Fraunhofer IWES

FRAUNHOFER INSTITUTE FOR WIND ENERGY SYSTEMS IWES

TECHNICAL RELIABILITY

Cost savings for the wind energy industry

IMPRINT

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RELIABILITY IS KEY

Operation and maintenance account for around 20 to 30 percent of the life cycle costs of a wind turbine. A large part of this is down to servicing and repair work necessitated by failure. Added to this is the loss of production resulting from turbine downtime – with offshore turbines, in particular, repair is logistically complicated and often cannot be realized in the short term.

The wind power industry operates under extremely strong competitive pressure nowadays - many key markets have been or are being converted to a competitive tendering procedure for pricing wind-generated electricity. The whole value chain is thus subject to additional pressure on costs. The reliability of wind turbines and their components, particularly those with high failure rates, thus plays a key role in reducing the levelized costs of energy.

In addition to developing an appropriate maintenance strategy, it is imperative that the reliability of the components is increased as they work towards higher reliability and reduced operations and maintenance cost. To achieve this, a comprehensive understanding of causes and mechanisms of failure is a fundamental requirement. However, these causes and mechanisms have often not been sufficiently clarified as yet.

Research undertaken at Fraunhofer IWES based on more than 2,700 turbines of various manufacturers shows that power converters fail on average once every two years. The economic loss is immense: On an annual basis, the extrapolated repair costs and production losses for the 50 GW of wind turbines currently installed in Germany amount to roughly € 200 million; approximately, 200 gigawatt-hours of energy are lost. That amount would suffice for an annual energy supply of 55,000 households.

Fraunhofer IWES offers a wide range of services to increase the reliability of wind turbines and their components and promote the further expansion of wind power by making the turbines even more economical to operate: With statistical analysis of field data, root-cause analysis, large component testing, field measurements, and our research into new methods for testing, we support turbine operators, project developers, manufacturers, and suppliers as they work towards more reliable turbines and reduced costs of operation and maintenance.

FIELD-DATA BASED ROOT-CAUSE ANALYSIS

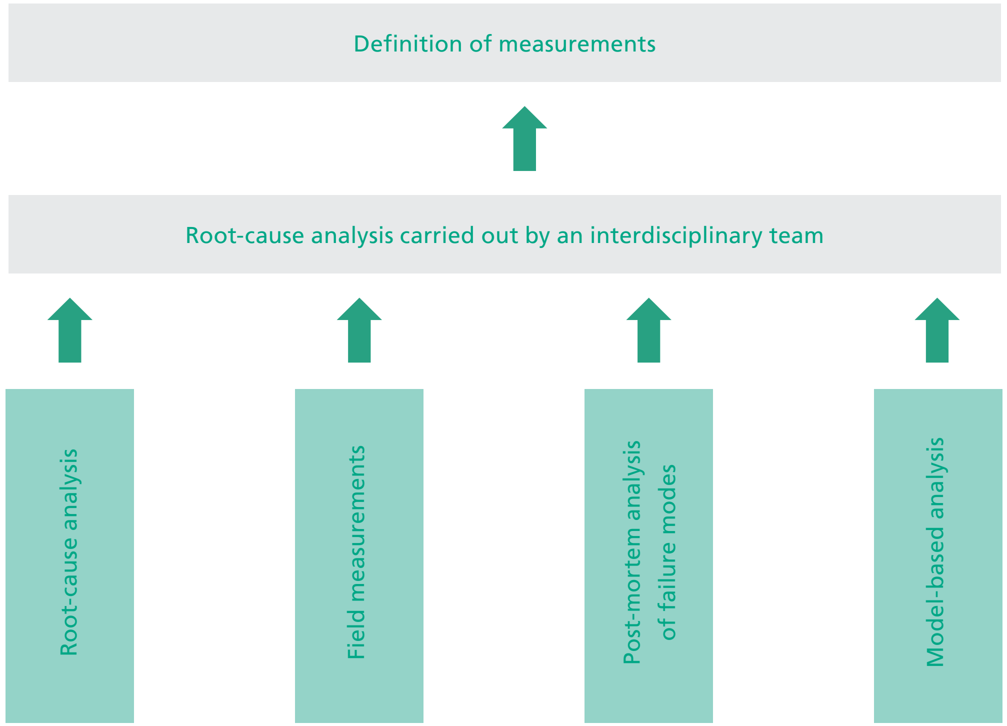
To increase the reliability of a turbine component, a fundamental step is to identify the factors which trigger the defect, and to understand the failure mechanisms. When both these things are known, effective countermeasures can be developed in order to effectively reduce the operations and maintenance cost of the turbine. Field data from wind farms in operation and observed damage scenarios provide valuable information which is condensed to a systematic evaluation and can be incorporated into the development of specific preventative measures.

