Fraunhofer
IWES

FRAUNHOFER INSTITUTE FOR WIND ENERGY AND ENERGY SYSTEM TECHNOLOGY IWES

CONDITION MONITORING OF WIND TURBINES: STATE OF THE ART, USER EXPERIENCE AND RECOMMENDATIONS

Project Report

January 2015

CONDITION MONITORING OF WIND TURBINES: STATE OF THE ART, USER EXPERIENCE AND RECOMMENDATIONS

Authors: Diego Coronado, Katharina Fischer

Fraunhofer Institute for Wind Energy and Energy System Technology IWES Northwest,
Am Seedeich 45, 27572 Bremerhaven, Germany

The project was funded by the VGB Research Foundation (VGB-FORSCHUNGSSTIFTUNG).

Project number: VGB-Nr.383, ∑-Nr.106070

			Issue 0	Issue 1
Authors:	Diego Coronado	Bremerhaven	28 January 2015	10 February 2015
	Katharina Fischer	Hannover	28 January 2015	13 February 2015
Approved:	Jan Wenske	Bremerhaven	29 January 2015	
	Christian Broer	Hannover		16 February 2015

Table of Contents

Abstract

Condition monitoring of technical assets aims at detecting changes in their condition that represent deviations from the normal operational behavior and indicate a developing fault. Condition-Monitoring Systems (CMS), in case of structural components also termed Structural-Health Monitoring (SHM) systems, are therefore facilitators for implementing a condition-based, preventive maintenance strategy, which allows an optimal utilization of component lifetime while avoiding unforeseen failures and costly advanced-stage damages.

Based on a comprehensive review of literature, standards and product information as well as on a survey among wind-turbine operators, this study presents the state of the art of CMS and SHM for online monitoring of wind turbines. For the sake of relevancy to practice, the focus is set on those turbine components and monitoring approaches, for which the monitoring technology is already available or is close to market introduction for field application: the drivetrain, the rotor blades and the support structures of onshore and offshore wind turbines. The different monitoring techniques are described, including the required instrumentation, the methods applied for data evaluation and diagnosis, the status of application as well as the utilization in the maintenance process. In addition to purpose designed CMS and SHM, the study reviews SCADA-data based condition monitoring and data-fusion approaches with respect to their potential, limitations and present application.
In view of the fact that making the right choice among the broad spectrum of available condition-monitoring options is a complex and challenging task for project developers and operators of wind turbines, a part of the study is dedicated to cost-benefit analyses of CMS and SHM systems. The factors influencing the cost-effectiveness of monitoring systems are explained, published analyses based on both deterministic and stochastic approaches are reviewed and the input data required for a sound cost-benefit analysis is summarized.

A survey carried out among six VGB-associated wind-turbine operators as a part of the project evaluates current practices and experiences with respect to CMS and SHM systems for wind turbines. The key challenges identified throughout the literature study, this survey and a workshop with the VGB working group "WindEnergy" are explained and recommendations for future work are derived from these. The report is complemented with a comprehensive overview of commercially available products for condition monitoring of wind turbines as well as with a compilation of standards and guidelines related to this topic.

The by far most developed and widely applied condition-monitoring technique for wind turbines is vibration-based monitoring of the drivetrain components. Gearbox-oil based CMS are gaining importance as complementary systems, but are still at an early stage with respect to sensor technology and validation as well as to their fault-detection capability. The same applies for rotor-blade SHM, for which an increasing number of products is commercially available, but the fault-detection performance of which is not considered sufficient to fully replace the regular inspection of rotor blades yet. SHM for monitoring the integrity of onshore and offshore support structures are mostly in the development phase. First systems are available on the market. Condition monitoring based on 10min-averaged SCADA data is found unsuitable as a standalone solution, but is considered a valuable complement for purpose-designed CMS to achieve better fault-detection performance. Among the topics recommended for future work, evaluating the fault-detection capabilities of the CMS and SHM systems experienced in the field as well as investigating the potential of high-resolution SCADA data for condition monitoring are considered to be particularly relevant to practice.

Kurzfassung

Die Zustandsüberwachung technischer Anlagen zielt darauf ab, Abweichungen vom normalen Betriebsverhalten zu detektieren, die auf die Entwicklung von Schäden hindeuten. Condition-Monitoring-Systeme (CMS), die im Fall von Strukturkomponenten auch als Structural-Health-Monitoring-Systeme (SHM) bezeichnet werden, ermöglichen so eine zustandsbasierte, präventive Instandhaltungsstrategie. Diese zeichnet sich durch eine optimale Nutzung der Komponentenlebensdauer sowie die Vermeidung von unvorhergesehenen Ausfällen und Folgeschäden an der Anlage aus.

Die vorliegende Studie basiert auf einer umfassenden Auswertung verfügbarer Fachliteratur, relevanter Normen und Produktinformationen sowie auf einer Befragung von Windenergieanlagen-Betreibern. Ihr Hauptgegenstand ist der Stand der Technik hinsichtlich der kontinuierlichen Zustandsüberwachung von Windenergieanlagen (WEA). Im Sinne größtmöglicher Praxisrelevanz liegt der Schwerpunkt auf solchen WEA-Komponenten, für deren Zustandsüberwachung Systeme bereits verfügbar sind oder zeitnah auf dem Markt zu erwarten sind: dem Triebstrang, den Rotorblättern sowie den Tragstrukturen für Onshore- bzw. Offshore-WEA. Die jeweiligen Monitoringmethoden werden zusammen mit der nötigen Instrumentierung, den wesentlichen Auswertungsverfahren und ihrer derzeitigen Bedeutung im Instandhaltungsprozess vorgestellt. Neben CMS- und SHM-Systemen werden auch Ansätze zur SCADA-Daten-basierten Zustandsüberwachung sowie zur Verschmelzung unterschiedlicher Monitoringverfahren behandelt.
Vor dem Hintergrund, dass eine unter wirtschaftlichen Gesichtspunkten sinnvolle Auswahl von CMS- bzw. SHM-Lösungen für Projektentwickler wie WEA-Betreiber eine Herausforderung darstellt, widmet sich ein Teil der Studie explizit der Kosten-Nutzen-Analyse von Zustandsüberwachungssystemen. Es werden die wesentlichen, das Kosten-Nutzen-Verhältnis bestimmenden Faktoren benannt, verschiedene bisherige Analysen dargestellt und die für eine fundierte wirtschaftliche Bewertung erforderliche Datengrundlage skizziert.

Über die im Rahmen dieses Projektes durchgeführte Befragung von sechs Betreiberunternehmen von WEA sind Einblicke in die Anwendungspraxis und die Erfahrungen mit der Nutzung von CMS- und SHM-Systemen in WEA gewonnen worden. Die hierbei, im Rahmen eines Workshops mit der VGB-Arbeitsgruppe „Wind Energy“ sowie in der Literaturstudie ermittelten zentralen Herausforderungen werden erläutert und auf dieser Grundlage Empfehlungen für die Ausrichtung zukünftiger Arbeiten formuliert.

Die mit Abstand am weitesten entwickelte und meistgenutzte CMS-Technologie ist die schwingungs- bzw. körperschallbasierte Zustandsüberwachung der Triebstrangkomponenten von WEA. Als ergänzende Systeme gewinnen derzeit CMS zum Getriebeöl-Monitoring an Bedeutung, die sich jedoch hinsichtlich der Sensortechnologie und des Fehlerdetektionsvermögens derzeit noch in einer frühen Entwicklungsphase befinden. Ähnliches gilt für die SHM-Überwachung von Rotorblättern, für die eine wachsende Zahl von Systemen am Markt erhältlich ist, deren Fehlerdetektionsvermögen jedoch derzeit zumeist noch nicht ausreicht, um auf eine regelmäßige Rotorblattinspektion ersetzen zu können. Die Zustandsüberwachung von WEA-Tragstrukturen befindet sich weitestgehend noch in der Entwicklung. Die Nutzung von 10min-SCADA-Daten eignet sich gemäß den Ergebnissen und Aussagen in der Literatur nicht als alleinige, jedoch als ergänzende Lösung zur Zustandsüberwachung. Im Hinblick auf zukünftige Arbeiten werden zum einen die quantitative Auswertung des Fehlerdetektionsvermögens heute in WEA eingesetzter CMS und SHM-Systeme sowie zum anderen eine Untersuchung der Nutzbarkeit zeitlich höher aufgelöster SCADA-Daten für die Zustandsüberwachung von WEA als besonders praxisrelevant erachtet.

Acknowledgments

The project «Condition Monitoring Systems (CMS) of Wind Power Plants: Status Quo, User Experience, Recommendations, Part I« was initiated and supervised by the VGB-European Working Group «Wind Energy«. The project was funded by VGB Research Foundation (VGB Forschungsstiftung), which is kindly acknowledged. In addition, the authors would like to thank the companies enercity, Fortum, Laborelec / GDFSuez, RWE, Steag and Vattenfall for their active participation in the survey among wind-turbine operators conducted within the project. Finally, thanks to Thomas Gellermann of Allianz Center for Technology, to Olivier le Fevere de ten Hove of Laborelec as well as to Alexandros Antoniou, Isabel Koprek and Claus Kupferschmidt, Fraunhofer IWES, for their contributions to this project.

1
Introduction

1.1
Maintenance strategies for wind power plants

The operational expenditure (OPEX) of wind turbines sums up to approx. 20-35% of their life-cycle cost (see e.g. [1] [2] [3]). To achieve a further reduction of the cost of wind energy, and with that an optimized return of investment from the generation assets, it is therefore essential to widen the focus from today's concentration on capital expenditure (CAPEX) to OPEX, covering the complete asset life-cycle. In order to reduce OPEX costs, the right choice of maintenance strategies for the wind-turbine components and their optimal implementation are important steps.

Figure 1 provides a general overview of the different types of maintenance strategies. In contrast to the conventional maintenance strategies of running to failure and subsequently performing repair (i.e. corrective maintenance) or doing preventive maintenance in a predetermined way, e.g. in fixed time intervals, condition-based maintenance (also known as predictive maintenance) is based on the information collected by means of condition monitoring.

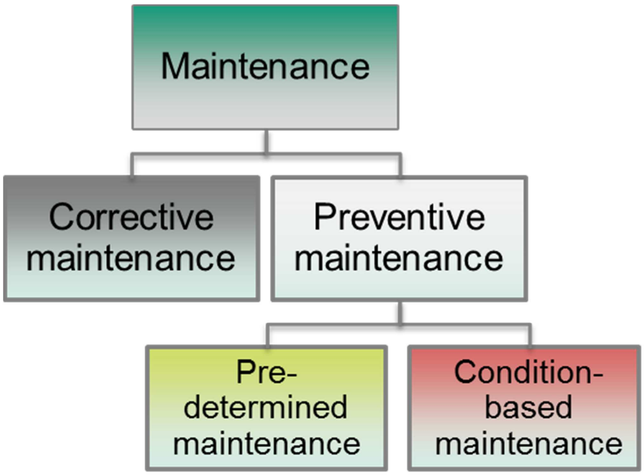


Figure 1: Maintenance strategies according to EN 13306 [4]

Condition monitoring of technical assets aims at detecting changes in their condition that represent deviations from the normal operational behavior and indicate a developing fault. Condition monitoring (CM) can be realized based on regular inspections, measurements or analyses, as e.g. in case of oil-sample laboratory analysis of wind-turbine gearbox oil, which is termed offline-CM. In contrast, online-CM is implemented using permanently installed monitoring equipment. In case of wind turbines, the monitoring of structural components as the support structure or rotor blades is often referred to as Structural Health Monitoring (SHM), while systems for monitoring other components, like e.g. the drivetrain, are usually called Condition Monitoring Systems (CMS). For the sake of simplicity, both types of monitoring systems will be named CMS in the following.

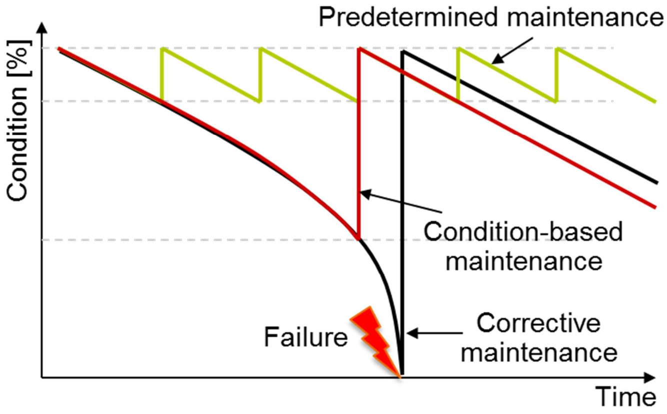


Figure 2: Influence of the maintenance strategy on asset condition

Figure 2 illustrates the influence of the different maintenance strategies on the condition of an asset:
While the corrective maintenance strategy has the advantage of fully utilizing the component lifetime, it is typically afflicted with long downtimes, the risk of secondary damage or even catastrophic failure and the fact that maintenance cannot be scheduled. Predetermined preventive maintenance has the advantages of being schedulable, of allowing an efficient spare-part management and of a higher availability than corrective maintenance. However, the waste of lifetime in cases when components could have lasted longer can make it a costly choice.

It is stated in [5] that in practice 99% of equipment failures are preceded by certain signs, conditions, or indications that a failure is going to occur [6]. This is the basis of condition-based maintenance (CBM): By means of early fault detection followed by preventive measures, severe damage of the monitored component and damage propagation to other components can be avoided; in some cases like e.g. the detection of imbalances and misalignment in a wind-turbine drivetrain, CMS may even allow to completely prevent the emergence of damage. This leads to lower repair costs, but also facilitates a better maintenance planning, which typically reduces the turbine downtime and the related revenue loss. In contrast to pre-determined preventive maintenance, CBM has the potential to optimally utilize the technical life of components (Figure 2). Unnecessary maintenance is avoided by carrying out maintenance only when there is evidence of abnormal behavior of a component. In this way, CBM is in many cases the most cost-effective maintenance strategy.

1.2
CMS and SHM: facilitators for condition-based maintenance

As proposed by [7] and illustrated in Figure 3, the utilization of CMS for CBM can be considered a three-step process:

(1) Data acquisition covers the collection and storage of raw data, e.g. the vibration amplitude measured on a certain component.
(2) Data processing is necessary to make use of the large amount of data collected in this way. It extracts features from the raw data, which are suitable indicators for the condition of the monitored component. A diagnostic step is required in order to relate the observations in the data to certain components and their faults. Therefore, this step covers the analysis and interpretation of the data, with the aim to detect if a fault is developing and where it is located.

(3) Prognosis of the remaining useful life (or residual-life prognosis) is an important step for the utilization of CMS data for maintenance planning and optimization. Having identified that a fault is developing and where it is located, this step aims at estimating how soon and how likely failure will occur.

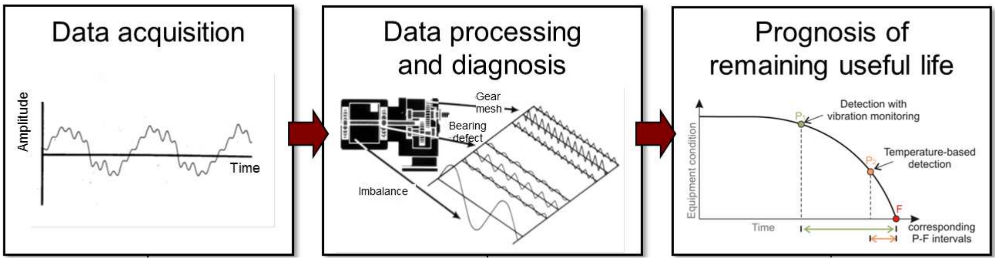


Figure 3: Three-step process of CMS-data utilization for condition-based maintenance (example case: vibration-based CMS)

Condition-monitoring systems are well established in many industrial sectors. However, wind turbines differ from the former areas of application: Their operation is characterized by strongly varying loads and rotational speeds as well as by a highly dynamic interaction of turbine components, all of which typically have an influence on the measured CMS data. This creates a challenge for the condition-monitoring process especially in view of the topology with separate devices for plant control and condition monitoring, which is still the clearly prevailing topology in wind turbines.
The vibration-monitoring of multi-MW turbines, in particular of direct-drive designs, is complicated by their low rotational speeds. Finally, an often rough operating environment can negatively affect the reliability of the monitoring system components such as the sensors. [8] [9] [10]

1.3 Report outline

In the following chapters, the state of the art in wind-turbine condition monitoring and structural health monitoring is presented. For the sake of relevancy to practice, the focus is set on online-CMS / SHM techniques for which the monitoring technology is already or is close to being available for field application.
This report includes an introduction to the monitoring principles, instrumentation and data analysis techniques used in wind-turbine CM / SHM. Additional chapters are dedicated to the utilization of SCADA data for condition monitoring, data fusion for enhanced monitoring performance and cost-benefit analysis of CMS and SHM for wind turbines.
The study is based on a comprehensive review of literature, standards and product information. In addition, it includes a survey among six VGB-associated operators of wind turbines, with a focus on their current practice and experiences in wind-turbine CMS and SHM. The survey results are presented in Chapter 5. Finally, Chapter 6 summarizes the identified key challenges and provides recommendation for future work.

2 State of the art of CMS and SHM for wind turbines

Today's commercially available CMS for wind turbines are predominantly vibration-based systems monitoring the rotating drivetrain components, namely the main bearing, the gearbox (bearings, shafts, gearwheels) and the generator bearings, often also tower oscillations. Vibration-based drivetrain CMS have become well established in wind turbines and have proven their usefulness in practice in many cases, so that they are recommended as standard equipment for multi-MW and offshore wind turbines [11]. The trend towards larger turbines, which implies a rising concentration of values, and towards installation at sites with limited accessibility as well as the need for cost-optimized maintenance suggest the extension of condition monitoring to additional wind-turbine components.

