5.3 Temperature influence on strain sensors

The purpose of this test was to compare the different methods for strain measurements including the effects of temperature changes. For this test the same test specimen have been used (Figure 5.2). The following sensors have been installed:

1. Two metallic strain gauges
2. One thermo couple
3. One optical temperature sensor

4. One optical strain sensor

The test specimen was placed in an oven and heated from room temperature (23^{o}C) to 60^{o}C and cooled down again to room temperature. This cycle has been repeated 7 times.

The strain signal was temperature compensated, so the test result should result in a constant value for the strain signal. However, it was observed that the temperature sensor showed a deviation of about 6 degrees at 60 ^{o}C, which already results in an error of about 60 $\mu\varepsilon$. Apart from this error, there are also other effects, such as a non-homogeneous temperature distribution in the test specimen and relaxation effects in the test specimen. In total the observed changes in strain were between 150 and 200 $\mu\varepsilon$. For the metallic strain gauges, the difference is in the order of 100 $\mu\varepsilon$.

5.4 Temperature influence on optical temperature sensors

The purpose of this test was to determine the accuracy of the optical temperature sensors and the effect of temperature compensation using these sensors. Eight optical strain sensors and three thermo couples were placed on a metal strip. This was placed in an oven. The temperature was increased from room temperature (23^{o}C) to 60^{o}C and cooled down again. This has been repeated three times.

The optical temperature sensors show initially a temperature difference of 9^{o}C. These "offset differences" do not have to be a problem when the temperature sensor is only available for temperature correction of the strain sensors, because in that case only the change in temperature (is change in wavelength) is used. However measuring the absolute temperature can cause serious errors. After compensation of the offset, the maximum difference over the whole cycle is 3^{o}C, which causes a strain difference of 42 $\mu\varepsilon$.

Apart from this, the noise levels of the temperature signals are rather high, which results in an increasing noise level on the compensated strain level as well.

5.5 Conclusions

Based on the experiments executed, data analysis performed, the opinion of blade producers and practical experience during handling, the following has been concluded:

1. The Bragg sensors perform very well as strain sensor when the temperature is constant. For load monitoring of the blades, only the bending moment is of interest, so that the temperature effects are eliminated by using opposite sensors in the root of the blade. The temperature should be distributed equally.
2. Calibration of the strain sensors for temperature effects is a serious problem, which has not been solved by temperature compensation only. The reason for this is not only the inaccuracy of the temperature sensor itself, but also expansion of the blade material. Also the stability of the temperature sensors was not sufficient, so frequent recalibration was necessary.
3. The accuracy of the optical strain gauges strongly depends on the accuracy of the temperature sensors. However, the accuracy and resolution of the temperature sensors is limited which implies large errors. A practical and reliable design of a temperature sensor based on Bragg technology is presently not available.
4. The sensor embedded in the laminate does not give problems. However handling the fibres and connectors is certainly a weak point, even in a laboratory environment. Using these technology requires good preparation and good choice of coatings and components.

6. Requirement specifications of Blade Monitoring System

For the application of blade monitoring, there are a lot of possibilities with respect to the configuration. Because several parties are involved in the choice of the concept, definition of a base line concept is a good starting point for further discussions, finally resulting in a more optimal solution. This chapter describes the base line concept for a "Blade Condition Monitoring System", the functions to be performed by the different modules, the background of the choices and possible alternatives.

6.1 Baseline configuration

The general set up of the blade condition monitoring system is sketched in Figure 6.1. In all individual turbines, the loads in the blades are measured and the results are transferred from the rotor to a local PC. The local PC processes the measurement data and makes the diagnostic results available for the external parties. This can be done at park level, so that the operator can use the diagnostic results for operation and planning of maintenance. Also access by specialists should be possible, in which case the information available should be more specific.

Direct messaging from the rotor part via separate communication is an option. In case of a very serious alarm, which causes exceeding thresholds, a message can be sent directly via e.g. GSM. This offers the possibility to detect serious damage, also when the network is not available. It can also be used for warnings about failure of the communication system so that data cannot be downloaded to the local PC's which implies loss of data.