Wide-ranging analysis of failure causes

At Fraunhofer IWES, the explorative analysis of failure data and operational data with the aid of statistical methods has proven to be a successful key element for identifying failure causes.

While specific field measurements are being taken, environmental and operating conditions are determined in a parallel process. For the most part, comparative measurements on turbines where downtimes are conspicuously frequent or particularly rare provide important indicators for the root-cause analysis. Post-mortem analyses of defective components using analytical methods in the laboratory likewise make a crucial contribution to clarifying the causes of failure. In some cases, it is useful to carry out a model-based analysis to supplement the above, in order to consider effects arising from the highly dynamic interaction of mechanical, electrical, and structural components under the impact of wind, grid, and turbine control in more detail.

The results of these investigations are collated and evaluated by an interdisciplinary team. When the main causes for the component failure have been identified, they are used as the basis for deriving measures to increase the reliability together with the client. In collaborations with operators and maintenance service providers, the focus is typically on measures for existing turbines (e.g., retrofit solutions, changes to the maintenance practice); when the cooperation partner is a component or turbine manufacturer, the emphasis is on adaptations to new turbines (e.g., changes to the design and operational management).



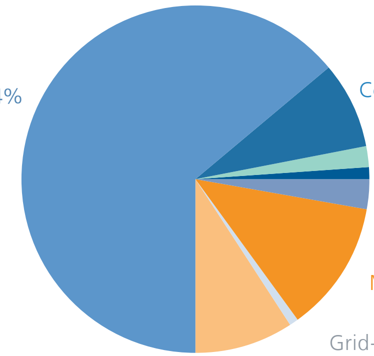
Applied method for root-cause analysis, based on four pilars

Power converter: a weak point

Electronic power converters in wind turbines top the failure statistics and incur huge repair costs and generation losses: In Germany, this leads to an economic loss of roughly € 200 million per annum. This problem has been known for many years, but the causes of the failures have still not been sufficiently clarified.

As part of a collaborative project within the Fraunhofer Innovation Cluster on Power Electronics for Renewable Energy Supply, numerous companies have provided converter-specific failure data from more than 2,700 wind turbines in 23 countries which made a comprehensive evaluation possible. These data have been used to investigate various issues, including:

- Which components within the overall converter system incur the highest annual repair costs and generation losses due to their failure
- Whether manufacturer-specific or site-specific differences in the failure rates show up
- Which design factors have a statistically significant impact on component reliability
- Whether early, random, or degradation-induced late failures dominate the failure behavior



Repair cost distribution of wind turbines with DFIG and partial converter

- Whether temporal or local patterns can be discerned in the failure behavior and whether they correlate with operating or environmental conditions
- To what extent is there a connection between the operating history of turbines and the incidence of failures

Among other things, the evaluations showed that

- The overall converter system shows on average failure rates as high as 0.5 failures per turbine and year
- The phase module components, comprising the power modules incl. driver boards, as well as the DC-link capacitors and busbars, are the main cost drivers
- The reliability of these key converter components is not higher in contemporary wind turbines than it has been in turbines commissioned 10-15 years earlier
- Higher failure rates were clearly evident in various regions at times of the year with high humidity

A key conclusion of the investigations was: The failures observed in the field were caused by failure mechanisms which were different to those that are generally assumed – they were not caused by fatigue effects known from other power electronics applications. Rather, environmental effects, particularly humidity and condensation, played a crucial role here.

The methodology used to analyze the causes of failure is equally suitable for electrical and mechanical system components and is already tried-and-tested for both.