Among the systems available on the market are, in addition to the vibration-based drivetrain CMS, complementary particle-counting systems for the gearbox oil and first systems for structural-health monitoring of rotor blades and support structures. Condition monitoring for e.g. electrical and electronic components, such as the main frequency converter, or for pitch and yaw systems have not left the R&D stage yet and are therefore not subject of this study.

2.1 Drivetrain CMS

Since the basic requirements for wind-turbine condition monitoring from the perspective of the insurance company Allianz were formulated in 2003 [12], CMS for the drivetrain have been the main focus for the wind industry. Currently CMS can be certified by Germanischer Lloyd [13]. This certification is basically prepared for vibration-based CMS. Oil-based CMS (specifically particle counting) is considered a suitable addition to vibration-based CMS, but not as a standalone solution. In contrast, SCADA systems are stated not to be suitable for condition monitoring and therefore cannot be certified for this purpose. The GL guideline gives basic requirements for a CMS including sensor measurement ranges, amount of sensors, data collection and assessment methods.

In order to provide a better understanding of CMS and its assessment, this chapter will introduce the state of the art in vibration-based, oil-based and other CMS approaches, which are currently implemented in wind turbine drivetrains, or which are on their way to be viable. This section will also provide a description of the different monitoring techniques, the required instrumentation and the diagnosis methods applied.

2.1.1 Vibration-based CMS

Vibration-based CMS are the most established systems for monitoring the drivetrain of wind turbines. These CMS make use of the fact that most damages in rotating machinery lead to excessive vibration and that each mechanical unbalance or defect generates a unique vibration pattern. Figure 4 illustrates how the time waveform of a vibration signal is decomposed into its spectral components and how characteristic frequencies in the resulting spectrum can be related to machine components.

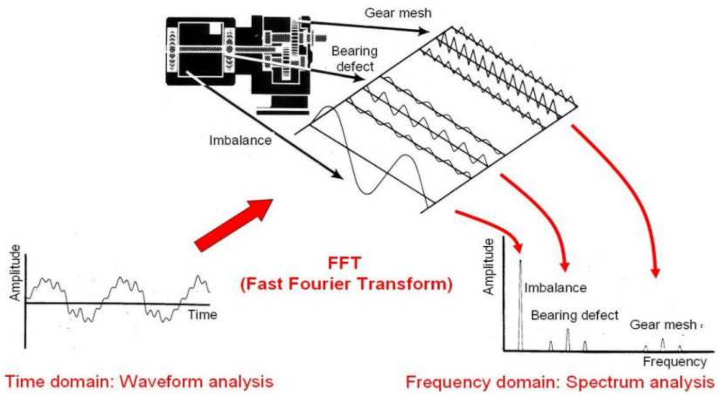


Figure 4: Vibration-based CM analysis approach (Figure from [9] **with parts from** [14]**)**

2.1.1.1 Instrumentation and data acquisition

The sensors applied for vibration-based condition monitoring include accelerometers, velocity transducers as well as displacement or distance transducers. Most of the sensors used for vibration-based CMS are accelerometers, which are installed in different positions in the drivetrain. Particularly for CMS on wind turbines, different types of accelerometers are used from the very low-frequency range to the high frequency range. Selecting a sensor requires taking into account not only the frequency range but also the dynamic range and the sensitivity of the sensor. This is important for example in the case of low frequencies where the acceleration amplitudes can be very small (depending on the frequency <1mg). In order to select the type of sensor for vibration-based monitoring, ISO 13373-1 [15] provides an overview of the commonly used types of transducers including their frequency range of application.

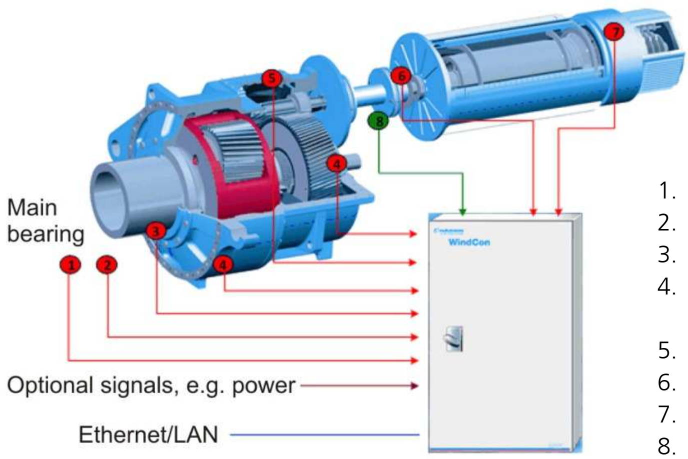
A standard nomenclature for sensor types used for wind-turbine CM (not limited to vibration sensors), their positions and orientation is found in ISO 61400-25-6 [16]. General requirements and recommendations regarding sensor positioning are given in the GL Certification Guideline from 2013 [13]. However, no specific positioning is recommended due the large variety in wind turbine designs. Table 1 summarizes the minimum requirements with respect to sensor number, position, orientation and frequency range for vibration-based condition monitoring of wind turbines as specified in [13].

The GL Certification Guideline also highlights the importance of ensuring that the vibrations are transmitted to the sensor as directly as possible. The sensors should be mounted in a way that allows reliably measuring all relevant frequencies. For wind turbines with gearboxes containing planetary stages, one sensor per stage should be installed in the area of the ring gear and at the level of the sun.

There is a considerable number of commercially available vibration-based CMS for wind turbine drivetrains (see Appendix 7.1). Most of them use a tachometer and accelerometers installed in the main bearing, gearbox housing and generator. Figure 5 illustrates the positioning of the sensors in the SKF WindCon system.

Component of the wind turbine	Necessary number of sensors per component	Direction of measurement	Frequency range
Rotor bearing	1 (+1 optional)	Radial + Axial	0.1Hz… ≥10kHz
Gearbox	4+1	Radial + Axial	0.1Hz… ≥10kHz at low speed shaft 10Hz… ≥10kHz at high speed shaft
Generator bearing	2	Radial	10Hz…≥10kHz
Tower with nacelle	(2 optional)	Axial in wind direction and transversal to the axial direction	0.1Hz…≥100Hz
Rotor blade	(2 optional)	In rotor axis direction and transversal to the rotor axis	0.1Hz…≥10kHz

Table 1: Minimum sensor requirements for vibration-based CM according to the GL Certification Guideline 2013 [13]



1. Main bearing radial
2. Main bearing axial
3. Gearbox, main shaft
4. Gearbox intermediate speed shaft (2X)
5. Gearbox, high speed shaft
6. Generator, drive-side
7. Generator, non-drive side
8. Tachometer

Figure 5: Example of sensor positioning for vibration-based CM applied in the SKF WindCon system [17]

The number of sensors and their positioning depends on both the wind turbine design and the used CMS. E.g. the amount of sensors for the WindCon can go up to 16, depending on the customer requirements. In addition, it allows the utilization of operating parameters such as real power, wind speed or temperature and an integration of oil-based CM [18].

A particular challenge in vibration-based CM is the early fault detection in planetary gearboxes. As described by [19], the vibrations measured by a sensor installed on the outer part of the ring gear of a planetary gearbox can have very different spectral structures depending on its geometric characteristics. Comprehensive work dedicated to this topic is presented in [19].

In the case of direct-drive wind turbines (DD-WT), the present focus of CMS on the detection of mechanical faults, such as e.g. bearing damages, is a limiting factor. Non-standard solutions are required to monitor the electrical components or special parameters like the generator air gap in this case [20]. The direct implementation of geared-turbine CMS into DD-WT has been questioned by [10] due to the higher failure rate on electrical components in these turbines, which cannot be detected by the conventional vibration-based CMS approach. In addition, the effectiveness of applying CMS designed for geared turbines in DD-WT is uncertain in view of the much lower rotational speeds and thus significantly different frequency range of vibrations in direct-drive turbines. Figure 6 shows an example of sensor positioning for a DD-WT.

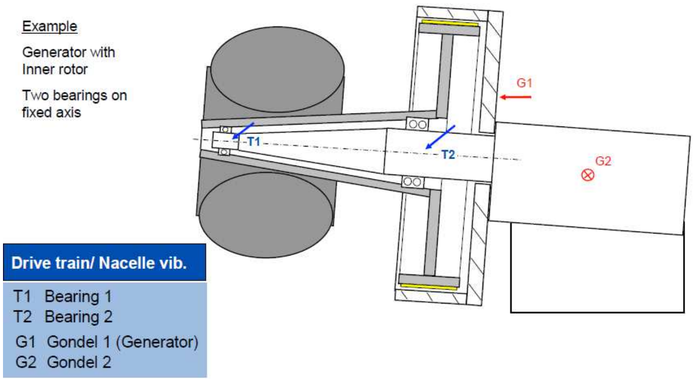


Figure 6: Example of sensor positioning in a direct-drive wind turbine [20]

Another important standard in the context of vibration measurement and evaluation in wind turbines is VDI 3834 [21], which is in the process of being extended and transferred to the international standard ISO10816-21 [22]. VDI 3834 provides criteria and recommendations regarding to the measurement and evaluation of the mechanical vibration of wind turbines and their components. It contains numerical values assigned to zone boundaries, which enables the evaluation of the measured broad-band vibrations (see e.g. Figure 7). The threshold values were obtained from a statistical analysis of vibration measurements on a large number of wind turbines. It is important to note that these threshold values are not sufficient for CM, as is clearly stated in the standard. The main reason is that condition-monitoring with the purpose of early fault detection and diagnosis requires more sophisticated techniques as e.g. frequency-selective monitoring, which is beyond the scope of VDI 3834. However, the broad-band vibration characteristics defined in this guideline are increasingly introduced in CMS as complementary monitoring parameters in addition to the distinct CM methods.

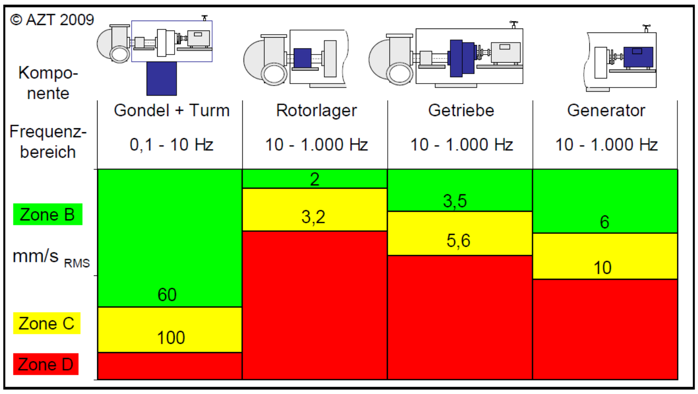


Figure 7: Suitable for broad-band vibration assessment, but not for condition monitoring: Guide values for vibration velocity according to VDI 3834 [8]

In regard to the data acquisition, it is stated in ISO 61400-25-6 [16] that the vibration measurements should be carried out based on the active power bin concept in order to reduce the risk of false alarms. As illustrated in Figure 8, this concept implies storing data in several active power bins in order to compare the evolution of the actual values with previous ones measured when the turbine was producing similar levels of active power. Using bins of active power is preferable over using bins of wind speed, as the vibration levels as well as the stress on the turbine components is typically closely related to the active power production of the wind turbine.

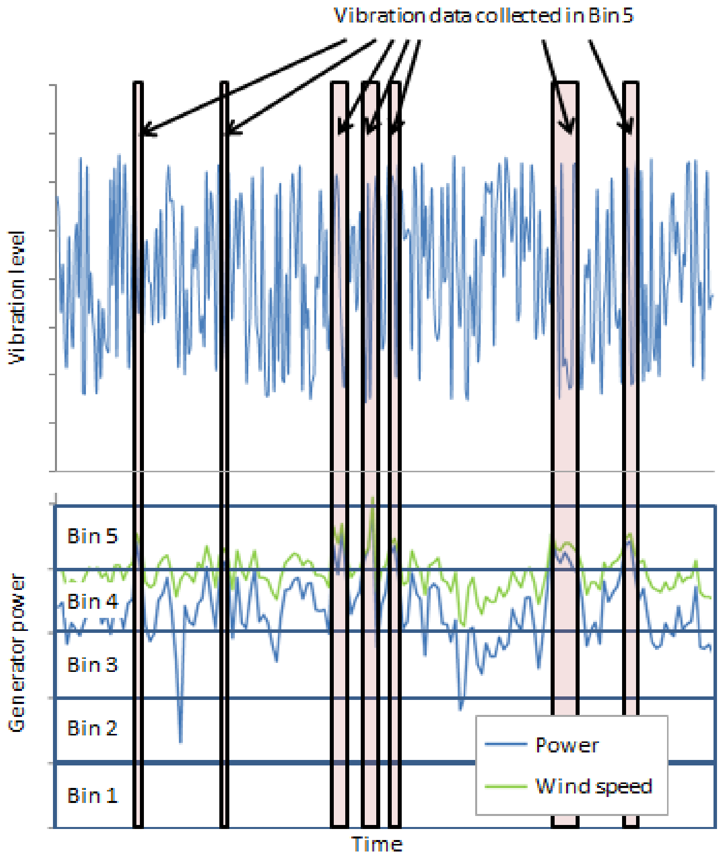


Figure 8: Active power bin concept according to ISO 61400-25-6 for better comparability of vibration measurements in view of the strongly varying operating conditions of wind turbines

2.1.1.2
Data processing and diagnosis

Vibration-based CMS rely on different signal processing methods. In [23], a general overview of vibration-based diagnosis methods for rotating components is presented. The most relevant analysis techniques, which are applied in wind-turbine CMS, are described in the following, based on information from [24], [25], [26] and [27]. For the sake of clarity, the methods are divided into time-domain and frequency-domain analysis techniques.

Time-domain analysis methods

Statistical and parameter-based methods use the assessment of statistical moments such as mean, variance, kurtosis, or of parameters such as e.g. minimum and maximum value, peak-to-peak value, root mean square (RMS) or crest factor. The values calculated by statistical or parameter-based methods are often the basis of more advanced analysis as described in the following.

Trend analysis is used to compare values from healthy operating conditions with the current operating values. Trend analysis can be also executed based on values obtained from the statistical and parameter-based methods or on specific descriptors obtained by means of more advanced techniques described below. As explained in [28], a descriptor is a data item derived from raw data e.g. vibration level at tooth meshing frequency. Its behavior can be described by a symptom when it indicates a fault. In [23], descriptors are recommended as parameters for diagnosis due to their selectivity with respect to faults facilitating the detection analysis process. Trending based on descriptors is a useful method not only to identify faults but also to assess their evolution dynamics and severity. The ISO 13379-1 should be consulted for further information concerning the use of descriptors for diagnosis.
An example of fault detection by means of trend analysis is illustrated in Figure 9: The vibration trends in a characteristic frequency range increase while a bearing fault develops. After replacement of the bearing, the vibration levels drop, suggesting that the faulty bearing had been the cause of the changes in the vibration trend.

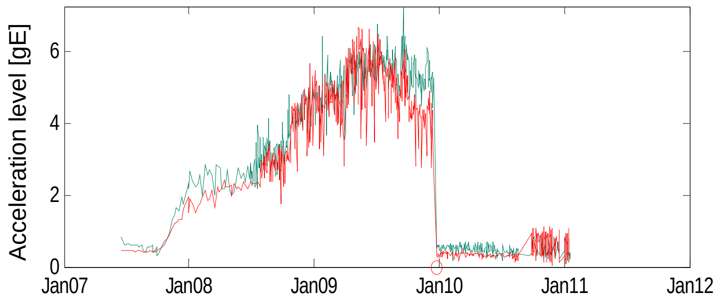


Figure 9: Example of fault detection in a wind-turbine generator bearing by means of trend analysis [9]

Time synchronous averaging (TSA): According to [27] and [25], the TSA is one of the most commonly used methods for gear condition monitoring. The main objective of the TSA is to resample the vibration data synchronously with a shaft rotation in order to extract periodic waveforms from noisy data [29]. This method is used for identifying rotating bearing or gearbox defects. TSA can be used to identify the vibration signal features taking place over a given period separating the vibration signature of the gear from other vibration sources e.g. noise that is not synchronous with the gear under analysis. Furthermore, it can work with non-periodic signal components filtering the noise of the time-domain signal. The TSA algorithm requires a reference pulse for aligning the data with respect to a given shaft and ensemble averaging the signal over several rotations. For this reason, phase information is highly recommended for TSA analysis. According to [30], two main difficulties need to be taken into account when applying TSA for wind turbines:

- The bearing damage signatures are usually non-synchronous to the shaft order. Difficulties could arise in planetary gears as not all gear meshing frequencies are integer multipliers of a shaft frequency. Therefore, instead of averaging in the time domain, order averaging should be considered to extract gearbox health features.
- If Acceleration Enveloping Analysis (AEA, a special form of TSA) is considered, the sampling frequency must be sufficiently high to ensure that the AEA is valid and that the crossing time detection is accurate.

In the most common cases the averaging is carried out from an order analysis (synchronous sampling). The averaging can reduce noise isolating a frequency of interest as shown in Figure 10. An increased number of averages lead to an improvement in the Signal to noise Ratio (SNR) [26].

Planet separation method is used to implement a TSA for planet gears. The central idea of this method is to capture the meshing period of each tooth when the planet gear is very close to the fixed accelerometer on the gearbox housing. As explained in [27], the initial step is to calculate the TSA signal with respect to the carrier rotation. Based on the number of teeth for each gear, a lookup table can be used to identify which tooth was meshing during the recorded time signal and stored in a specific location. This recording of the data windows is repeated for each tooth during several rotations of the carrier. In order to provide an assembled vibration signal for each gear tooth, the number of rotations is defined as the reset time for the planet or sun gear. This process is repeated until several assembled signals can be constructed. Finally, the created waveforms are ensemble averaged, and this completes the process for extracting the TSA signal. A more detailed description about the implementation of this approach can be found in [27].