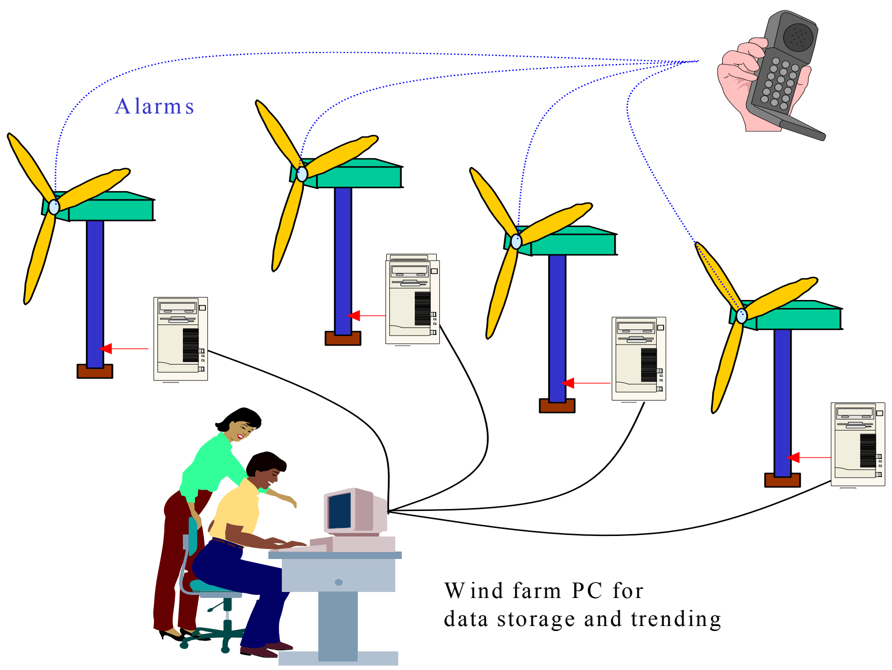

Figure 6.1: Blade monitoring system in a wind farm

The baseline system is presented in more detail in Figure 6.2.

Each blade is equipped with three optical fibres. Each optical fibre accommodates up to 5 Bragg sensors, for measuring the strain or temperature.

The optical fibres from all three blades are connected to the "Rotor Module", which can accommodate 9 optical lines. This module includes the necessary optical provisions, intermediate data-storage and processing facilities. As a possible option, the Rotor Module could also perform checks on the measured data in order to detect alarms. These alarms can than be sent immediately by GSM/SMS. For more extensive analysis, the time series are sent to the "Turbine Module" via wireless LAN. The system can be accessed remotely for all common user functions such as start, stop, reset, data downloading, parameter modifications and program uploading and downloading. A UPS provision should be included to improve system capabilities for event recording.

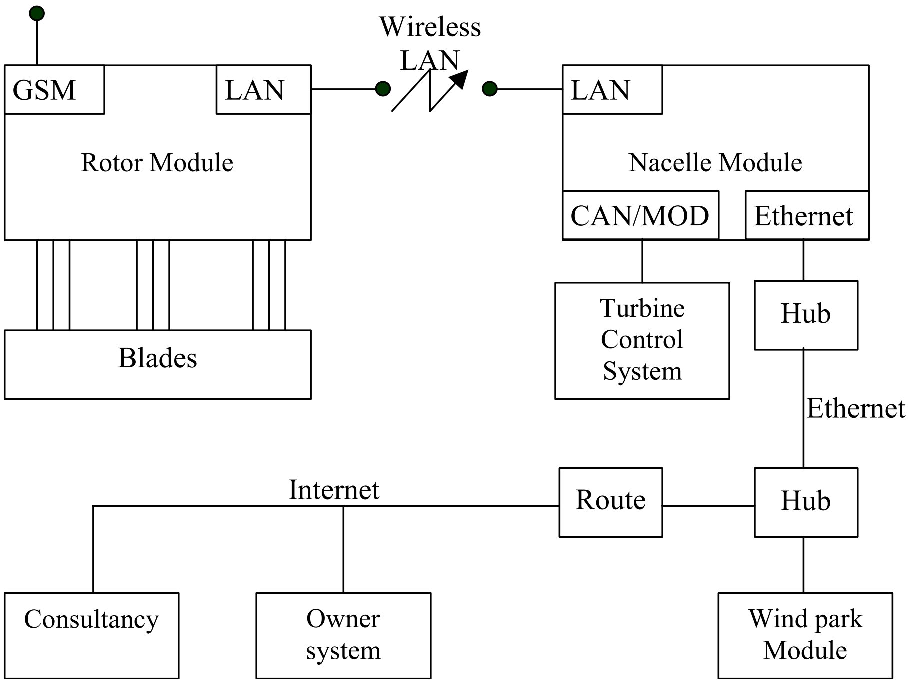

Figure 6.2: Base line configuration for blade monitoring in wind farm

A Turbine Module will be installed in the nacelle or tower base. Besides the blade-data, the system also collects data from the wind turbine, such as rotor speed, electrical power, wind speed, yaw angle and pitch angles. The turbine module will include hard disk storage capacity, so that sufficient data can be stored. For some analyses external data might be required, such as material properties or data from other turbines. This information will be supplied via an Ethernet connection. Remote access for this system is also required.