Damaged converter module

Our services:

- *Explorative analysis of failure data and operational data by means of statistical methods*
- *Field measurements to characterize environmental and operating conditions*
- *Post-mortem analysis of defective components with analytical laboratory methods*
- *Model-based analysis which takes the whole turbine into account*
- *Recommendation of measures to improve reliability and reduce the consequential costs of failure*

RELIABILITY OF BLADE BEARINGS

Rolling bearings have a very long service life in most industrial applications. Since the first attempts were made at the beginning of the 20th century to calculate this life, the methods have been refined further and further and are considered to be very accurate for standard applications. The conditions under which rolling bearings of wind turbines are used differ considerably from this, however: high stochastic loads, continually changing rotational speeds, and interfaces with complex stiffness profiles increase the probability of failure and lead to a situation where failures are not unusual long before the end of the calculated fatigue lifetime.

Phenomena which cannot be calculated, such as "white etching cracks" in the bearings of the gear stages and in the generator often lead to problems, in wind turbines especially. The certification authority currently does not require a service life calculation for oscillating rolling bearings as are used for the rotor blade bearing; methods used to date cannot be applied reliably. Standstill marks (false brinelling), ring fractures, contact corrosion, core failure, and wear and tear, are therefore typical examples of occuring damage mechanisms.

Large-bearing test bench for accelerated, realistic tests

In 2013, Fraunhofer IWES began conducting research on large rolling bearings of wind turbines to increase their reliability and pioneer new calculation methods and designs. The "Large Bearing Laboratory" (LBL) at the institute's newly established site in Hamburg bundles these activities together and expands them to include experimental test facilities for bearings of next-generation wind turbines. Experienced bearing experts at the institute have developed their own methods for creating long-term test programs for this purpose. The programs use

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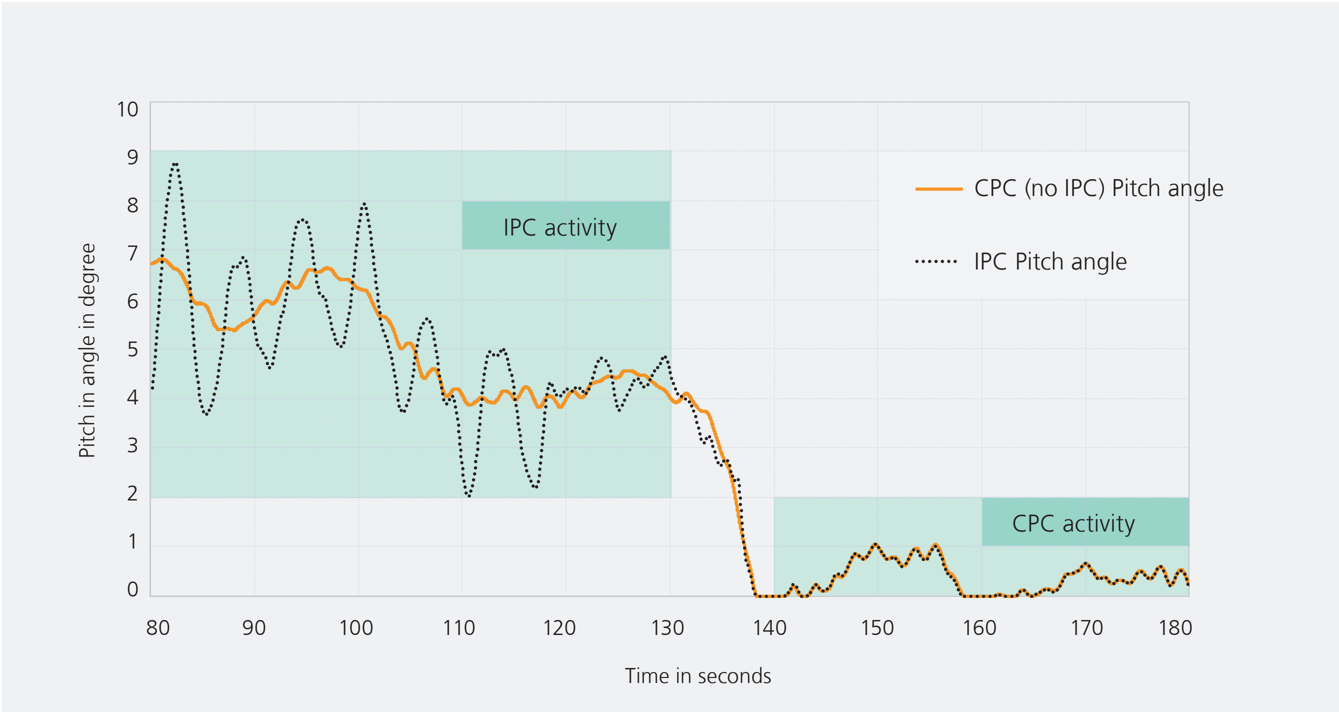
Technical parameters BEAT6.1 test bench