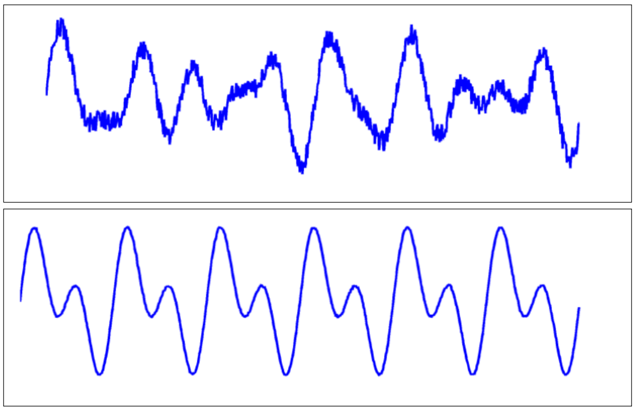


Figure 10: Time synchronous averaging: Representation of a noisy signal (top) and the same signal after 250-time synchronous averaging (bottom) [26]

Amplitude demodulation: According to [25], despite some difficulties in its implementation, demodulation has proven to be appropriate for assessing defects that produce impacting, e.g. in rolling contacts in bearings and tooth-to-tooth contacts in the gear meshes. This method allows the extraction of low amplitudes and frequencies that cannot be easily detected because they can be hidden by vibrations with higher energy. A good visualization of bearing defects frequencies without the interference of gear mesh frequencies in the same spectrum is also an advantage. In [31], an approach for analysis of vibration based on amplitude and phase modulation is presented. For performing this analysis, the synchronous average signal for each shaft is extracted. A band-pass filter around a dominant gear mesh frequency is used and usually includes a number of sidebands around the gear mesh frequency peak. The Hilbert transform is then performed on the filtered signal; the modulus and phase of the analytical signal provide the envelope and phase modulation signals, respectively.

Frequency-domain analysis methods

Fast-Fourier Transform and spectrum analysis: A vibration spectrum is typically obtained from a time waveform by means of a Fast Fourier Transform (FFT). Taking into account the specific geometries and kinematics of the machine components, such as e.g. bearings or gearwheels, it is possible to distinguish between normal rotation and characteristic defect frequencies. In this way, the vibration spectrum can reveal detailed diagnostic information about the location of a fault. This is particularly valuable for monitoring complex systems containing a variety of bearings, shafts and gears such as a wind-turbine gearbox.

A more advanced method is the analysis of the overall spectral energy (RMS value) in the sidebands divided by the tooth mesh amplitude. The analysis can be carried on a power density spectrum and can be applied e.g. to gearboxes, where the degradation of gearwheel teeth can be observed as an increase in the energy of the sidebands [24].

In order to illustrate the functionality of the frequency spectrum analysis, Figure 11 shows the vibration spectrum of a signal obtained from an accelerometer monitoring the high-speed shaft (HSS) of two gearboxes investigated in the so-called Round Robin study at the US National Renewable Energy Laboratory NREL. This study covered the analysis of a gearbox that had suffered from bearing and gear damage due to lubricant leakages and an intact gearbox of identical design. The gearboxes were equipped with CMS and tested under defined conditions on a dynamometer test stand at NREL to investigate the detection performance of different vibration algorithms. For further details on the subject and results of the Round Robin study, please see [26].

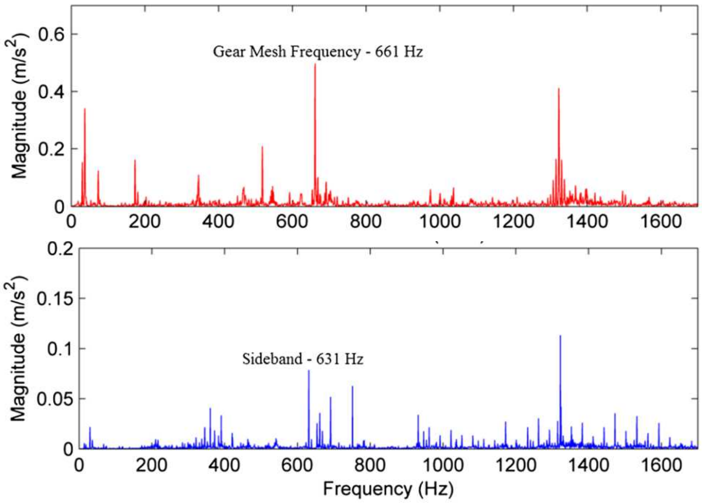


Figure 11: Frequency spectrum from a HSS gear in a wind-turbine gearbox in healthy (top) and degraded condition (bottom) [27]

In the frequency spectra shown in Figure 11, the gear mesh frequency peak for degraded and healthy condition are similar; however, in the case of the degraded gearbox, the appearance of side bands gives an indication of the damage. The sidebands are spaced at 30 Hz corresponding to the HSS rotational speed, showing the side bands as an indicator of the gearbox degraded condition.

Order analysis: In variable-speed wind turbines, the permanently changing rotational speed of the wind turbine rotor causes a shift of the kinematic excitation frequencies and thus a continuously moving frequency spectrum. In order to still enable vibration spectrum analysis, the so-called order analysis is used in many CMS for wind turbines today.

Order analysis is a method based on synchronous sampling e.g. data collected from the shaft rotation and not from the time signal. This means that the samples are recorded at equidistant rotation angles instead of equidistant sampling times [30]. In this way, a smearing of the amplitude energy in the frequency domain, which would otherwise result from rotational-speed variation during the data acquisition, can be avoided [29], see Figure 12. Order analysis is therefore a useful method to improve the efficiency and accuracy for the extraction of damage features in wind-turbine drivetrains [30].

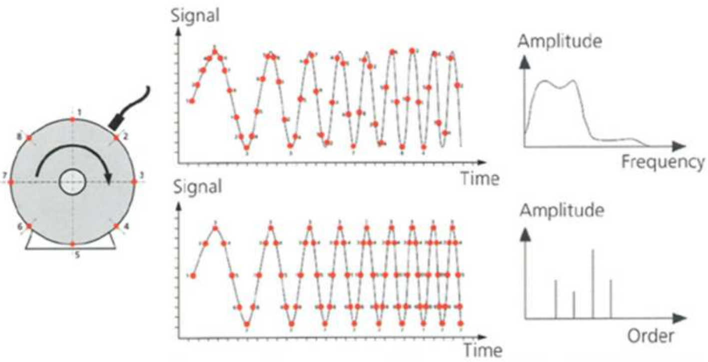


Figure 12: Order analysis - representations for time synchronous and shaft-angle synchronous sampling [32]

Cepstrum analysis facilitates the identification of harmonics families from the different components in a gearbox including bearings, shafts and gears. Mathematically, the power cepstrum is defined as the inverse Fourier transform of the logarithmic power spectrum. According to [27], the cepstrum is a suitable method to analyze a series of sidebands that are spaced at a given shaft speed. Comparing the cepstrum from a baseline healthy condition, the condition of each gear wheel could be evaluated. The peaks in a cepstrum are related to a frequency which can identify the affected shaft. The cepstrum is very similar to correlation analysis. The main difference as stated in [33], is that the inverse Fast Fourier Transform is performed on the logarithm of the power spectrum and not on the original power spectrum. Due to the use of the logarithm values, the cepstrum takes into account lower harmonics in comparison to the auto-correlation which takes into account the highest values of the spectrum and is more sensitive to the shape of the time signal. Cepstrum analysis was investigated e.g. during the previously mentioned Round Robin study [26], where the cepstrum of a healthy and a degraded gearbox was compared. In Figure 13, the family of harmonics can be identified by peaks in the plot corresponding to the intermediate shaft rotational speed (7.5Hz-spaced peaks). An additional peak can be observed at the high speed shaft frequency (30 Hz) in the degraded-gearbox plot indicating damage in the gear wheel.

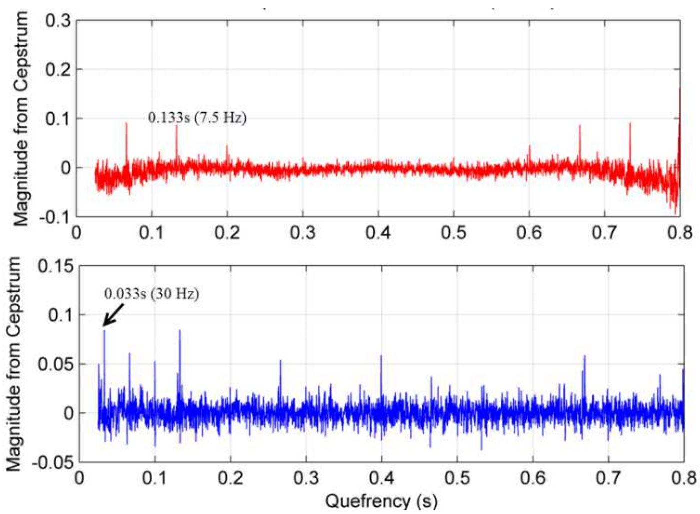


Figure 13: Real cepstrum from a HSS gear in a wind-turbine gearbox in healthy (top) and degraded condition (bottom) [26]

Envelope curve analysis: The envelope curve analysis (also: «envelope analysis« or «enveloping«) is a process of demodulation of vibration components with small amplitude in a narrow frequency band, which are often covered by vibration components with higher amplitude in a wider frequency band (e.g. mesh frequency)

[34]. According to [35], envelope analysis allows detecting faults with a high certainty. The most usual application is in the diagnostics of gearboxes and ball/roller bearings.

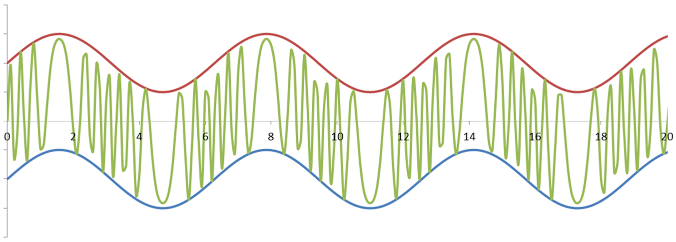


Figure 14: Illustration of an envelope curve

According to [27], envelope analysis is among the most effective techniques for bearing condition monitoring. In order to perform an envelope analysis, it is necessary to apply a band-pass filter around an excited natural frequency. After filtering the signal, the Hilbert transform is used to extract the envelope signal, which is further analyzed in the frequency domain. For a bearing with damage on the rolling element or bearing races, the bearing fault frequency peaks are usually much easier to distinguish in the envelope spectrum when compared with the frequency spectrum. However, the method typically requires a high sampling rate to capture the excited resonance frequencies, which are often >10 kHz. A both crucial and challenging aspect in envelope analysis is the suitable selection of the band-pass filter center frequency and bandwidth, which is subject of ongoing research.

Spectral kurtosis filtering is based on the calculation of the short-time Fourier transform (STFT) of the vibration signal. The main objective is finding an impulsive fault signature that can be hidden in the raw vibration signal. This impulsive signature can indicate faults in damaged gears or bearings. An advanced, multi-step mathematical procedure is necessary for this purpose; see e.g. [27]: The average value of the fourth power of the STFT is divided by the mean square value of the STFT, which provides kurtosis values as a function of frequency. In the next step, a wiener filter is created using the kurtosis values for each frequency bin. The frequency bin is only included if the kurtosis value is above a statistical threshold at a given confidence level. Finally, the signal obtained from the filtering is multiplied by the frequency-domain representation of the original signal, and the result is transformed back to the time domain.
In [27], spectral kurtosis analysis is applied to a degraded planetary gearbox stage under three different operating conditions:

- Case A: Output speed 1200 rpm, 25% of rated electric power
- Case B: Output speed 1800 rpm, 25% of rated electric power
- Case C: Output speed 1800 rpm, 50% of rated electric power

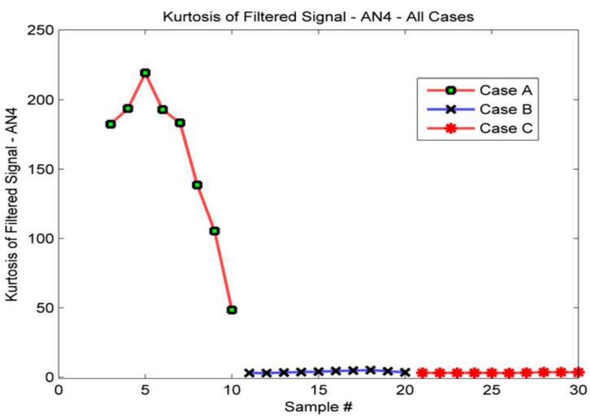


Figure 15: Kurtosis filtered signal of a degraded gearbox under different operating conditions [27]

As shown in Figure 15, high kurtosis with values in the range of 50…>200 were observed for scenario A, allowing a clear identification of the faults in the planetary gearbox stage. In contrast, under the operating conditions described by the cases B and C, the kurtosis remained at low values of <4, not giving any indication of damage. This means that the operating conditions have an influence in the detection performance of this method. In spite of this, [27] found spectral kurtosis filtering to be among the most effective analysis algorithms for early fault detection in planetary gearbox stages, compared with the previously described frequency-domain analysis methods, see Table 2.

Table 2: Fault-detection performance of different data processing and diagnosis methods applied in a comparative study on wind-turbine gearbox CM [27]

Failed component	Frequency domain	Cepstrum	Spectral kurtosis	Bearing envelope analysis	TSA – residual signal	TSA – ampl. / phase modulation
HSS pinion	H	H	NA	NA	L	H
HSS gear	L	L	NA	NA	L	M
ISS pinion	M	M	NA	NA	L	L
ISS gear	L	M	NA	NA	L	L
Ring gear	NA	NA	H-stage	NA	L	H
Sun pinion	NA	NA	H-stage	NA	M	L
ISS upwind bearing	NA	NA	NA	H	NA	NA
ISS downwind bearings	NA	NA	NA	H	NA	NA
HSS downwind bearings	NA	NA	NA	H	NA	NA
Planet carrier upwind bearing	NA	NA	NA	M	NA	NA

H: high confidence; M: medium confidence; L: low confidence; NA: not applicable or evaluated

Wavelet analysis is a time-frequency technique similar to the STFT, which presents some additional advantages for non-stationary signals. According to [36], wavelet analysis gives better frequency resolution at low frequencies and better time resolution at high frequencies, compared to STFT, which is an advantage in most practical cases.

Wavelet transforms have been applied in fault detection in mechanical systems not related to wind energy [37]. Its implementation for wind turbines has been evaluated in order to monitor vibration levels in gearboxes and to identify bearing problems [38] [39]. Its application and comparison with a FFT and other approaches is discussed in [40]. Validation of this method for generator damage diagnosis on a test rig has been presented in [36].

2.1.1.3
Severity assessment and residual-life prognosis

In case a CMS has detected a developing fault, it is of crucial importance to be able to assess the severity of the damage and with that the urgency of remedial maintenance measures. As explained in Section 1.2, a prognosis of the remaining useful life, i.e. an estimation how soon and how likely the detected fault will develop into a failure, is therefore an important step for successfully implementing condition-based maintenance (CBM).

A comprehensive review on machinery diagnosis and prognosis for implementing CBM in general, i.e. not being limited to wind turbines, has been published in [7]: The authors summarize different methods suitable for combined data analysis of event data and CMS data for the purpose of failure prognosis, among them the Proportional Hazards Model, Hidden Markov Model, Delay-Time Concept, and stochastic process models. In [41], an early wind-turbine specific overview of condition monitoring and failure prognosis is provided. The review includes the related technologies of Health and Usage Monitoring Systems (HUMS) and Engine Management Systems (EMS) in civil and military aviation. According to [41], failure prognosis could significantly increase the value of condition monitoring in the drivetrain and the rotor of wind turbines.

On this background, a method for predicting the residual life of wind-turbine components based on their age and online-CMS data has been developed in [9]: A lifetime-prognosis model has been implemented for the case of generator bearings in wind turbines using vibration-CMS data, with the objective to investigate the applicability of the approach. Figure 16 shows results obtained using this prognosis model: It illustrates the residual-life prognosis calculated at three different times during the operational life of a generator bearing, namely at ages of approx. 600, 800 and 1000 days, based on the vibration-levels history shown in Figure 16a. As the fault develops and additional CMS data becomes available, the uncertainty of the updated forecast reduces, until the bearing finally fails in agreement with the residual-life prognosis at an age of 1047 days (see Figure 16b and c).

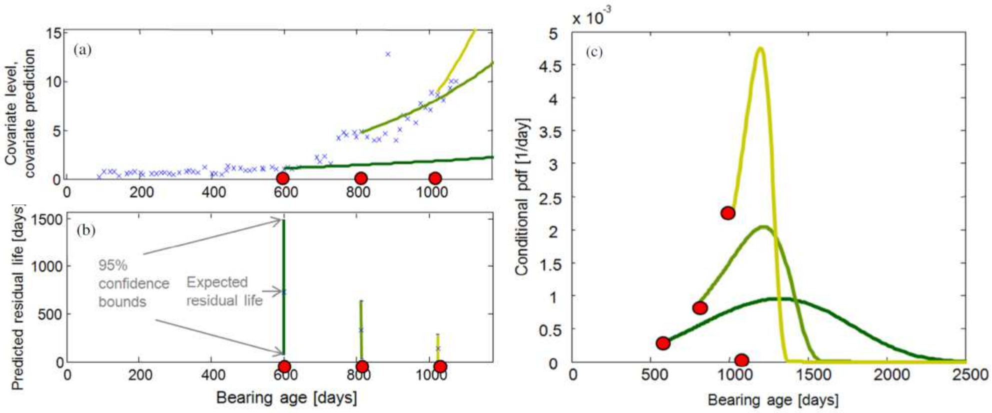


Figure 16: CMS-data based residual-life prognosis for a generator bearing in a wind turbine; (a) CMS-data history and prediction, (b) predicted residual life including confidence intervals and (c) predicted lifetime distribution

According to a literature study and discussions with providers of wind-turbine CMS, the severity assessment and residual-life prognosis is performed based on expert judgment, while quantitative methods are not applied for this purpose yet. In combination with the common practice that the condition-monitoring analysts manually set and adapt the alarm-threshold values for the CMS signals, the recommendations on maintenance measures are considerably dependent on the subjective judgment of individual monitoring experts.