The Turbine Module can be accessed via LAN/internet by a wind park computer, another system at owner level and/or by consultants, specialists and contractors. With these systems, remote control of the Turbine Module and Rotor module can be achieved. The connection can also be used for data back-up. Also status information will be sent to the park/owner systems. In case of abnormalities specialists can be consulted, who also have access to the system. Another approach could be to commission the safeguarding to a third party to perform certain tasks. The system set-up should have the flexibility to cover different approaches, depending on the requirements of the wind park owner.

When the system implemented as an turbine option, just like other monitoring provisions, the communication between the rotor and the nacelle can also be realised via available sliprings. The wireless option is more suitable for using the system in existing installations, where the communication provisions are not available.

6.2 Detailed description of the modules

6.2.1 Rotor module

The rotor module will be installed in the hub, see Figure 6.3. The system should be suitable to function there for the lifetime of the turbine. So it should be robust for vibration, dust, moist, EMC a.s.o. The system should not have moving parts like a hard disk or fans. This means that the storage capacity is limited.

For a system in a rotor environment, it is important to keep the interfacing as simple as possible. Because of the link with the nacelle, which is different for every type of turbine, the interface should also be flexible. Usage of existing data communication provisions (mostly sliprings) should be avoided. For this reason, a wireless LAN connection for the data-transfer is considered as the most realistic. The wireless LAN systems are commercially available for an acceptable price. However the transmittance might be sensitive for the shielding properties of the hub and the availability of systems for a harsh environment is limited. The location of the antennas might be critical and require extra attention. Besides the optical connection, the system only requires power supply.

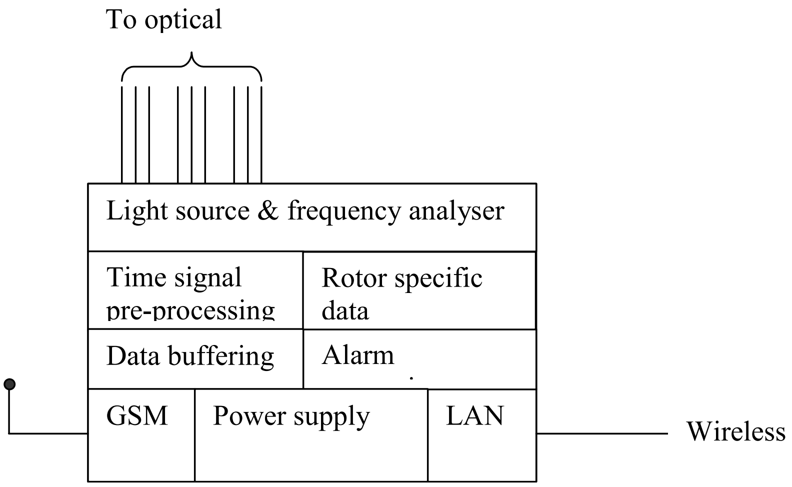

Figure 6.3: Rotor Module

The functions of the "Rotor Module" are:
1. Dedicated measurement system, 9 optical lines, 5 sensors per line, strain / temperature
2. Time signal pre-processing (temperature compensation / scaling)
3. Calibration function
4. Alarm detection on extreme loads
5. Buffering of measured data (1 day capacity)
6. Alarm messaging via GSM
7. Data transfer via wireless LAN

Each blade is equipped with:
- Four strain sensors and one or four temperature sensors at the blade root
- Four strain sensors and one or four temperature sensors at 15 meter radius (optional)
- Eight strain sensors at critical shear web locations (optional).

These sensors should be scanned with a frequency of 20 Hz. Temperature compensation will be carried out real time. The Rotor Module shall also perform some simple safeguarding functions, without interference of other modules. So the possibilities of alarm detection based on extreme loads or extreme changes of eigen-frequencies should be considered. This requires some additional data processing, such as load calculation and detection. In case of alarm, a sms-message could be submitted, which functions completely independent from the rest of the network.