- *Test bearings with diameters of 3 - 6.5 m*
- *Introduce static loads up to 50 MNm*
- *Dynamic bending moments of +/- 25 MNm at 0.7 Hz*
- *Highly integrated control and data acquisition system with very high processing speeds - autonomous operation possible for months*
- *Measurement system with 500 high-resolution measurement channels and redundant data bases*
- *Accelerated testing: simulation of loads from 20 years of operation in 6 months*
- *Emulation of interface parts and their properties*

Adaption of the pitch angle – with and without individual pitch control



complex data analysis to generate the time series necessary for long-term tests which can imitate the different damage mechanisms (contact fatigue, wear, structural fatigue).

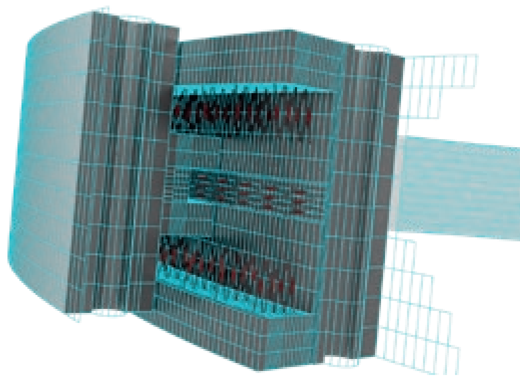
At the large rolling bearing test bench, complex interfaces such as rotor blade and rotor hub close to the rotor blade bearings are emulated by adapter components which reproduce the stiffness behavior of the components so as to be accurate in every detail and thus allow the test specimens to be loaded realistically.

The results of the fatigue and wear tests can be used to improve the dimensioning methods and reduce the risk of failure. On the test bench, which will go into operation at the end of 2018, a bearing can be certified long before it is first used in a wind turbine. It furthermore serves the industry's interest in shortening test times so that new products can achieve proven commercial viability faster. As part of the current collaborative project known as HAPT (Highly Accelerated Pitch Bearing Test), six bearings with a nominal diameter of five meters will initially be analyzed in functional and long-term tests on the bearing test bench.

Complete life cycle of a large rolling bearing

The simultaneous simulation of the bearings supports the testing work and comprises individual contact simulations as well as global bearing models for FE and MBS analyses. The interfaces (bearing housing, rotor blade, transmission housing, rotor hub, nacelle) are likewise reproduced in FE models. All simulation models are compared and validated with measured data. Individual controllers and aeroelastic turbine models furthermore facilitate the investigation of changes in the operational management, for example with individual pitch control and the associated reciprocal effects on the bearings. The analysis of simulation and measurement data facilitates the estimation of dominating damage mechanisms and the detailed calculation of fatigue life. It is not only the bearing as a whole which is calculated here, but individual raceway sections, so as to be able to provide precise information. From concept development, simulation, design, and testing through to evaluation, the range of services offered by IWES spans the complete life cycle of a large roller bearing.

In addition to the large bearing test bench BEAT6.1, Fraunhofer IWES operates further test infrastructure for rotor blade bearings and main bearings, as well as smaller test benches to carry out basic engineering tests and to test large batches.