2.1.1.4 Utilization in the maintenance process and related challenges

Due to the fact that the interpretation of CMS data requires specific expert knowledge, vibration-based condition monitoring is usually carried out from dedicated condition-monitoring service centers. In case of abnormal observations, the wind turbine operator is informed by means of a diagnosis report from the monitoring service center. These standardized reports indicate possible faulty components based on the signals from the sensors installed in the monitored turbines. A common procedure is the use of a color code to indicate the condition of a component sending a general recommendation including inspection or special attention. It is then in the responsibility of the operator to verify the diagnosis by means of component inspection and to take preventive action in order to avoid a failure.

This approach is afflicted with several challenges. One of the most relevant difficulties is the typically very limited information exchange between the operator and the external condition-monitoring service providers. In many cases, the monitoring center does not receive any feedback about the inspection results or measures taken in the field after an alarm has been reported. This lack of information flow hinders assessing the fault-detection performance of the CMS, which results in a sparse or even missing basis for improvement of the condition-monitoring process. In addition to this, a challenge resulting from the lack of information exchange is related to the fact that the vibration-based condition analysis requires detailed knowledge of the specific configuration of the wind turbine: In case the condition-monitoring service provider is not being informed about changes in relevant components in the field, this can negatively affect the condition analysis.

Some wind turbine operators perform the assessment of their CMS signals in-house. This approach could be beneficial as no-third party is involved, which typically facilitates the communication. On the other hand, this implies additional effort in order to develop the necessary expertise for performing a substantiated diagnosis from the CMS signals, including both personnel and software.

The fault-detection performance of vibration-based drivetrain CMS varies between monitoring systems, monitored components and failure modes. According to [42], the detection rate for damages in the high-speed stage of gearboxes or in roller bearings is estimated to approx. 96%, while for low-speed components like rotor bearings and planet bearings it is claimed to be above 80%. On the contrary, discussions with users of CMS indicate a lower detection performance particularly in case of faults in planetary gearboxes. Besides further improving the detectability of faults, another important task is the reduction of false alarms from CMS [9] [10].

2.1.2 Oil-based CMS

In wind turbines, oil condition monitoring (OCM) can be applied to the gearbox. In the context of OCM, it is important to distinguish between two different objectives: On the one hand, properties of the oil are being monitored in order to assess the quality of the lubricant oil including the effectiveness of the filter system and to determine the necessity of an oil change. On the other hand, information obtained from OCM as e.g. wear debris content can indicate developing faults in the mechanical components of the gearbox and thus can contribute to monitoring the condition of these components. Also in case of OCM, it is important to distinguish between offline and online monitoring: The regular oil sampling and laboratory analysis of gearbox oil is an offline-technique for oil condition monitoring. It is thus a part of wind-turbine maintenance in which CBM is widely implemented practice already. In contrast, in line with the initially stated scope of this study, the main focus in the following sections will be on online methods for OCM.

2.1.2.1
Instrumentation and data acquisition

The market offers a large range of products for oil-based condition monitoring. The sensors installed for OCM of wind turbines include mainly sensors for measuring pressure, temperature and particles. There is a variety of parameters, which have a negative effect on the oil performance and can therefore lead to problems in the drivetrain. Figure 17 summarizes the most relevant parameters, which are affecting the oil properties and are therefore of interest for an OCM system.

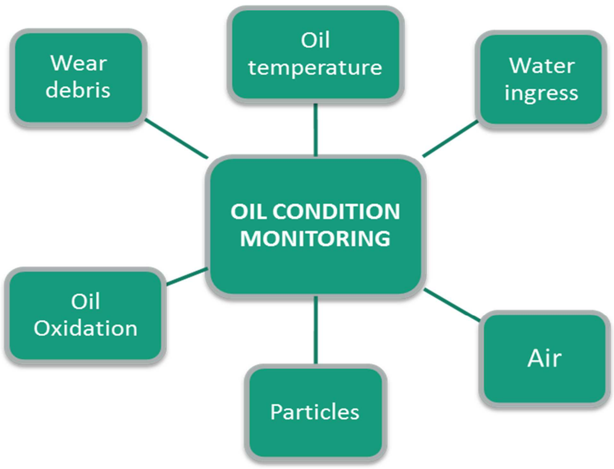


Figure 17: Parameters affecting the oil properties, which can be part of an OCM approach

A detailed overview of OCM sensor technologies for several applications is provided in [43]. The study highlights the importance of capacity and viscosity sensors and how dielectric constant sensors could contribute to monitoring oil degradation.

The most relevant sensor manufacturers involved with OCM are listed in the Appendix 7.1. The commercially available sensors for OCM include, among others, sensors measuring the water content, particles concentration, wear-debris production, dielectric constant, viscosity and oil quality. Table 3 gives an overview of the most common sensors and indicates their current status of implementation in wind turbines. While particle-counter sensors are already part of the standard CMS installation provided by some wind turbine manufacturers, the majority of sensor types have not left the phase of lab or experimental field testing for application in wind turbines.

Table 3: Overview of commercially available sensors for oil condition monitoring

Type of sensor	Output signal	Status of implementation in wind turbines
Water-content sensors	Water saturation (%)	Only laboratory tests, validation for wind turbines required
Particles-concentration sensors	Particles size distribution according to ISO 4406	Laboratory tests and experimental test in a wind turbine
Wear-debris sensors	Quantity of particles per unit of time and size	Part of standard CMS of some wind turbine manufactures
Dielectric constant sensors	Dielectric constant	Laboratory tests for several industry applications
Viscosity sensors	Kinematic viscosity	Laboratory tests for wind turbine applications
Oil-properties sensors	Viscosity, temperature, density, dielectric constant	Experimental test in some wind turbines
Oil-quality sensors	Color code, quality index	Laboratory tests for wind turbine applications

An introduction to each sensor type and its characteristics is provided in the following:

Water-content sensors: These sensors measure the relative humidity or the saturation level of the oil. They are also known as humidity or moisture sensors. Water has several negative effects on the oil and can reduce bearing life already at small concentration levels [44] [45]. Water catalyzes oxidation affecting the lubrication capacity of the oil and accelerates corrosion of ferrous materials. In addition, water causes additives to precipitate and fosters the growth of microorganisms [46].
A water sensing technology widely applied in the industry is capacitance measurement. Capacitance sensors are basically capacitors with polymer dielectric and platinum nickel or gold metallic electrodes. They are suitable for a wide range of applications. The capacitance responds to changes in the relative humidity which can be correlated to the saturation level in the oil [47]. The saturation depends on the type of base stock and additive package. Due to the fact that the operating conditions such as pressure and temperature also have an influence on this value, the saturation level cannot be directly correlated to the water content in parts per million. In this case the saturation curve of the oil is necessary. The significance of water sensors lies in their capability to give information about the saturation level and about the changes in the absolute water content.

Particle-concentration sensors are programmed to quantify particles based on ISO 4406. The ISO standard defines a cleanliness level by means of three numbers *a*/*b*/*c* that refer to an ISO range code, where

- *a* represents concentration of particles ≥4µm,
- *b* represents concentration of particles ≥6µm and
- *c* represents concentration of particles ≥14µm

in 1ml of fluid. Based on [48], [49] [50], particle contamination reduces significantly the lubricant performance and accelerates wear. Particles having a similar size as the lubricating film between bearing surfaces creates overpressure in the elasto-hydrodynamic lubrication (EHL) film thickness and local stresses at the surface [48], [44]. In the case of bearings, this could shorten their life span considerably. Small particles can also form silt and cause erosion wear [46]. Particle concentration sensors are usually installed in parallel to the main lubrication circuit due to their working volume flow rate. Their sensitivity to air bubbles on the particle counting makes necessary a previous conditioning of the oil to avoid air bubbles flowing through the sensor. According to [48], these sensors are not very effective for early fault detection, but can give information about the oil filter performance and the contaminants production.

Wear-debris sensors are used to monitor the gearbox condition instead of the oil cleanliness. As stated in [48], monitoring wear debris can give an indication of important damages like e.g. pitting. These sensors detect particles larger than 50µm and exhibit detection limitations related to the flow rate. For example, a sensor with a flow of 120l/min can only detect particles >100 µm. According to [51], the oil debris damage is progressive and gives alert from a potential failure several months in advance. Tests in the field have demonstrated that OCM based on wear debris can detect damage in the planetary gear teeth and the high speed bearing. Figure 18 shows an example case using this approach, in which the downtime was reduced and increased availability was obtained as the wind turbine continued in operation until the damage limit to carry out maintenance at an optimal point.

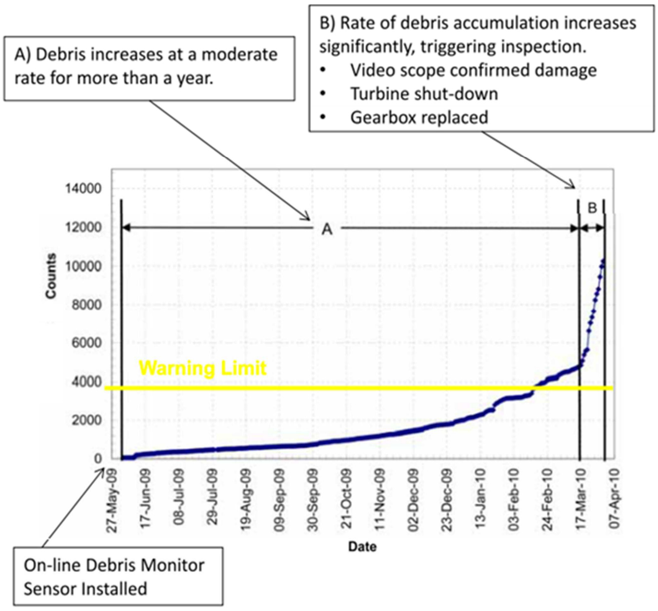


Figure 18: Example of gearbox fault detection by means of a wear debris sensor [51]

Dielectric constant sensors: During oil degradation, an oxidation process takes place. The amount of polarized molecules increases, changing the dielectric constant of the oil. The dielectric constant is also known as relative permittivity. The value of the dielectric constant varies with the frequency of the applied electric field [52]. According to a study presented in [53], it is not possible to measure the dielectric constant directly, but capacitive sensors give highly accurate indirect measurements and rapid dynamic response. These are necessary characteristics for online oil condition monitoring sensors. Experimental tests executed by [54] revealed some correlations between the moisture content, acid number, iron content with the dielectric constant.

The dielectric constant showed a direct proportional correlation with the previously mentioned parameters, and exhibited to be more sensitive to changes in the moisture content than to changes in the acid number or the iron content.

Viscosity sensors: Viscosity is one of the most important properties of the oil because it is directly related to the lubricating film thickness. Viscosity determines the flow internal resistance of the fluid. Viscosity measurements need the fluid to be sheared. In order to achieve oil shearing, several approaches have been developed. As stated in [55], some considerations should be taken into account to analyze a viscosity sensor. The performance of the sensor depends on the measurement principle and the environmental conditions. As stated in [55], the system pressure can lead to stress that will give data with an inaccuracy of more than 10%, which is a problem for industrial applications. Another example, an acoustic measurement principle will present inaccurate results for high viscosity oils, like gearbox oil, due to the damping which affects the sensing element. The operating conditions and the ingress of contaminants have an influence in the remaining useful life of the lubricant; therefore a change in the viscosity could be caused by several combined effects leading to different oil life spans. For this reason, it is very difficult to correlate a change in the viscosity to a specific cause. It should be considered that a permanent change in the viscosity could lead to lubrication problems due to the important role of viscosity in the lubrication film.

Oil-quality and oil-properties sensors: The terms «oil-quality sensor« and «oil-properties sensor« typically denote combined sensors based on the measuring principles mentioned previously. Oil quality sensors include a user friendly interface showing a color code or an oil quality index indicating the oil condition based on dielectric constant, capacitance or conductivity measurements. However for the purpose of condition monitoring, a crucial present challenge lies in the lack of a standard procedure for the choice of threshold values, which would allow to determine if an oil is acceptable for further use or not. The oil-properties sensors give an indication of the oil condition based on several measurements including dielectric constant, temperature or viscosity. However the correlation of the measured parameters and the interpretation of the data for wind turbines are still under development.

2.1.2.2
Data processing and diagnosis

Compared with vibration-based CMS, the data processing and analysis for the above described OCM techniques is straightforward. In case of online-OCM, trend analysis is typically used to monitor the development of the measured parameter(s) over time.
Oil-based condition monitoring is generally still at an early stage. This applies to sensor technology and validation, but in particular to the fault detection and diagnosis capabilities. As mentioned above, oil particle-counters have been already implemented by some wind turbine manufacturers as a part of their CMS. Some sensor manufacturers have carried out measurement campaigns to demonstrate the functionality of their system, see e.g. [49], [56], [57], [51].

An important question concerning OCM is the choice between online and offline oil analysis [58]. As pointed put by [59], oil analysis results depend on the operating conditions during oil sampling. The analysis results according to the ISO 4406 codes change considerably for smaller particles, depending on the time at which the sample is taken: a sample taken after stopping the turbine showed a higher particle content that a sample taken after several hours of operation. A continuous measurement by means of an online-OCM as displayed in Figure 19 illustrates the variation after a stop-startsequence in a wind turbine: It can be observed that during the first hour the particle content is higher. After two hours the ISO code particle-concentration values are lower and show a more stable behavior. The operation-dependency of oil-sampling results gives rise to questions on the effectiveness of offline OCM by means of oil sampling.

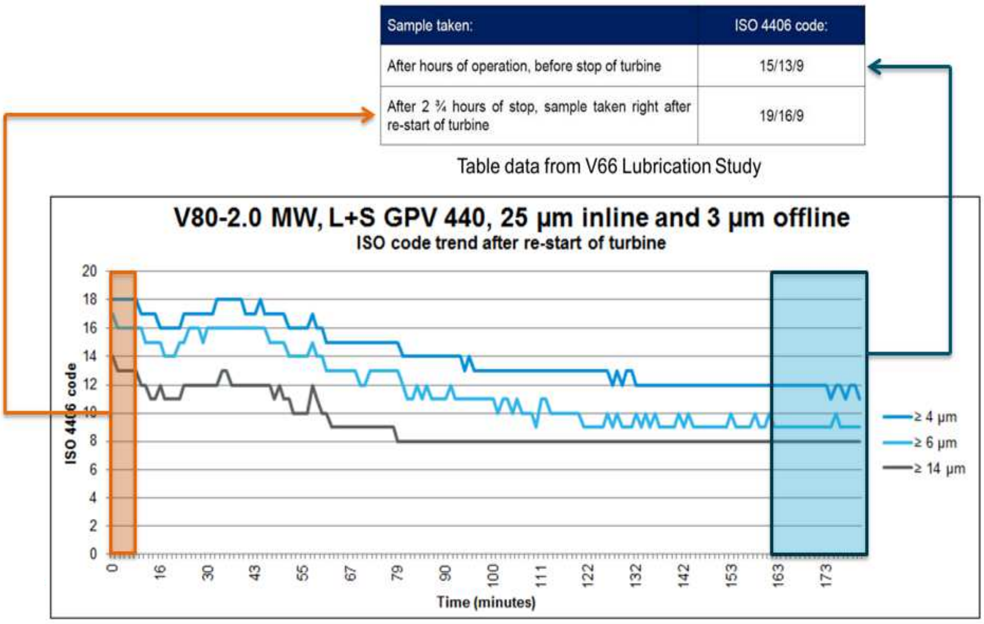


Figure 19: Dependency of oil-sampling results on the operating conditions [59]

Oil cleanliness is also a topic of interest to define the condition of the lubricant and to help identifying problems with the filtration system [48]. The filter is an important part to maintain oil quality, as stated by [60]. A typical filter configuration including inline and offline filtration of the gearbox oil is shown in Figure 20.

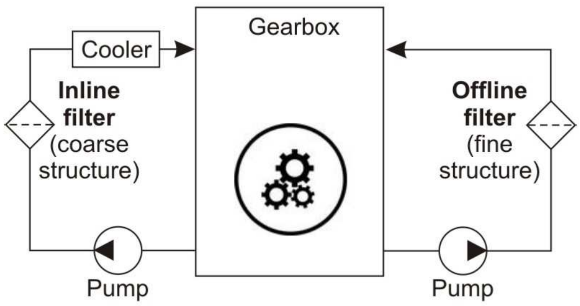


Figure 20: Filter configuration with inline and offline oil filtration in a wind-turbine gearbox [61]

In a study presented in [62], the lubricant contamination and degradation was monitored on the inline and the offline filter loop. The results confirm that the oil cleanliness can give indication of the degradation of the oil condition by an increase in the particle content; however, the effectiveness of the sensors is affected by their positioning, having different counting for the inline and the offline filter loop.

2.1.2.3 Residual-life prognosis

As both OCM data acquisition and diagnosis as preceding steps are at an early development stage, it cannot surprise that this is particularly the case for OCM-based residual-life prognosis.