Calibration of the sensors is initially necessary. This can efficiently be done during the commissioning phase of the wind turbine during low wind speeds. During idling, the calibration factors can be calculated based on the weight of the blades. The calibration should be done in work position and vane position of the blades. Because the "turbine information" is not available in the rotor module, the calibration procedure should be performed manually.

The calibration factors should be stored in a non-volatile part of the memory. This part should also contain other blade specific information like identification, start of operation, weight, detected alarms, etc.

During operation, data transfer via the wireless LAN might be interrupted. This means that data-buffering in the rotor module is recommended. The capacity should be at least one hour of data.

The measurement data are transmitted to the nacelle module in a binary format, representing the temperature compensated strain. Data will be transmitted each second. The requirements are summarised in Table 2.

Table 2: Requirements for Rotor Module

Item	**Requirements**
Number of optical lines	3x3
Number of sensors	5 sensors per line
System	Solid state components only
Measurement frequency	20 Hz
Storage capacity	one hour
Instantaneous warnings/alarms (GSM)	1. Extreme loads 2. Extreme frequency shifts
Data transfer (wireless LAN)	1. 16 Hz time series 2. Alarm messages
Alarm messages	1. Alarm messages (SMS) directly in case of exceeding detection levels 2. Storage of alarms in Blade signature file 3. Copy of message via wireless LAN to Nacelle Module
Blade signature (each blade seperately)	1. Start date operation 2. Balance data 3. Weight 4. Material properties 5. Temperature coefficient 6. Instantaneous alarms history
Sensor configuration	1. Location co-ordinates of each sensor 2. Calibration value
Calibration data (Blade horizontal)	1. strain flapwise (blade angle 90 deg) 2. Strain edge wise (blade angle 0 deg)
Temperature compensation	Measurements should be temperature compensated.
Remote access	1. start / stop / reset 2. uploading programmes, parameters, detection levels. 3. Downloading programmes, parameters, measurement data.
System start-up	Automatic start up after power-up

6.2.2 Turbine module

A separate unit in the nacelle or tower base is necessary because of the limited range of the wireless bridge. Besides this data communication problem, there are two other reasons for the choice of a separate Turbine Module:

- In the rotor module, a large storage capacity cannot be realised. The Turbine Module can also accommodate hard disks for data storage.
- For diagnostics, the system also needs turbine parameters, such as power, rotor speed, wind speed. This information is normally available in the nacelle and not in the rotor.

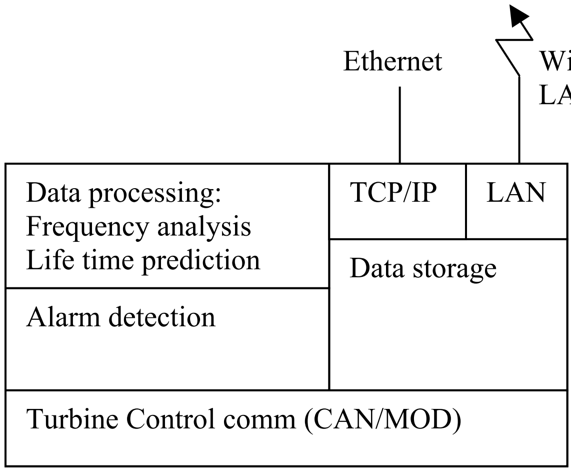

Figure 6.4: Turbine Module

The functions of the "Turbine Module" are:

1. Intermediate storage of time series (input via wireless LAN) and wind turbine parameters (1 week).
2. Copy of blade signature data
3. Collection of wind turbine parameters (via CAN/MOD-bus) (wind speed, rotor speed, power, yaw angle)
4. Storage of reference data (Material data, reference spectra)
5. Frequency analysis (FFT's)
6. Life time prediction analysis (Rain flow counting, load analysis)
7. Diagnostics based on 5 and 6, detection of events and preparation of log files (5 minutes before and 5 minutes after event)
8. Communication with external work stations via internet
9. Remote access to Rotor module (start / stop / reset / program uploading / a.s.o.)

The Turbine Module receives the measured data as time series, representing the strain. Besides the strain, also turbine parameters are available via a standard bus-system or an analogue interface. The choice of the bus depends on the wind turbine.

For the diagnostics, the Turbine Module also has real time access to:

- Initial blade information
- Information of other turbines of the same type
- IEC-load spectra
- Material data

The blade information can be downloaded from the rotor module. The other information should be updated by external workstations.

The Turbine Module shall perform its tasks fully automatically and send the results to a client system. This depends on the park configuration and operation. Besides that, downloading of measurement data shall be possible on request. Also for back-up of information, there should be a provision on park level or owner level.