Visualization via global FE model of a three raw rolling bearing

RELIABILITY CONTROL

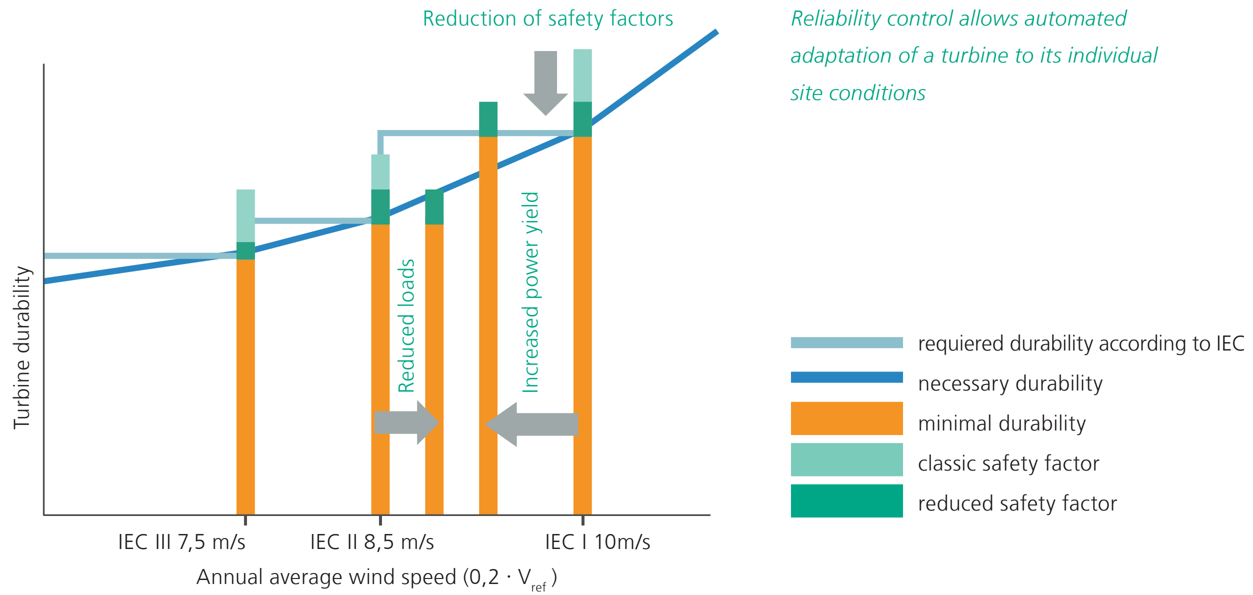
Wind power is already one of the most economic ways of generating electricity from regenerative sources. Yet in order to successfully compete with photovoltaics and other technologies, the cost must still be reduced further. Fraunhofer IWES develops methods that enable an individual wind turbine to autonomously adjust itself to the environmental conditions at its site and to the damage it has already accumulated. These methods lead to better utilization of material, the use of less material, more efficient maintenance, and increased power output.

Wind conditions at a site are the main drivers for the design and the expected lifetime of a turbine. During turbine development, only insufficient knowledge about wind conditions is available, but has to be taken into account nevertheless. This is done by classifying them into one of the three wind turbine classes in accordance with IEC61400-1. Within one class, identical turbines are operated with minimal adaptations to very different sites. The turbine design is based on nominal site conditions. Since the turbines must always be able to withstand the most adverse conditions of a wind turbine class, most turbines are overdimensioned.

Longer operation period or maximum power production in 20 years?

Wind turbine life-time is limited by fatigue loads. Usually, turbines are designed for a minimum service life of 20 years. In most cases, some usable service life remains after the end of the planned time of operation, which can sometimes be exploited by extending the service life period. However, structural integrity must be assessed for each individual turbine to show that it can continue to operate safely.

However, there are cases in which it is not possible or desirable to have a lifetime extension. Reasons can be due to e.g. economic, legal or technical constraints. A different operating strategy comes into play in these cases: maximum energy yield during the pre-specified useful life of the turbines is desired. Increased power of a wind turbine, for example by employing highly dynamic control or by accepting short-term overloading, can usually only be achieved at the expense of increased degradation. At the same time, this must not lead to unexpected early failures so as not to diminish system reliability. Ideally, the power of the turbine is increased just enough to distribute the damage over its complete useful lifetime. This way, the physically limited service life is exploited completely and at the same time, maximum energy production is achieved.



Reliability control allows automated adaptation of a turbine to its individual site conditions

Automated adaptation to site and damage

Fraunhofer IWES is developing higher-level control strategies for wind turbines for this purpose. They detect the current degradation state of the turbine and feed this information back to the operational control. Closed-loop reliability control is comprised of the detection of the current degradation state, determination of the required turbine configuration and an adjustment of the operational controllers. Reliability control thus autonomously adjusts the behavior of a standard turbine to its individual site. The site conditions are taken into account via the real operating history, the loads and the accumulated damage. If the turbine is located at a site where the loads are lower than assumed during the design phase, this is converted into a permanent increase in turbine performance. The inverse of this is also possible: a turbine designed for a low-load site can be operated at a site with slightly increased loads. In this case, the performance is reduced automatically in order to achieve the desired useful life.