Some prognosis studies have been carried out by [63], where an analysis of performance parameters describing degradation could allow a prognosis of the remaining useful life (RUL) of the oil. The approach is based on viscosity measurements and dielectric constant sensors. A model was developed to establish a correlation between oil degradation and particle content, which were validated by laboratory tests. The prognosis was accurate enough for the condition of the tests leading to the conclusion that viscosity or dielectric constant sensor could be implemented for OCM. However, the study implies that further research is required to validate dielectric constant and viscosity sensors diagnosis and prognosis confidence for the different operating conditions on a wind turbine.

2.1.2.4 Utilization in the maintenance process and related challenges

Currently, the validation of oil sensors plays a key role for their implementation in wind turbines and utilization in the maintenance process. Particle-counters to detect wear debris have gained higher interest from the wind turbine manufacturers as their cost is affordable [10] and their installation is relatively simple. Concerning particle-concentration sensors, their implementation is not very extended as these sensors are more expensive and their installation requires a conditioning system including a pump, which implies a more complex installation involving higher costs. Testing sensors under realistic conditions to assess their detection performance is an important prerequisite step for a massive implementation in wind turbines. The development of diagnostics techniques and coupling with vibration analysis plays also a significant role. As has been shown in [64], [65], it is essential to test oil sensors before installation to ensure their functionality.

2.1.3 Further techniques for drivetrain condition monitoring

As discussed in the previous sections, the most common condition-monitoring practices are based on vibration or oil analysis. This chapter introduces alternative approaches for monitoring the condition of wind-turbine drivetrain components. The implementation of these methods is subject of ongoing R&D or developed systems are presently in the pilot phase. A selection of methods considered being most relevant for practical application, namely fault detection based on Acoustic Emission (AE), thermography, measurement of electrical or mechanical parameters as well as a holistic approach, are briefly described in the following.

Acoustic emissions (AE) are high frequency transient elastic waves generated by the sudden release of energy due to strain or damage within or on the surface of a solid material, or by the interaction of two media in relative motion [66]. AE-based condition monitoring relies on surface-mounted piezoelectric sensors to detect and locate the origin of these waves within a structure. The signal can be characterized in terms of amplitude and energy [24]. The frequency range of AE is typically in the range 20 kHz–1MHz [19] [67].
The primary focus of applying AE in wind turbines are the generation and propagation of cracks. In addition, the analysis of stress waves can be used to detect lubrication film thickness abnormalities in bearings [68]. This technique could present some improved early fault detection capabilities in comparison with other approaches such as vibration analysis [19]. However, some practical problems related to noise from other equipment can complicate its implementation due to reduced quality in the output signals [6].

AE sensors have been used successfully not only in the monitoring of bearings and gearboxes [67], [19], but also for damage detection in blades of a WT as discussed in

[69]. There are a few commercially available AE-based monitoring systems, among them e.g. Swantech SWANwind applied in the previously mentioned Round Robin study, as described in [70].

Figure 21 illustrates a typical AE signal of a spur gear. According to [71] and [72], the burst or peaks in the AE signal are due to the rolling at the pitch point and sliding is the cause of the AE continuous signal.

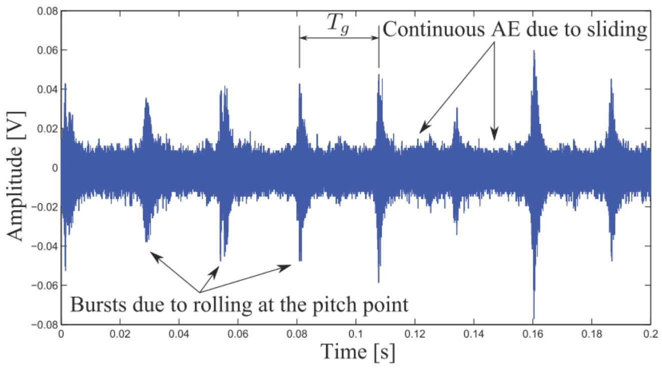


Figure 21: Typical acoustic emission signal on a spur gearbox [19]

From the continuous signal, a time-driven data analysis can be carried out e.g. using RMS or absolute energy. The burst type requires a descriptor analysis e.g. amplitude, counts to peak. However, it is still necessary to develop a capture method to monitor faults progression [67].

Thermography is a non-intrusive monitoring method based on infrared (IR) temperature transmitters or high resolution thermal imaging cameras (IR-cameras) [73]. The sensors or cameras need to be mounted close to the monitored component in order to obtain reliable results. This method has been implemented to monitor several types of installations and machines in other fields of application, including thermal power plants [73] [74]. Thermography monitoring is usually performed manually during operation of the mechanical or electrical asset. This is particularly difficult for wind turbines due to safety reasons. In [73], the application of IR-technology for wind turbines is analyzed suggesting that this method could contribute to condition monitoring. An assessment from the feasibility point of view has been completed. The results show that IR-Technology could be applied especially for monitoring:

- Electrical systems (power electronics, control system)
- Transformer
- Nacelle (fire detection)

Thermography is considered a suitable complementary method to improve the fault-detection capabilities. It also can be used for commissioning, service inspections, monitoring and control of a cold start-up sequence among others. However, due to the high cost of IR cameras, thermography is unlikely to gain much importance for online CM of wind turbines [10].

Electromechanical parameters: A variety of different electrical and mechanical quantities measured in wind turbines can potentially be used to perform fault diagnosis. Some studies analyzed the torque and power generated with wind time-series taken in the field and from tests carried out on a test bench to detect generator winding faults, rotor and electrical imbalance [75] [76] [77].

Current signals measured at the generator terminals are being investigated for identifying faults in generators, see e.g. [24] [75]. With this method, which is also termed Machine Current Signature Analysis (MCSA), it is possible to detect stator phase inductive unbalance, rotor phase resistive unbalance, phase resistive unbalance and turn-to-turn faults. These results have been obtained from a test rig at Durham University; validation in multi-MW wind turbines is a subject of ongoing research. Literature on current-based fault detection techniques for direct-drive wind turbines (DD-WT) is still sparse. [78], [79] [80] published some studies on fault diagnosis for DD-WT based on current measurements to detect imbalance and bearing faults on a small wind turbine. The publications highlight the importance of current based diagnosis due to its non-intrusive nature. The bearing fault signature diagnosis is based on power spectral density (PSD) analysis. A second methodology is proposed based on current frequency and amplitude demodulation algorithms of one-phase stator current, assuming that a bearing fault induces shaft torque variation in the generator modulating the amplitude and frequency of the current signal. It is important to note that characteristic frequencies of bearing faults in the current demodulated signal are not constant when the generator operates at variable rotational speed. This may cause difficulties in the extraction of the bearing faults signature due to the components created by the variable speed, which interfere in the current-demodulated signals. A generator-rotor misalignment detection method is proposed based on one-phase stator current. The method consists of the estimation of the shaft rotating frequency from the generator current by using a phase-locked loop (PLL). The PLL processes the information in order to obtain constant values in the PSD frequency signal. In this way, the variable characteristic frequencies of the imbalance faults can be detected. This technique identifies the excitations at the characteristic frequencies of imbalance faults; however their implementation in CMS is still under development. The proposed method is less complex than other signal analysis methods, such as wavelet analysis or amplitude demodulation. However, it has been tested only in laboratory experiments using a small wind turbine. Further research is required to validate the concept on multi-megawatt wind turbines in the field.

Holistic CMS: The approach of holistic CMS (also called global CMS, see e.g. [24], [81]) seeks to move from monitoring single components or subsystems with mostly separate monitoring systems to a more comprehensive CMS covering the turbine as a complete system. The process towards developing a holistic CMS consists of analyzing and selecting the most relevant parameters that could allow a diagnosis. A very detailed assessment will be difficult to execute due to the global nature of the approach. According to [24], a holistic CMS involves two major challenges:

- the complexity of an entire-system analysis involving the diagnosis parameters and the interaction among subsystems, subassemblies and components
- the high development effort to obtain practically useful results

One approach for achieving a holistic CMS is the system-identification approach. This suggests a model-based CMS, which makes use of signals from the turbine control system. The main objective is to develop a model that can recreate the behavior of the real system in a healthy operating condition. If the system presents an abnormality or a fault is causing changes in the operating conditions, the system behavior will deviate from the model signal allowing the identification of a faulty condition. This can be complemented with the observer-based approach where an observation error is calculated between the real operating parameter and the output of the reference model. Depending on the design of the observer, the sensitivity against model uncertainties and external disturbances can be enhanced. According to [24], only a few industrial applications have been reported so far.

2.2 Rotor-blade SHM

The fact that the wind-turbine blade design is certified for 20 years of operation has been misinterpreted and the first wind farm business plans were based on the assumption that the blades were requiring limited or even no maintenance. This has initially hindered the development of structural-health (also: structural integrity) monitoring solutions for wind-turbine rotor blades. However, it has been experienced during the years that also the blades fail, see Figure 22, and that the failures are afflicted with considerable repair cost and revenue losses due to downtime.

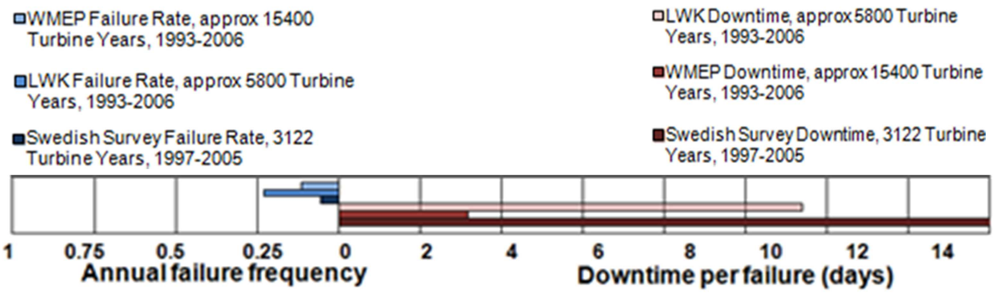


Figure 22: Annual failure frequency and the corresponding downtime per failure (excerpt from [82] [83])

During the past five years several monitoring systems have reached the market, with a focus on the identification of damage-initiating factors and damage incidents as well as their communication to facilitate preventive maintenance action. The most frequent causes of damages of rotor blades that might result in structural failure are listed in Table 4, together with examples of commercially available monitoring systems having the respective focus.

Table 4: Common causes of structural damage in rotor blades and related commercially available monitoring systems

Damage-initiating factor or cause	Description	Commercial monitoring system suppliers
Lightning strike	Lightning strikes occur often, especially in mountainous areas	GLPS [84]
Icing	From +2°, -…° it appears in winter, results in rotor imbalance	Hainzl [85] Wölfel [86]
Material/structural performance	Fatigue of the composite laminates, buckling in sandwich panels, bondline failure, root bolt connections	Wölfel [86] Bosch Rexroth [87]
Rotor imbalance (aerodynamic, mass)	Due to rain erosion, pitch-control errors and mass differences from blade to blade	Moog [88]
Overload	Pitch- or yaw-control errors	Moog [88]

The detection of lightning strikes, ice formation or rotor imbalances as well as the minimization of both pitch- and yaw-control errors can prevent severe subsequent damages not only in the blade structure but also in the adjacent components as e.g. the blade bearing, the bolt connection to the hub or the main shaft. However, it is not uncommon that blades fail due to inferior material or structural performance or due to imperfections during the manufacturing process. According to [89], the most frequently reported damages are:

- Manufacturing issues (waviness & overlaid laminates)
- Bad bonds
- Delamination & voids
- Leading edge erosion
- Trailing edge splits
- Scorching and split due to lightning

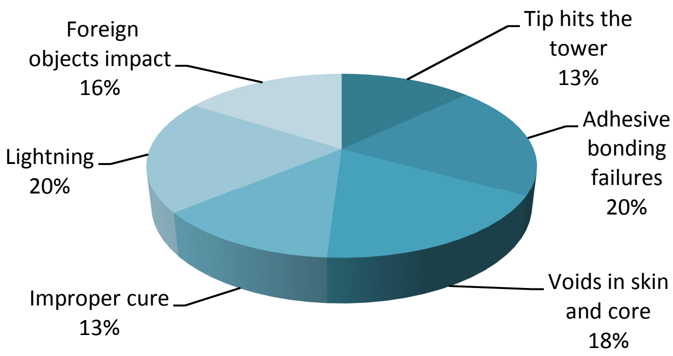


Figure 23: Distribution of rotor-blade failure modes according to data from [90]

The state of the art structural health monitoring (SHM) systems available in the market are offering integrated systems, which detect the structural-damage initiation and propagation. A typical system consists of two basic parts, the hardware and the software. The hardware comprises the sensors, a hub box at the blade root for data recording, a cabled or wireless connection for transmitting the data to the nacelle and the end unit performing the data evaluation. The evaluation is performed through the software, which typically indicates the identified state of health using predefined categories such as e.g. «Normal«, «Warning« and «Alarm« as in case of the monitoring system by Woelfel [86]. New integrated systems are also offering connection to the turbine controller in order to respond actively by e.g. sending a stop signal to the turbine in case of an emerged damage or by restarting it as in the case of the Bosch Rexroth system [87], which is a GL certified procedure.

Figure 24: Rotor-blade SHM system comprising sensors, hub box and data evaluation unit [91]

In the following, the monitoring techniques applied in commercially available SHM systems for rotor blades are shortly characterized, including the principles of the monitoring approaches, the required instrumentation as well as the key features and limitations of the different techniques. A more detailed introduction to monitoring principles and sensors for rotor-blade SHM is found in [92].

2.2.1 Vibration-based methods

Vibration-based SHM techniques, also known as Operational Modal Analysis (OMA), are among the most common methods applied for rotor-blade SHM (e.g. in BLADEcontrol by Bosch Rexroth [87] or as a part of the SHM.Blade system by Wölfel [86]). They are based on measurements of the blade vibration spectra and make use of the fact that any changes in the geometric or stiffness properties of the blade will modify the eigenfrequencies of the blade. As described in [93], there are typically around 30 natural frequencies per direction and blade, which appear as peaks in the vibration spectrum and form an individual vibration signature of a blade. However in addition to the natural frequencies of the blades, which can carry information about their structural integrity, the blade vibration spectra are also influenced by the wind excitation spectra, which are dependent on the wind turbulence.

The sensor types used for the vibration-based SHM techniques are accelerometers, piezo-electric sensors and micro-electromechanical systems (MEMS) [94].The definition of the allowable change margins during the operation are defined based on experience. Most of the systems are based on a continuous comparison of the monitored characteristics of all blades and use a deviation in the behavior of a single blade from the others as an indicator of a potential damage [93]. A damage localization and quantification usually requires supplementary analysis using finite-element models [92].

Blade monitoring systems based on vibration require a ‘learning’ process starting from the first operational day and lasting for a specific time. During this period the SHM system identifies and records the blade characteristic (normal) performance. Especially the normal frequency dependence on temperature has to be integrated in the software acceptable deviation limits in order to exclude fault alarms due to e.g. seasonal changes. This means that the monitoring systems do not assess the structural integrity of the blade from the time of commissioning, but implement a comparative algorithm based on the learning period. Therefore, intrinsic flaws which do not particularly contribute in the overall structural stiffness like local manufacturing flaws e.g. wrinkles in the spar caps, water absorption in crucial areas around bolt connection or in the balsa wood, might not be identified. However, these flaws might abruptly lead to a catastrophic failure.

In addition, the vibration spectra measured on a rotor blade are a result of the wind excitation spectra (depending on its turbulence) and the blade transfer function (depending on its mechanical condition and health). The measured spectra are therefore not just images of the blade natural frequencies. Moreover, the modal characteristics of a rotor blade are basically determined by the load-carrying parts, i.e. the spar caps. Therefore, the system frequency resolution is typically not high enough to identify small cracks in the bond line or in the aerodynamic shells. However, also these might be crucial for the overall structural integrity.

2.2.2 Acoustic Emissions (AE)

Also the Acoustic Emissions method is among the most used method for monitoring rotor blades. It is applied e.g. as a part of the previously mentioned, combined system SHM.Blade by Wölfel [86]. The piezoelectric-sensor based AE technique aims at detecting high-frequency structure-borne elastic waves related to the initiation of damages such as cracking or debonding [20] [92]. In order to allow the detection of small damages as well as the localization of faults in large structures as rotor blades, a high number of distributed sensors is necessary [92].

2.2.3 Ultrasonic Wave Propagation

Another monitoring approach using piezoelectric technology is Ultrasonic Wave Propagation. However, in contrast to the previously described methods, which do not apply any additional excitation to the monitored structure, this one is an active technique: It introduces ultrasonic waves into the blade by means of an actuator and captures the transmitted and reflected signal with an ultrasound receiver. Any damages being located perpendicular to the direction of wave propagation will modify the characteristics of the ultrasonic waves. A detailed determination of the damage location is considered difficult with this technique. [92]

2.2.4 Strain measurement

An approach which is predominantly applied for the purpose of load monitoring in rotor blades but also suitable for the detection of damages is strain measurement. This method is applied e.g. in the Rotor Monitoring System (RMS) by Moog [88] and in Fos4Blade by FOS4X [95]. For this purpose, foil strain gauges or fiber-optical strain gauges are installed in critical parts of the blade. As pointed out in [92], a high number of sensors is required in order to allow the detection of small damages.