Access of the Turbine Module could be realised at different levels. E.g. the following three levels can be defined:

Level 1: Consultation of diagnostic results;
Level 2: Access and downloading of all information, including history and time series;
Level 3: Remote control of the system, i.e. all functions including uploading of algorithms, modification of data, start, stop and reset.

The requirements are summarised in Table 3.

Table 3: Requirements for Turbine Module

Item	**Requirements**
System	System shall be sufficiently robust for operation in the Nacelle
Measurement frequency of wind turbine data	20 Hz
Information to be stored	1. Time series of measurement data (temperature compensated strain) 2. Time series of wind turbine data 3. Reference data such as IEC-spectra, material properties 4. Blade signature data (copy of Rotor Module) 5. Analysis results 6. Warnings and alarms 7. Event based log files
Storage capacity	1. Time series: 1 week 2. Other data: 1 year
Data transfer / communication	1. Wireless LAN with Rotor Module 2. Industrial bus (MOD / CAN) for wind turbine data 3. TCP/IP for external communication
Alarm messages to external system (e-mail)	1. Instantaneous alarm messages (copy of SMS messages) 2. Diagnostic information in case of exceeding warning levels 3. System life messages each 24 hours
Calibration data (Blade horizontal)	1. History of calibration data 2. Copy of calibration data
Remote access	1. start / stop / reset 2. uploading programmes, parameters, detection levels. 3. Downloading programmes, parameters, measurement data 4. Access to Rotor Module
System start-up	Automatic start up after power-up
Back-up of data	1. Sent data for back-up of analysis results 2. Sent event based log files
Data reduction	Preparation of event based log-files
Time synchronisation	Time server

6.2.3 External communication

The Rotor Module and Turbine Model together form the complete blade monitoring system. They perform the monitoring task automatically and sent messages and data to external systems on a regular basis (system life messages) or event basis (diagnosis and level detection).

Remote access is necessary for system modifications, data analysis, etc. For these functions, external systems should be available to perform these tasks. However, the configuration depends on the available systems on park-level and owner level. It is also possible that access is required for third parties, such as consultants or blade manufacturers. Because also other condition monitoring systems, focussed on gearbox, generator and bearing, will be implemented to an increasing extend, integration of these functions can be expected. For this reason, the design of the system should be focussed on the required functions and access levels rather than on the available hardware and systems

A more detailed requirement specification can be found in Ref. 7.

6.3 Software development for on-line analysis

For the analysis of the strain and temperature measurements, a dedicated module should be developed. This module includes the functions as defined in Ref. 1.

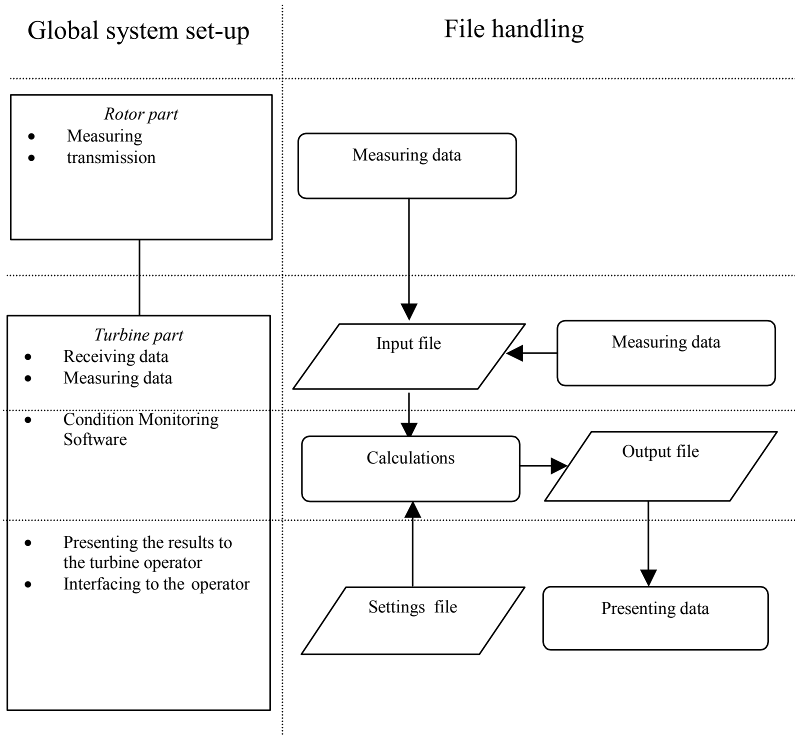

Figure 6.5: Software set-up

The dedicated analysis tool should be suitable for implementation in the environment of the condition monitoring system. For this reason, the interfaces should be defined before starting the software development.