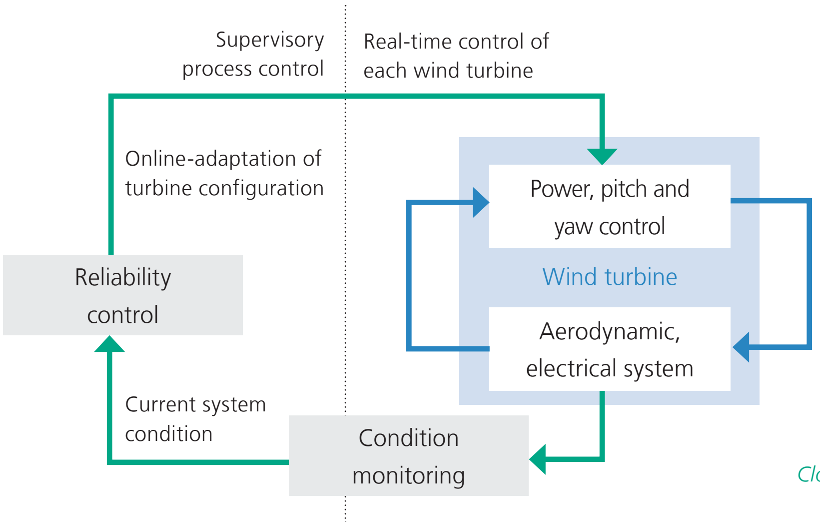
Automated reliability control contributes to a reduction of the cost of energy in several ways:

- Lower investment costs through better utilization of material and use of less material.
- Increase of turbine performance such that the desired useful lifetime is achieved with a minimal safety margin. This reduces the variance of the time-to-failure, safety factors can be reduced, and the turbine can be designed less robust.
- Better maintenance planning and more efficient execution of maintenance work reduce operating costs. Critical components or the turbine as a whole are systematically subjected to lower loads to defer imminent faults to coincede with other planned maintenance actions.
- All measures increase the maximum power output, contributing to a further reduction in the cost of energy

In addition to these operational benefits, a direct increase in profit is possible: the balance between damage induced in the turbine and performance can be set to prioritize performance. This increases power output and allows to use temporarily increased feed-in tariffs fully to increase profit.

Our services:

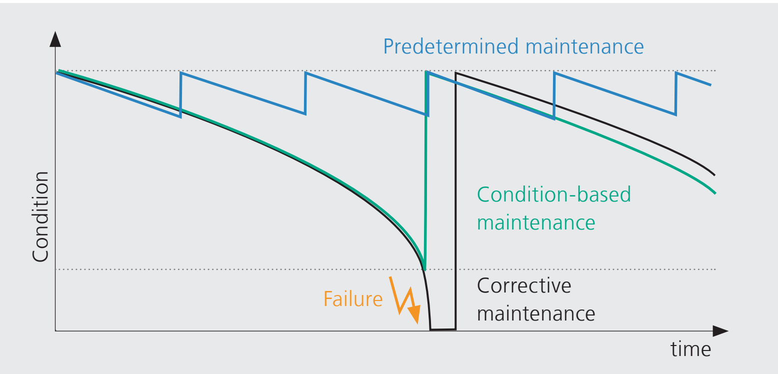
- *Supervisory control strategies that fully utilize a turbine's service-life*
- *Condition monitoring data tied directly into the operational control*
- *Autonomous adjustment of a turbine to its site and its accumulated damage*



Closed-loop control of reliability

EARLY FAULT DETECTION WITH CONDITION MONITORING SYSTEMS

The large majority of equipment failures is preceded by certain indications of a developing fault. If these are detected early and preventative measures are initiated, costly serious damage and potential secondary damage can often be avoided. Besides lower repair costs, continuous condition monitoring offers the additional advantage of improving the maintenance planning. This leads to shorter turbine downtimes and reduces the lost earnings in electricity generation. In individual cases, such as the detection of imbalances or misalignments in the drive train, it is even possible to completely avoid the evolution of a damage with the aid of condition monitoring.