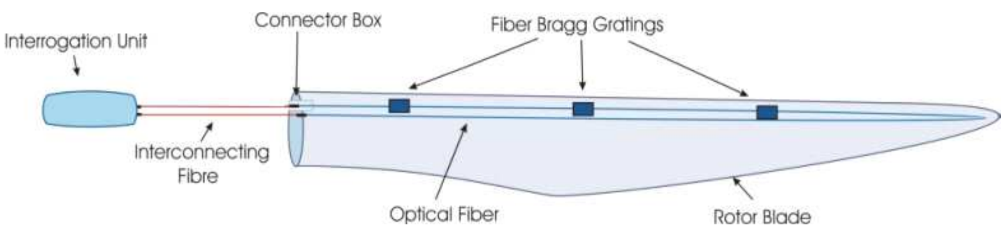


Figure 25: Fiber optical sensor (Fiber Bragg Gratings) based monitoring of wind-turbine blades using distributed strain measurements [96]

2.2.5 Deflection-based methods

Another approach applied for rotor-blade monitoring is based on deflection measurement, e.g. by means of laser technology as in case of the SKF Blade Monitoring System [97] [98]. This system measures the amplitude of the deflection at the tip of each blade in the instance at which the blade crosses the laser beam. Taking into account the operating conditions of the turbine such as wind speed, pitch angle and rotor speed, the deflection can be utilized for detecting changes in the bending stiffness of the blade. By relating the current behavior of the blade to its own behavior recorded in the past as well as to the other two blades, changes can be identified and related to icing, pitch errors, aging or structural damages. [20] [92] [97].

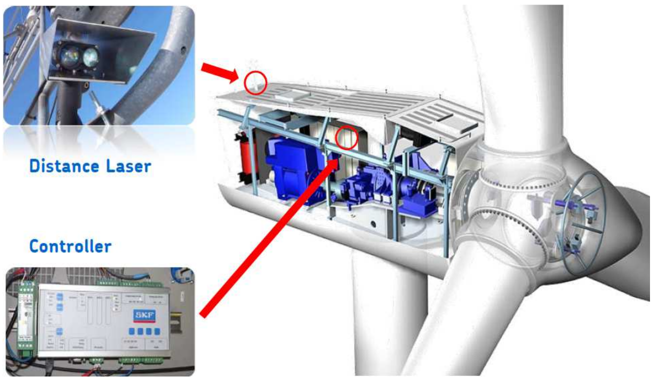


Figure 26: Blade-deflection measurement by means of a distance laser as applied in the SKF Blade Monitoring System [97]

2.2.6
Utilization in the maintenance process and related challenges

In spite of the availability of first rotor-blade monitoring systems on the market, [92] states that rotor-blade SHM must be considered being in a development stage and that visual blade inspections remain necessary for making decisions on maintenance or safety-related turbine shutdown. This is explained with a not yet high reliability and in some cases disputable sensitivity. In addition, considering the systems' time on the market, the field experience collected with these is still limited.

2.3
Onshore support-structure SHM

The tower and the foundation constitute the support structure of an onshore wind turbine. There are different types of towers in use [99]:

- tubular steel towers, which are the most common type,
- lattice towers,
- towers made of reinforced concrete, and
- hybrid towers consisting of concrete sections in the lower part and tubular steel sections in the upper part

Most foundations of onshore wind turbines are spread foundations consisting of concrete and steel. In soft grounds, pile foundations are applied instead. Failure of wind-turbine towers and foundations occurs seldom, but is afflicted with substantial cost and even the risk of a total loss of the wind turbine. E.g. in [100] an accident of a tower collapse is presented. The study also shows 62 well documented accidents occurred in towers from 1997 until 2009. The results of the investigation indicate strong winds, insufficient strength of bolts and poor bolt quality control during construction as the likely causes of the tower collapses. The recommendations to avoid this type of accident are related to the design.
On the part of foundations, [99] investigates cracks in the foundations of onshore wind turbines, which are mainly related to deficiencies in the structural design, to poor workmanship or inappropriate material selection.

A comprehensive review of SHM techniques not only for the rotor blades, but also for support structures of wind turbines is provided in [92]. Another extensive review of methods and instrumentation for SHM is found in [24]. The SHM of onshore and offshore support-structures as well as of rotor blades of wind turbines has similarities with respect the applied equipment and analysis approaches. This section describes the most known sensing technologies and methods for performing SHM on towers and foundations for onshore wind turbines.

2.3.1 Data acquisition and diagnosis

A list of suppliers of sensors and complete systems for monitoring the support structures of wind turbines is provided in the appendix. The following types of sensors are being applied or investigated for SHM of towers or foundations:

Strain gauges: SHM can be carried out with strain gauges by using peak strain measurements in structures caused by loads. This information can be analyzed to verify design assumptions about loading patterns. In combination with fatigue models, it can also be used to predict residual life [101]. However, the implementation of strain gauges in wind turbines is restricted by their limited performance under impact and fatigue loads [10].

Optical-fiber sensors (OFS) based strain measurement: OFS are suited for SHM due to their lightning safety and robustness against electro-magnetic interference. Compared with electrical strain gauges, OFS are preferably applied in wind-turbine SHM also due to their higher resistance to disbanding, creep and fatigue [24]. However, OFS require temperature compensation. Fiber Bragg Grating (FBG) sensors are a type of OFS that allows establishing a direct physical correlation between the measured Bragg wavelength and strain. FBG have been installed in wind-turbine towers to measure strain [102]. According to [24], recalibration of the FBG sensors is not required, even if the signal processing unit is exchanged. A major obstacle for the implementation of OFS is their high costs: Based on the current market prices, OFS are up to 50 times more expensive than strain gauge sensors.

Vibration and temperature sensors: Accelerometers are used to monitor the operational vibration of the support structure. Because temperature information is required for the assessment of the measured vibration, thermocouples are installed to monitor operational temperatures along the different structure sections [103]. Oscillations of the tower head are often monitored as a part of vibration-based drivetrain CMS described in Section 2.1, with a typical frequency range of 0.1Hz…>100Hz [13].

Inclination sensors have been implemented as an additional measurement in research projects to monitor the stability of the tower [101], [104].

Displacement sensors such as infrared sensors, linear variable differential transformers (LVDT) or Hall-effect sensors are proposed for foundation SHM on wind turbines in [105].

Photometry and laser interferometry have been studied for operational modal analysis of a wind turbine in [106] and [107]. However, [101] highlights that these are afflicted with high cost for the measurement equipment and that the durability in the long time is uncertain.

Comprehensive research on wind-turbine support structure SHM is presented in [101]. The study includes an overview of the different sensors, the measurement system and data management. As an example, Figure 27 illustrates the sensor positioning on a wind turbine tower.

In [104] an approach to improve the design of towers is presented by the assembling of joints using friction connection with opened slotted holes. A monitoring system is implemented on a wind turbine of type Repower (Senvion) MM92. The main objective was to extract the dynamic behavior including an accurate modal identification of the system, the section loads acting in different segments of the tower and the performance of the assembling joints. The system measured strains on the inner surface of the steel cylinder and in some of the bolts. The acceleration at several sections, the inclination of the upper part of the tower and the surface temperature at fixed levels were also monitored. The measurement consisted of nine acceleration sensors, 92 strain gauges, four temperature sensors and two inclinometers. Some important conclusions have been extracted from this study:

- The measurement system confirmed that the stress variation along the tower height is low, since the cross section varies in diameter and thickness.
- The strains measured on the cylindrical shell presented some increase with wind speed and decreased beyond a certain speed level, in this case 12 m/s. This is due to the blades pitch rotation to keep constant power production, which at the same time reduces the loading of the tower.
- The stress fluctuation inside pre-stressed bolts is independent of the wind speed, as very low variations for different wind speeds were observed.
- The bending moment distribution along the tower height is almost linear. The tower behaves like a cantilever connected in the base with similar moment variation. The loads at the top were mainly due to moments and transverse loads (maximum measured bending moment at the top: 2300kNm, maximum bending moment measured at the bottom: 25000kNm).

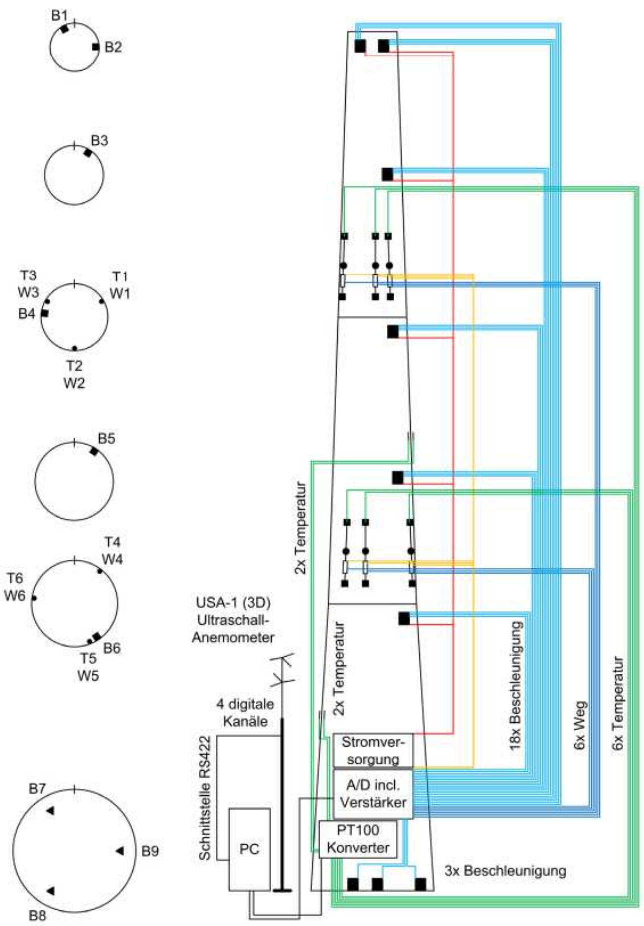


Figure 27: Example of sensor positioning on an onshore wind turbine tower and foundation [101]

2.3.2
Residual-life prognosis

An estimation of the residual life based on the evolution of damages is demonstrated in [101]. The method comprises fatigue analysis including welded and bolted joints, linear damage accumulation, the influence of the temperature compensation, the availability of measurement data and a continuous monitoring of the damage evolution. The analysis was performed on a pitch-controlled wind turbine of 500 kW.

2.3.3
Status of application in wind turbines

SHM systems for towers and foundations of onshore wind turbines are in the development phase. The sensors are typically installed within the scope of pilot projects to monitor the turbine support structure. The main utilization comes from the research side to perform prognosis or to identify possible weaknesses in the design. Practical application of online monitoring methods for early fault detection and condition-based maintenance is not reported in the literature.

A system to continuously monitor the onshore foundation displacement has been recently developed, see [108]. This system monitors the movement of the foundation in both vertical and horizontal direction. However, detailed information about this system and its fault-detection performance for wind-turbine foundations is not publicly available.

2.4
Offshore support-structure SHM

In case of offshore wind turbines, there is a large variety of different support-structure types. Figure 28 shows the monopile, tripod, jacket and gravity-based design, which are the four prevailing types in use.

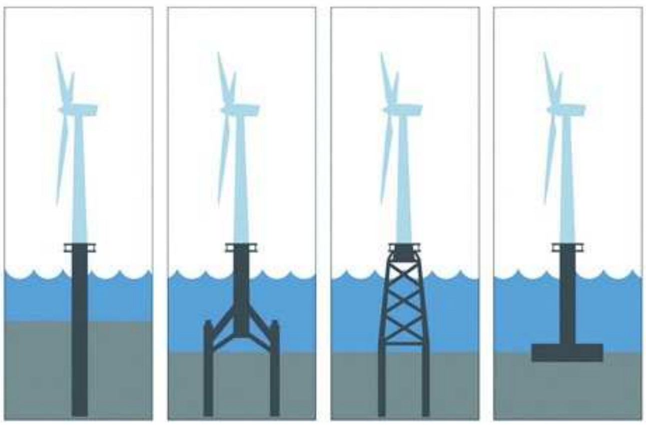


Figure 28: Offshore support-structures of monopile, tripod, jacket and gravity-based type (from left to right) [109]

The R&D efforts towards understanding the loading and stresses of offshore wind-turbine support structures and towards their structural-health monitoring have been considerably intensified during the recent years. Among the key motivations is that the "Bundesamt für Seeschifffahrt und Hydrographie" (BSH) included the mandatory utilization of online monitoring of the support structures in the BSH standard "Design of Offshore Wind Turbines" [110]: The standard requires that at least 1 out of 10 wind-turbine support structures is equipped with a CMS. Another factor enhancing the R&D efforts towards the development of monitoring systems for offshore support structures are problems experienced with the grouted joints in more than 300 wind turbines in the UK, see e.g. [111].

The most common type of support structure for offshore wind turbines is the monopile. Therefore most of the research activities concentrate on monitoring the grouted connections between the monopile and the transition piece with sensors located in this area.

2.4.1 Instrumentation and data acquisition

The most common sensors installed on offshore support structures according to [111] are:

- Strain gauges
- Temperature sensors
- Displacement sensors
- Accelerometers
- Additional sensors: Inclinometers, load cells, wind speed and direction, and wave height sensors

In addition, according to [112], optical fiber sensors (OFS) are being utilized and offer several advantages, like corrosion resistance, humidity resistance and the capability of performing high-strain measurements over a longer period of time. Fiber Bragg Grating (FBG) sensors are used in the wind energy sector in combination with temperature compensation, which is necessary due to the different positions of the sensors in the structure. Other aspects like the installation, circuitry and sensor positing have an influence on the assessment of the output signals. The positioning of the sensors depends on the type of support structure and the monitoring requirements. In the case of monopiles, the sensors are typically installed at the grouted connection and on the transition piece [111]. To provide an example, Figure 29 illustrates the sensors positioning on a jacket and on a tripod structure.

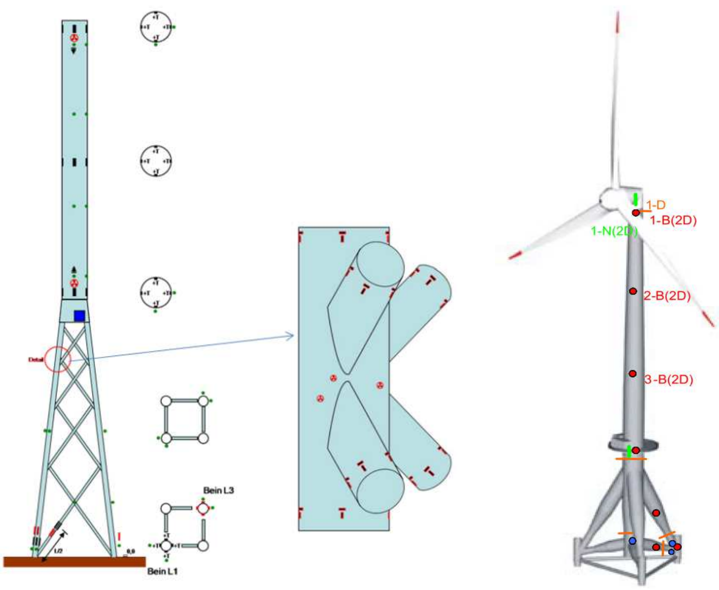


Figure 29: Sensor positioning for SHM of a jacket-type (left) and a tripod-type (right) support structure [113] [114]

The sensors in the tripod shown in Figure 29 were installed to carry out an analysis on the system quality requirements for the instrumentation of the support structure. The system installed in the tripod consisted in total of 111 strain gauges, 14 accelerometers and 4 inclination sensors. Due to the high number of sensors, this approach is not suitable for commercial application because of the immense related measurement-equipment cost [114].

The sensors in the jacket structure shown in Figure 29 were installed during the research project «OGOwin« in order to analyze different solutions for sensor mounting and numerical model verification [115]. Therefore also in this case, the sensor positioning shown is not representative of any commercially available monitoring solution.

2.4.2 Data processing and diagnosis

Based on [92], an overview of the different SHM approaches for support-structures of wind turbines is presented in the following. For this purpose, it is distinguished between local and global monitoring methods.

Local monitoring approaches

Fatigue monitoring is carried out based on strain or vibration measurements. The rain flow counting algorithm is commonly used to estimate the damage accumulation in the structure.

Scour monitoring: This monitoring approach has arisen from the potential effect scours at the sea bed can have on the dynamic behavior of the support structure. The scour is related to the pile diameter and can affect the stability of the support structure if it reaches several meters. Currently scour is monitored by means of beam echo sounders installed on the structure or from a vessel. Storms or harsh environmental conditions are important factors that influence the dynamics of scour formation.

Grouted joints monitoring: The grouted joints are monitored as this section has been critical in offshore wind turbines, as mentioned above. Additionally to strain sensors installed in this section, horizontal displacement transducers can be installed to collect data and verify movements in correlation with strain measurements and waves.

Splash zone monitoring: The main motivation to perform a splash zone monitoring is the variety of loading and environmental conditions to which this section is exposed. The splash zone is under the permanent impact of waves and wind and therefore subjected to a highly corrosive environment. Wave monitoring can be carried out by pressure cells to assess the impact of breaking waves as depicted in Figure 30. This monitoring technique has been applied at the wind farm Alpha Ventus.