The calculations are executed in a separate module, which receives the measurement data from an input file. This input file includes the 10 minute time series as well as the calibration data. The definition of the signals is defined in a separate settings file. This set-up makes it possible to develop a flexible calculation module, which performs the analysis for the signals as defined in the settings file based on the measurements available from the input file. The results are stored in an output file, which also includes accumulated data.

For the presentation of the results for the user, separate software should be developed, which presents the calculation results in the appropriate form.

6.4 Conclusions

As a result of the project, a baseline for the condition monitoring system has been defined. This system set-up makes it possible to operate the system remotely. System access is possible for retrieval of diagnostic data as well as for system configuration and maintenance. It is also suitable for installation in existing turbines.

7. Commercial realisation of project results

The results of the project form the basis of an experimental phase. The hardware as well the software is defined in sufficient detail to start the development of an experimental system. This can be installed on one or more turbines on the test field of ECN.

The supplier of the system (FOS) is interested to develop such a monitoring system, based on the specs as reported in chapter. ECN will supply the analysis software. FOS is also interested in the development and support of these systems for wind turbine application. ECN and FOS are both willing to work together during the realisation and to make an agreement on that. ECN will deliver and maintain the analysis software, which can be implemented by FOS in the system. FOS will pay a license fee for that software. A market analyses learned that from 2008 on, approximately 200 systems will be installed per year.

The development of the system (hardware and software) will be done during the experimental phase. Apart from the development, also optimisation of the analysis software and the man-machine interface is foreseen. The experimental phase will cover a period of about 3 years.

Apart from the interest of FOS to enter this market, also other parties have been contacted. This opens the possibility to push the further development of the blade condition monitoring application based on fiber optic measurements with Bragg sensors or alternatives.

From the side of the operators, interest also exists for this technology. For a following application of Blade Condition monitoring systems, a project has been defined together with a Spanish partner.

8. Realisation of indirect energy profit

The project results contribute to the indirect energy profits in a wide extend on the longer term. The results of this project are limited to the definition of an experimental system and the realisation is expected not earlier than in about 3 years.
After realisation of the product, the following contributions have been identified:

1. Innovation:
   The project contributes in the realisation of a reliable load measurement system, with a life time in line with the wind turbine. Conventional strain gauges are not a serious alternative for this because of their low lifetime and sensitivity for failures. The new system opens the possibility for using load measurements in the blades in operation and control in wind turbines. The current performance is however not yet sufficient to realise this in a short term.
2. Bottlenecks:
   The development of the technology is hindered at this moment by:
   - ⇒ The price of the read out unit has decreased significantly during the project. Although competitors offer systems based on other read out techniques for a much lower price already than the current used technology, these systems is not considered as sufficiently robust to choose for that at this moment.
   - ⇒ The temperature sensitivity of the Bragg sensors is a serious problem. A reliable and competitive solution for temperature compensation is not yet found. There are some alternatives identified during the trade off study. These solutions are rather complicated and have a strong increasing effect on the price of the sensors and/or read out unit.
   - ⇒ The developments are also hindered by the absence of a strong industrial party which can effort the development and market entry costs for such kind of systems. Developers of fibre optic instrumentation are normally small companies, which have to choose for more profitable work to generate short-term cash flow.
3. Effect on COE:
   Load monitoring will contribute to lowering the COE generated by wind turbines because of the following effects:
   - ⇒ The load measurements can be used for integration in the controller of the turbine. A reduction of the loads can be expected, which will have a lowering effect on the investment costs. This should be considered as a spin-off effect on the longer term.
   - ⇒ Condition monitoring of the wind turbine blades will lower the maintenance costs of the turbine. The increase of intervals for visual inspection reduces the costs and early fault detection will lower the resulting damage.
   - ⇒ The lifetime of the blades can be increased when the encountered loads during operation are lower than the design loads.
   - ⇒ Insurance costs will be lowered if the risk of damage of the blades can be reduced by condition monitoring.

The total operational costs are expected to decrease with approximately 5 to 10%. At present, the annual O&M costs are in the order of 30 €/kW for an onshore location or 3 M€/year for a 100 MW wind farm. So a reduction of the O&M costs of 150 to 300 k€/year is expected for an onshore wind farm.

9. References

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