Condition-based maintenance minimizes damages as well as yield losses, and facilitates the planning of repair works

Blade bearing testing:
Monitoring of bearings with strain gauges, measurement of vibration and lubrication film thickness

Nacelle test stand:
Condition monitoring by means of vibration and temperature sensors, strain gauges and thermography

Full-blade testing:
Digital image correlation system makes deformations visible simultaneously on the pressure and suction side. Moreover: thermography, ultrasonic sound, strain gauges and acoustic emission sensors

Support structures:
SHM systems for monitoring large-scale models, e.g. sensors for acceleration, distance, inclination and strain

Main shaft test bench:
Condition monitoring via temperature sensors, strain gauges, laser span sensors, oil particle counting and structure-born sound measurement

Track record: Fraunhofer IWES has been applying CMS/SHM sensors and systems in its test benches over various years

Reliable CMS/SHM ensures economic turbine operation

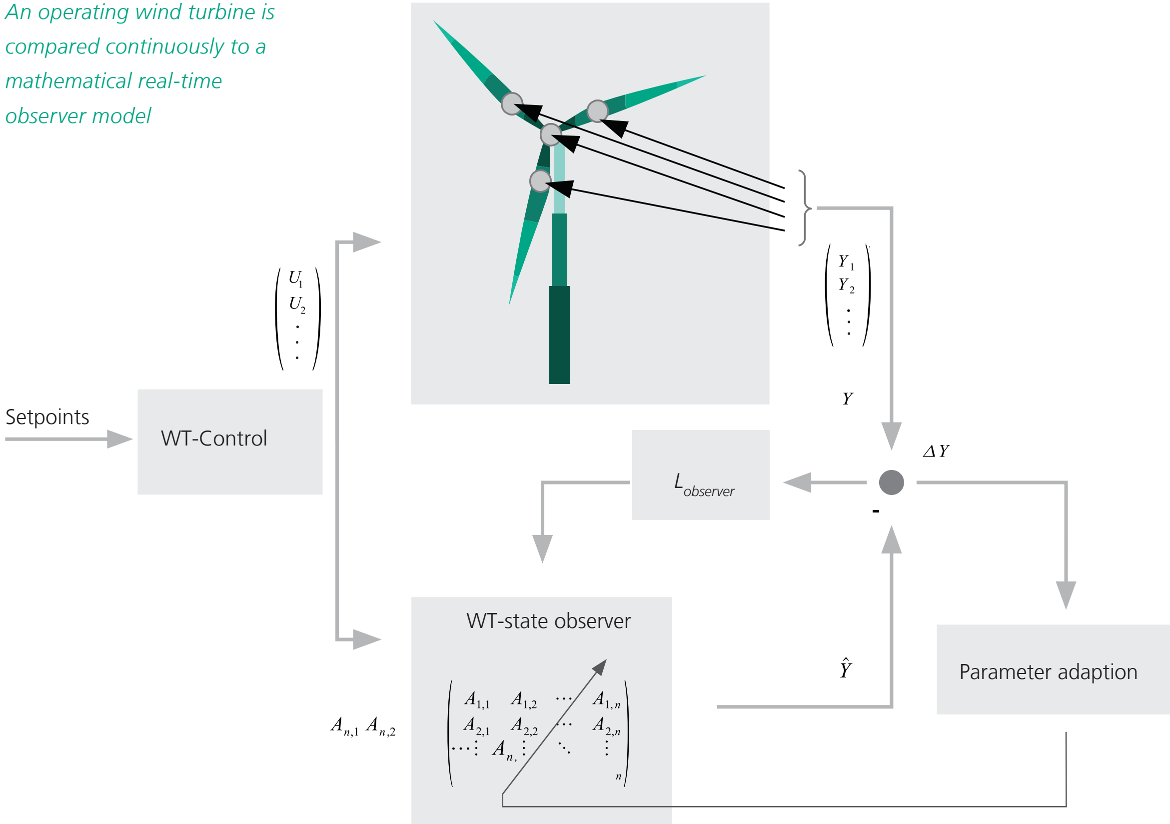
Condition monitoring systems (CMS), which are also called structural health monitoring systems (SHM) in the case of structural components, thus play a key role in the technical availability of wind turbines: they allow condition-based maintenance which prevents failures while at the same time the service life of components is exploited to the full. However, the users of today's monitoring systems and corresponding sensor systems complain about a sometimes insufficient reliability and fault-detection performance. Complex regular inspections of rotor blades and offshore support structures, for example, thus continue to be indispensable.