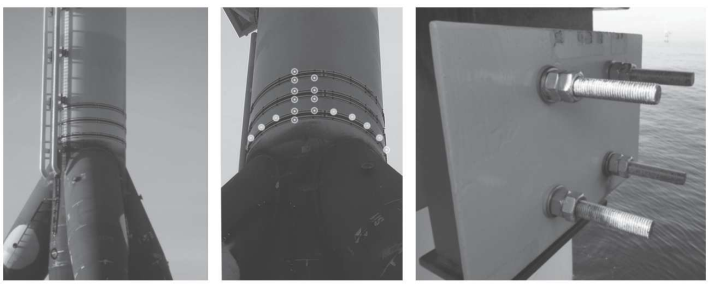


Figure 30: Installation of pressure cells for wave monitoring in the splash zone of offshore wind-turbine support structures [98]

Corrosion monitoring, which often also includes corrosion-protection monitoring, is crucial to maintain the integrity of the structure. According to [113], corrosion-monitoring techniques can be based on:

- Corrosion coupons (weight loss measurements)
- Electrical resistance
- Linear polarization resistance
- Zero resistance ammeter
- Hydrogen penetration
- Microbial and erosion effects

Global monitoring approach

The global monitoring approach relies on Operational Modal Analysis (OMA). The main objective is to detect damages which could change the modal parameters of the structure. As stated in [92], small damages could be correlated to high frequency local modes. Large damages and structural changes have an influence on the global modes. The changes could be reflected on the Eigen-frequency, mode shape, and modal curvature among others. The study points out that the natural frequencies may not provide sufficient damage-related information as these frequencies are not very sensitive to damage. This can be worsened by the environmental and operating conditions. Automated extraction of modal parameters has been suggested as an alternative to perform an analysis, e.g. using Fuzzy logic. More advanced methods use different algorithms based on stochastic approaches in order to provide a general dynamic behavior instead of focusing on specific frequencies or modes.

2.4.3 Residual-life prognosis

In [113], the support structures are observed from the system level to characterize their dynamic behavior. In order to perform this analysis, sensors are installed to monitor the load distribution and to enable a lifetime prognosis of the structures. Such a lifetime estimation calculation is presented in [101]. This prognosis is also carried out based on continuous monitoring of the support structure by means of OMA. A second study is carried out on the evaluation and analysis of the measurement data during operation. The results show that the calculated damage curve is influenced by the frequency distribution of the wind direction as well as by the wind speed.
Note that the residual-life prognosis in the case of support structures is based on a different approach than the vibration-CMS data based prognosis described in Section 2.1.1.3 for drivetrain components: In the case of support-structure SHM, the residual life is calculated from the measured loads, which can be translated into life consumption by means of suitable models. On the contrary, in the above mentioned case of drivetrain CMS, a residual-life prognosis would typically be based on the magnitude and evolution of the condition indicator instead of load counting.

3
SCADA-based condition monitoring and data fusion approaches

The operating and environmental conditions of virtually all wind turbines in operation today are recorded by the turbines' supervisory control and data acquisition (SCADA) system in 10-minute intervals. The number of signals available to the turbine operator varies considerably between turbines of different manufacturers as well as between generations of turbines by the same manufacturer. The minimum data set typically includes 10min-average values of:

- wind speed
- wind direction
- active power
- reactive power
- ambient temperature
- pitch angle
- rotational speed (rotor and/or generator)

However, in modern wind turbines, the SCADA data often comprise hundreds of signals, including temperature values from a variety of measurement positions in the turbine, pressure data e.g. from the gearbox lubrication system, electrical quantities such as line currents and voltages or pitch-motor currents, tower vibration etc. Comprehensive SCADA data sets often contain not only the 10min-average values, but also minimum, maximum and standard-deviation values for each 10min-interval.

The fact that this data is already being collected and available to the operator suggests utilizing it for the purpose of condition monitoring. Comprehensive research has been carried out in the recent years to develop methods for this purpose and to investigate the fault-detection performance achievable with SCADA-based condition monitoring. In the following, an overview of the main approaches together with their performance and limitations will be presented.

According to a review on this topic provided in [116] and [117], the approaches for utilizing SCADA data for condition monitoring can be grouped into three categories, namely Signal Trending, Artificial Neural Networks (ANN) and Physical Models.

3.1
Approaches for SCADA-based monitoring

Signal Trending: The relatively simple Signal Trending approaches use the comparison of SCADA signals against the corresponding signals obtained from other turbines operating under similar conditions, e.g. in the same wind park. In addition, but also alternatively, the current SCADA signal of interest is compared against values measured on the same turbine during an earlier period of time. Typically, the signal is normalized with the average value of the wind park. [117]
Figure 31 shows an example based on SCADA 10min-average temperature data measured on a drivetrain component of one test and four reference wind turbines. The increasing deviation observed in the time series corresponds to a developing fault in the main bearing of the test turbine.

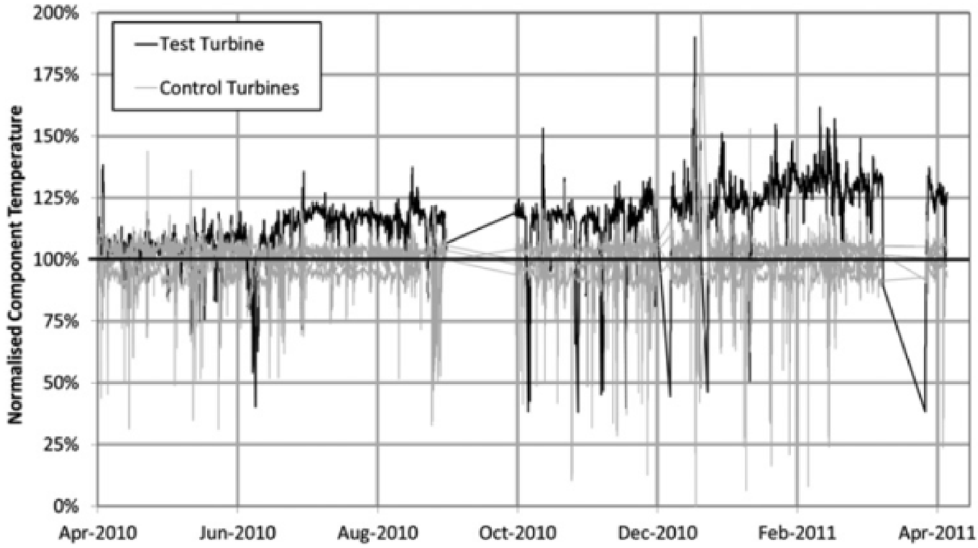


Figure 31: SCADA-based monitoring by means of Signal Trending; time series of normalized drivetrain component temperature of a test turbine compared with four reference turbines [116]

Artificial Neural Networks (ANN): ANN methods train artificial neural networks to model the normal operating behavior, usually based on «known-good« data. Among these, the method of Self-Organizing Map (SOM) is considered the most promising for the purpose of condition monitoring, according to [117]. The SOM is trained using a period of data which covers the complete range of normal operation. Applying this method to SCADA data of wind turbines provides a time series of quantization errors, which describe the deviation of the test dataset to the benchmark dataset [116] [117]. Compared with the previously described Signal Trending approach, a higher effort is required for implementing ANN-based methods. Figure 32 illustrates the neural-network architecture used in [118] for the purpose of SCADA-based condition monitoring following an ANN approach.

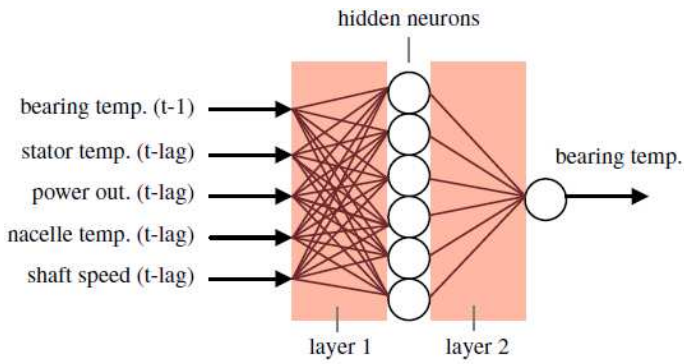


Figure 32: Architecture of a neural network applied for the purpose of SCADA-based condition monitoring [118]

Physical models: As described in [117], methods falling into this category use regression models that are created based on knowledge of the underlying physical processes. The parameters of the regression model are determined based on time series data from a training period with «known good« turbine condition. For the purpose of condition monitoring, the resulting regression model uses the SCADA signals defined as model input to predict the value of the quantity of interest under these operating conditions. In the example of a wind-turbine drivetrain component shown in Figure 33, e.g. active power, shaft speed, nacelle and surrounding temperature as well as cooling-system duty would be used as model input signals in order to calculate the expected component temperature under these conditions.

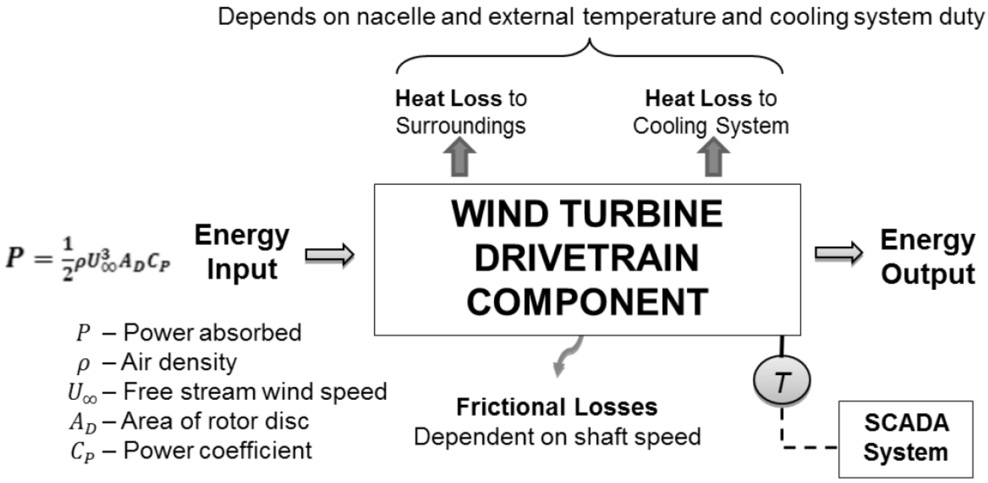


Figure 33: Energy balance for a drivetrain component forming the basis of a Physical Model used for SCADA-based condition monitoring [116]

Deviations of the predicted value and the measured SCADA signal can be used as an indicator of abnormal component condition. The Physical Model approach has been applied in wind turbines e.g. for fault detection based on temperatures of the main bearing, of gearbox bearings, of generator bearings and generator winding (see [116], [118] and [119]). Also the empirical monitoring approach described in [81], which uses so-called similarity-based models created from historical data, falls into this category. According to [117], the Physical Model approach is the most suitable for SCADA-based condition monitoring.

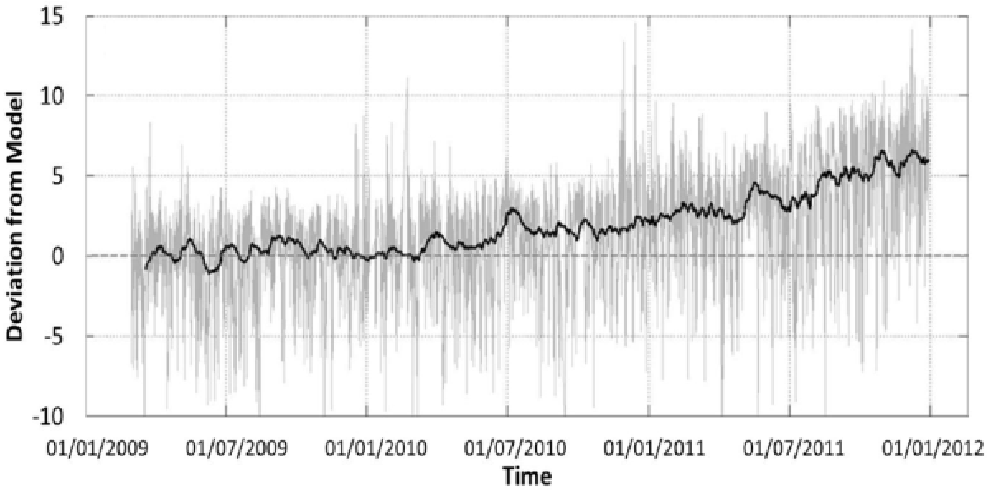


Figure 34: SCADA-based condition monitoring using the Physical-Model based approach; deviation of the measured main-bearing temperature from the model-predicted value (grey line) and rolling-average value of this deviation (black line) [116]

3.2 Performance and limitations of SCADA-based methods

For the SCADA-based monitoring by means of the Physical-Model approach, a field-data based validation study is reported in [116] and [117]. In this study, the method was validated based on SCADA data covering 472 wind-turbine operational years.
In a «blind test«, the method was applied to historical data in order to detect damages in the main bearings, the gearbox (intermediate-speed and high-speed shaft bearings) as well as in the generator windings and bearings. The model-based «detections« were then compared with the real failure history of the wind turbines to assess the performance of the method with respect to condition monitoring. In total, 24 out of 36 real failures were detected correctly, while there were three false alarms (i.e. model-based «detections« of damages in absence of real component faults).

An important question in the context of condition-monitoring methods is, how long before failure a method can detect a fault, i.e. if the advance-detection periods (or P-F intervals) are sufficiently long for practical application. Figure 35 shows the range and distribution of the advance-detection periods observed in the above described validation study. Their lengths range from one month to two year, with the majority of faults having been detected within six months before failure.

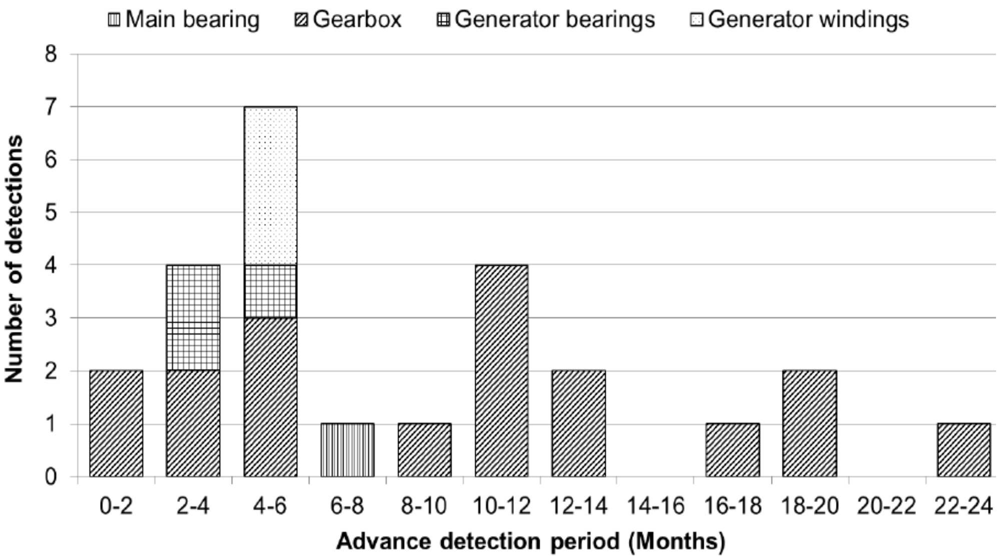


Figure 35: Distribution of advance-detection periods for faults detected based on SCADA data (Physical-Model approach) in the validation study [116]

The result that only 2/3 of the failures could be detected by means of the 10min-SCADA-data based monitoring methods demonstrates that the detection performance is too low for using it as a standalone condition-monitoring solution. While obviously SCADA-based monitoring is preferable over performing no condition monitoring at all, it cannot at the present stage replace a professional purpose-designed CMS. This is in line with the conclusions in a recently published review on the technical and commercial challenges of wind-turbine condition monitoring [10] as well as with the GL Guideline for Certification of Condition Monitoring Systems for Wind Turbines [13], which states that SCADA data was not suitable for the purpose of condition monitoring. It is additionally pointed out in [10] that the bandwidth of 10min-SCADA data was not sufficient for diagnosis compared with CMS and that SCADA-based monitoring provided a late-stage indication of faults which would often imply a too short lead time for practically useful condition monitoring.

3.3
Data fusion for enhanced fault-detection performance

Every known condition-monitoring methods is afflicted with a certain – in some cases lower, in others higher – risk of false alarms and missed faults. On this background, it was stated in [70] that no single condition-monitoring technique could provide the comprehensive and reliable solutions needed by the wind industry.

A possible solution to this problem is the concept of data fusion: It implies that data from multiple sensors (and possibly different monitoring techniques) are combined to allow inferences that would not possible based on a single one. An introduction to data fusion for the purpose of wind-turbine condition monitoring is found in [120].

Each monitoring technique has its own strengths and limitations: E.g. oil-based CMS will not detect machine imbalance, misalignment, shaft cracks or resonances as

SCADA-based condition monitoring and data fusion approaches

vibration-based CMS can, while at the same time the latter would not detect water or particles in the lubricant [70]. In this way, different monitoring techniques reveal different details of the monitored part of the wind turbine. Data fusion can enhance the fault-detection performance, but only if the strengths and limitations of the integrated methods are known.

One of the data sources that can contribute to enhancing fault-detection performance is SCADA. While the evaluation of 10min-SCADA data alone was found to be insufficient for condition monitoring, SCADA-*assisted* monitoring can on the contrary provide significant added value:

On the one hand, such added value can be generated by informing the CMS-data interpretation with SCADA signals. Drivetrain vibration-CMS typically require information on the operating point of the wind turbine, such as e.g. rotational speed or electrical power, for condition assessment. Unless this is provided by the SCADA system, additional sensors such as a tachometer must be installed to provide the rotational-speed information. Knowledge of an active yaw allows eliminating misleading excessive vibration data. Adding another example, successful rotor-blade SHM requires the knowledge of the current blade pitch angle [121].

On the other hand, SCADA data can be utilized by merging condition information drawn from this data (using methods as described in Section 3.1) with condition information from other CMS or SHM systems. This is illustrated in Figure 36 for the example case of a wind-turbine gearbox: The diagnosis obtained from the conventional vibration-CMS could be compared with the indications provided by a particle counter, with gearbox temperature data available in the SCADA as well as possibly with observations from a vibration-based rotor-blade SHM, which often measure drivetrain-induced vibrations as in-plane accelerations in the blades. While a first step can be to combine these systems but to have the interpretation (including the «fusion« of information) done by a human analyst, a real data-fusion based monitoring system would merge the information sources by means of quantitative methods and provide an overall, high-certainty diagnosis (and possibly prognosis).