In addition, for many components afflicted with high repair costs, systems for a reliable condition monitoring are not available yet. A condition-based maintenance of these components is therefore currently not possible.

Evaluation and selection of monitoring systems

Fraunhofer IWES supports project developers and operators to select CMS or SHM systems which make sense from economic and technical points of view. A systematic assessment of the detection performance (with respect to fault detection and false alarm rates and how early fault detection occurs) can be given on the basis of field data, for example, or a probabilistic cost-benefit analysis of monitoring systems can be carried out.

An operating wind turbine is compared continuously to a mathematical real-time observer model



Our services

- *Testing of sensors and complete CMS/SHM systems under controlled, reproducible conditions on the component test benches*
- *Manufacturer-independent advice on monitoring systems and methods for various components and the complete turbine*
- *Development of model-based CMS and SHM methods: continuous comparison of measured and simulated*
- *Turbine behavior to detect anomalies*
- *Evaluation methods to use high-resolution operational data for early fault detection*
- *Remaining life analysis on the basis of CMS data*
- *Assistance with selection of CMS/SHM systems*

New approaches to innovative solutions

Through operating its large test benches, Fraunhofer IWES has used a broad variety of CMS/SHM and sensor systems over many years for test monitoring and early fault detection. IWES scientists have used their operational experience to develop and refine innovative monitoring methods and systems. In addition, they are working on developing suitable methods for low-cost structural monitoring of whole towers, rotor blades, bolted connections between tower segments and on rotor-blade flanges, for lubricant-film monitoring in large bearings, and early fault detection in power converters.

A novel, very promising approach is being pursued with a model-based, sensor-assisted condition monitoring system. It is based on a continuous comparison between the operating wind turbine and a real-time-capable, mathematical observer model, which replicates the turbine´s behavior and is part of the turbine´s controler.

Use of operational data for early fault detection

Improved condition monitoring expanded to include additional turbine components does not necessarily require additional sensor systems. Today's standard instrumentation acquires operational data which can likewise be used for early fault detection. The low information content of data averaged over 10-minute intervals greatly limited the possibilities to do this in the past. Experts at Fraunhofer IWES see considerable potential in the use of operational data which is nowadays available with high temporal resolution. In order to exploit this potential, suitable evaluation methods need to be generated and tested - an important topic for applied research. Fraunhofer IWES offers joint method development not only for fault detection and diagnosis, but also for CMS-data based remaining life prediction.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ACCREDITED FIELD MEASUREMENTS

Fraunhofer IWES carries out accredited load measurements on wind turbines in accordance with IEC 61400-13 in the field, on turbines of third parties, as well as on a 8-MW research turbine in Bremerhaven, where it is possible to test sensor systems on behalf of clients. As part of the load measurement, damage-equivalent cumulative loads (standardized damage) are calculated, making it possible to quantify the vibrational damage suffered previously. As part of a short measurement campaign and the evaluation of historical meteorological data, information about the remaining lifetime of the wind turbine will be available in the future.

The institute has built up sound meteorological know-how in the course of numerous campaigns and research projects so that it can systematically evaluate and interpret measured data. Operational data are condensed into events to ensure early fault detection, or to find the cause after damage has occurred, and develop effective prevention concepts. The research turbine is measured very intensively and the operational data are stored pretty frequently so that the multiple measurement data thereby obtained can be used to optimize fault cause analyses and early fault detection methodologies.

New sensors are often installed, new measuring points equipped, and systems tested. Basically, campaigns can be started as defined by the customer to detect specific factors, including loading conditions, vibrations, temperatures, tilts, etc.

With the data of an 8-MW research turbine at its disposal, Fraunhofer IWES compares operational data from the field with the results from test benches, and improves its testing methods and design further. If new turbine designs are systematically validated by the experimental examination of load assumptions and accelerated tests on the large test benches, the risk when launching next-generation wind turbine systems is significantly minimized.

Field measurements provide input data to monitor and improve the performance of the field data-based analysis of failure causes, investigation of the reliability of bearings, reliability control, and the use of condition monitoring systems. The experience from the field is thus reflected into research activities.

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