Figure 36: Principle of achieving an enhanced-certainty CMS by means of data fusion from different sources

Examples of existing combinations of monitoring systems are SCADA-integrated CMS, the use of vibration-CMS together with oil particle counters as it is e.g. the case in modern Senvion turbines. A prototype installation of a combined system of a rotor-blade monitoring system (BLADEcontrol) and a vibration-based drivetrain CMS (DMT Windsafe), with the option to include further sources such as oil-CMS or SCADA/control data, was reported in [121]. Another example of a system using multiple sources of condition information is the Condition Diagnostic System described in [122], which is stated to provide fully automated machine diagnostics on vibration levels, load and oil properties, without expert involvement.

4
Cost-benefit analysis of CMS and SHM systems

Opinions with respect to the cost-effectiveness of wind-turbine CMS have varied widely, not least because the cost-optimal solution typically depends on a variety of factors. In Europe, the majority of wind turbines with a rated capacity >1.5MW is equipped with CMS today [10]. In contrary in the US, the attitude towards CMS is still more hesitant.
The trend towards increasing capacity of wind turbines implies

- a higher value of assets,
- higher standstill losses, but also
- increasing failure rates [123],

while the tendency towards more installations offshore and in remote onshore areas leads to

- high access cost and
- long access time.

All these factors tend to increase the benefits of performing condition-based maintenance. However, for project developers and operators of wind turbines, making the right choice among the broad spectrum of available condition-monitoring options is a complex and challenging task.
Figure 37 summarizes the scope of CMS and SHM recommended for multi-MW and offshore wind turbines from the perspective of the insurance company Allianz [20].

Component		AZT Requirements accord. [8]	Extended scope of CMS						
		Vibration	Vibration	Displace-ment	Strain/ Inclination	Oil particle counting	Oil quality	Tempe-rature	Electric parameter
Rotor blades		x 1	•	o	o				
Pitch bearings				o					
Rotor bearing		x		•		• 3	o 3	•	
Gearbox with toothing+bearings	Low Speed	x		o				• 4	
	Interm. Speed	x				•	o	• 4	
	High Speed	x						• 4	
Generator bearings	High Speed	x						•	
	Direct driven	x		• 2				•	
Generator winding	High Speed							o 5	•
	Direct driven							• 5	•
Tower+Foundation		x 1	•	o	o				
Electric Drives	Pitch								o
	Azimuth								o

x = AZT-Requirements, • = recommended Extension, o = additional possible Extension

Foot notes: 1: indirect via low-frequency nacelle/drive train vibrations, 2: Air gap monitoring, 3: if oil lubrication, 4: at bearings, 5: distributed temperature measurement points

Figure 37: Recommended scope of CMS for multi-MW turbines according to [20]

When an investment decision with respect to CMS and SHM systems is to be made, the key question is: Which monitoring systems are cost effective in the given individual constellation of site (wind resource, accessibility), turbine size and turbine reliability? In other words, for which systems and services does the cost benefit over the turbine life exceed the expenses for CMS installation and continuous monitoring services?
An objective answer to this question can be achieved by means of quantitative analysis methods. A quantification of the added value of CBM can be done using a

Cost-benefit analysis of CMS and SHM systems

deterministic or stochastic approach. The deterministic approach uses «best guess« estimates for each parameter. The outcome of such an analysis approach is also a fixed value, without any information about the probability that the real outcome will be equal to this value. In contrast in stochastic approaches, probability distributions are used for the key input parameters in order to take into account the probability that a parameter takes on a certain value. Monte-Carlo simulation is a frequently used method for this type of analyses. As illustrated in Figure 38, the results obtained by means of stochastic approaches are probability distributions describing the possible outcome, which are considerably more informative than a single-value result.

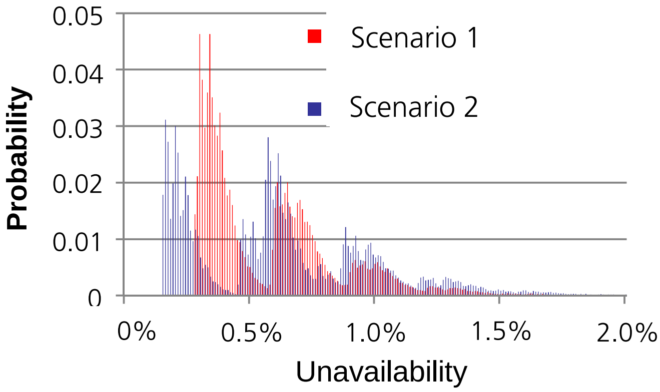


Figure 38: Probability distributions being the typical outcome of a stochastic analysis

In the following, selected examples of cost-benefit analyses for wind-turbine CMS and SHM available in the literature will be presented along with their strengths and limitations. Note that the input data such as CMS cost or feed-in tariffs – and with that also the results - are strongly dependent on the studied case as well as on the time at which the analysis was performed.

4.1 Deterministic analysis

The first example of a cost-benefit analysis using a deterministic approach is taken from [124]. It deals with the specific case of an inner-ring failure of a high-speed shaft (HSS) bearing in the gearbox of a 2MW wind turbine. The calculation together with the input data used is summarized in Figure 39.

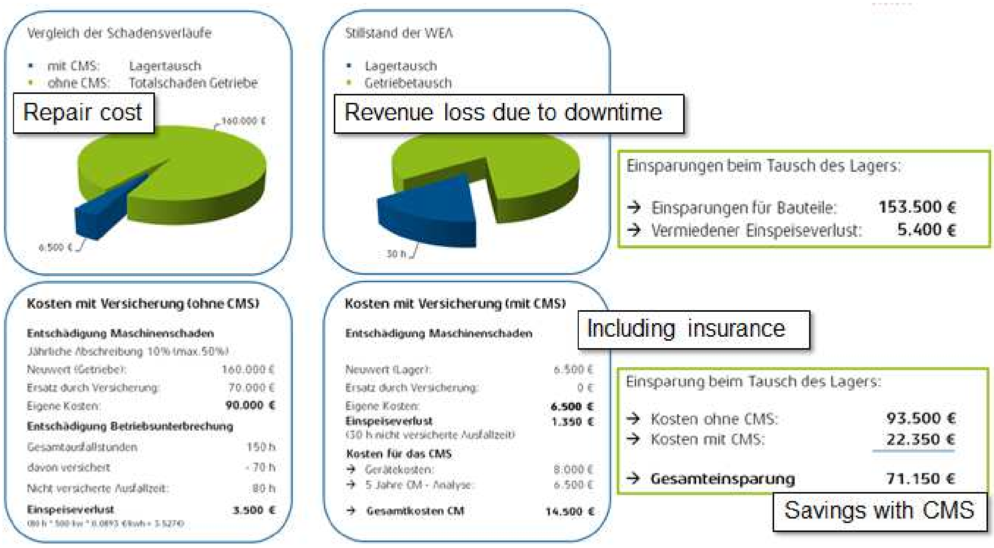


Figure 39: Example of a cost-benefit analysis of drivetrain CMS using a deterministic approach [124]

Cost-benefit analysis of CMS and SHM systems

As shown in the upper part of Figure 39, it is assumed that on a turbine without CMS, the above described bearing failure would lead to a complete loss of the gearbox (replacement cost: 160000€), while with a CMS installed only a bearing replacement would have been required (cost: 6500€). The resulting potential saving in repair cost per failure is therefore 153500€. In addition to the repair cost, the revenue loss due to turbine downtime is taken into account, which is assumed to be 150h for gearbox replacement vs. 30h for HSS bearing replacement. With a capacity factor of 25% and a feed-in tariff of 0.0893€/kWh, this translates into an approximate revenue loss of 6700€ in the first and of 1300€ in the second case. The resulting avoided revenue loss is therefore 5400€. Taking into account both repair cost and lost revenue, the potential saving per HSS bearing failure in the present example is 158900€. This is far beyond the assumed cost of CMS of 14500€ (8000€ investment + 6500€ for 5 years of condition-monitoring service). In the lower part of Figure 39, the example is extended for the case that parts of the costs are covered by insurance.
The advantage of this estimation is its simplicity and limited required input data. On the other hand, it is afflicted with a number of simplifying assumptions, e.g. that the CMS is perfect, and fully neglects the probability that a failure of this type occurs, which limits its significance.

In contrast, the latter factor is taken into account in the second example, taken from [10]. Also this example deals with a gearbox bearing failure. The considered turbine has a rated capacity of 3MW and the analysis is carried out for the two different scenarios of onshore and offshore operation of the turbine.
The key input data as well as the calculation results are summarized in Table 5. Additional assumptions not provided in the table are:

- In presence of a CMS, it is assumed that only a bearing replacement is required, while the complete gearbox must be replaced in the case without CMS.
- Capital cost of the gearbox vs. the bearing: ~170000£ vs. 2500£
- Gearbox vs. bearing replacement: 3 days vs. 1 day of work
- Cost of maintenance by two technicians: 1200£/day (onshore), 1400£/day (offshore)
- The CMS costs around 14000£ for software, transducers, cabling and installation. Regular costs for condition-monitoring services are neglected.
- The CMS is perfect, i.e. it detects 100% of the faults in time and does not trigger false alarms.

Table 5: Cost-benefit analysis of drivetrain CMS using a deterministic approach based on average values, including consideration of the probability of failure [10]

	3 MW onshore WT	3 MW offshore WT
Turbine capacity	3 MW	3 MW
Number of turbines in study	1	1
Capacity factor	0.30	0.27
Price of saleable energy	£50/MWh	£76/MWh
Gearbox failure rate (failures/turbine/year)	0.15	0.20
Downtime per failure (days)	30	41
Failures per year	0.15	0.20
Annual downtime (days)	4.5	8.2
Annual cost of maintenance, A	£180	£840
Annual cost of lost energy, B	£3240	£6998
Annual cost of replacement gearbox, C	£25,500	£34,000
Total annual cost of failure, $T = A + B + C$	£28,920	£41,838
Annual cost of replacement bearings assuming failure is avoided, D	£375	£500
Approximate number of CMSs paid for by early detection of a gearbox fault including bearing replacement $(T - D)/CMS_{cost}$	2	3

WT = wind turbine, WF = wind farm, CMS = condition monitoring system.

According to the results, the drivetrain CMS would have paid off 2-3 times *every year*, indicating that using CMS in this case was clearly cost effective. However, this extreme result must partly be ascribed to the relatively high gearbox failure rates, which are based on overall failure rates of gearbox systems reported in older reliability databases (dominated by turbines built in the 1980es and 1990es). The outcome is also related to the implication that the CMS is perfect and that a CMS-based early detection of faults would fully avoid any gearbox replacement or even the need for workshop repair of gearboxes.
In addition, some systematic error in favor of CMS utilization is introduced by considering solely annual average values instead of the complete turbine life cycle, taking into account the time value of money (which is common practice for economically appraising long-term projects).

4.2
Stochastic analysis

A thorough analysis of the cost benefit of implementing a CMS in gearbox of a 3MW onshore wind turbine is described in [125] [126] [127]. The study is carried out from the point of view of the gearbox manufacturer and is based on comprehensive and detailed field reliability data as well as cost data provided by the gearbox manufacturer. The analysis uses a Life-Cycle Cost (LCC) approach to compare two maintenance strategies: Strategy 1 consists of a combination of time-based preventive maintenance and corrective maintenance, while strategy 2 describes the implementation of condition-based maintenance based on continuous condition monitoring by means of a drivetrain CMS. A stochastic Monte-Carlo simulation model is used to calculate the LCC distribution in case of the two maintenance strategies. It includes Net Present Value calculation in order to take into account the time value of money. A particular focus is set on modeling the detection performance of the CMS, both with respect to the fault-detection performance, the advance-detection period (or P-F interval) and false alarms.
Figure 40 shows the resulting LCC distributions for the case with and without CMS, respectively. It reveals that the risk of high life-cycle costs is considerably reduced by using CMS and that consequently the mean LCC is significantly lower for the condition-based maintenance strategy. Also in this case, the CMS is found to be cost effective, with a payback period of approx. 6-7 years. Not surprisingly, the value added by a CMS increases with the number of failures, i.e. with the unreliability of the wind-turbine components. An important result of the study is that considering the fault-detection performance of the CMS is crucial for a realistic cost-benefit analysis.

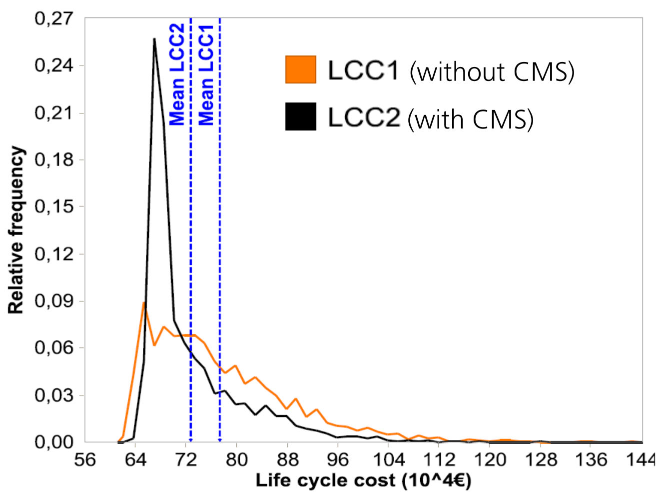


Figure 40: Stochastic life-cycle cost analysis for wind-turbine gearbox maintenance with and without drivetrain CMS [126]

A cost-benefit analysis for rotor-blade SHM based on a stochastic approach can be found in [128]. The case study is carried out for a 5MW offshore wind turbine. Taking the perspective of the turbine operator, the analysis compares the blade maintenance cost over the turbine life-cycle for the cases of performing maintenance based on

Cost-benefit analysis of CMS and SHM systems

- regular visual inspections,
- regular inspections using non-destructive testing tools, and
- permanent monitoring by means of an online SHM system.

Also in this case, the model uses a Life-Cycle Cost approach including a discount rate for future cash flows (Net Present Value concept) and is implemented by means of Monte-Carlo simulation. Figure 43 shows the expected values of the blade maintenance cost. In case of the two inspection-based scenarios, it can be seen that the inspection intervals have a strong impact on the LCC. Nevertheless in the studied case, the use of online-SHM is found to be the optimal strategy (more specifically: it is optimal for crack-initiation rates >0.006 cracks/year and for a crack time to failure <1.1years for the rotor blades).

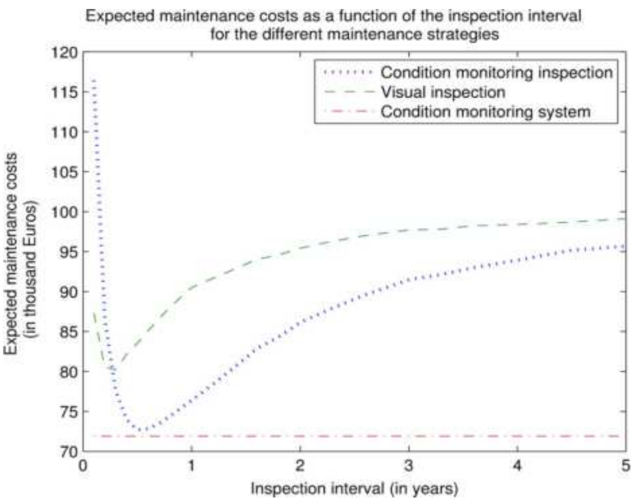


Figure 41: Stochastic life-cycle cost comparison for rotor-blade maintenance based on inspection vs. online-SHM system [128]

4.3 Required input data

Comparing the above examples of cost-benefit analysis using deterministic and stochastic approaches, it can be concluded that the stochastic approaches require a higher analysis effort, but have a considerably better capability to provide realistic results. As a basis for major investment decisions, a comparative stochastic Life-Cycle Cost analysis is therefore the preferable choice.
A sound analysis using this approach requires the following input data:

- detailed field reliability data (component specific; if possible: failure-mode specific)
- cost for corrective maintenance vs. preventive maintenance (for sum of working hours, parts, equipment, logistic costs in case of workshop repair),
- diagnostic time, waiting time (spares lead time, equipment lead time, wind turbine accessibility), repair time
- revenue per generated kWh
- if applicable: insurance cost and payments
- CMS / SHM system cost (installation, annual operation cost e.g. for monitoring services)

- detection performance of the CMS or SHM system under consideration

While all information named in the upper part of the list is typically available at wind-turbine operators, this is often not the case for the last item, covering the questions: What proportion of failures can be detected? Where in the deterioration process can they be detected? What is the risk and cost of false alarms?
Even in case of the above described stochastic cost-benefit analysis published in [126] and [127], see Section 4.2, the detection performance of the CMS had to be modeled based on (potentially optimistic) values provided by the CMS suppliers and based on assumptions.

5 Survey results: CMS utilization and experiences from the operators' perspective

With the objective to identify the current practices and key challenges in wind-turbine CM and SHM, a survey among VGB-associated wind turbine operators (WTO) has been carried out as a part of this project. Six WTO contributed to this survey. The most relevant results obtained are presented in the following. Selected additional results are included in Appendix 7.4.

The survey responses are based on experience from the operation and condition monitoring of a fleet of 2621 turbines. Approx. 20% of these are direct-drive turbines, the rest uses a classical geared drivetrain concept. The fleet did not include any medium-speed, hybrid-drive turbines. It is not distinguished between onshore or offshore wind turbines in this context. Figure 42 characterizes the considered wind turbine fleet with respect to the rated power.

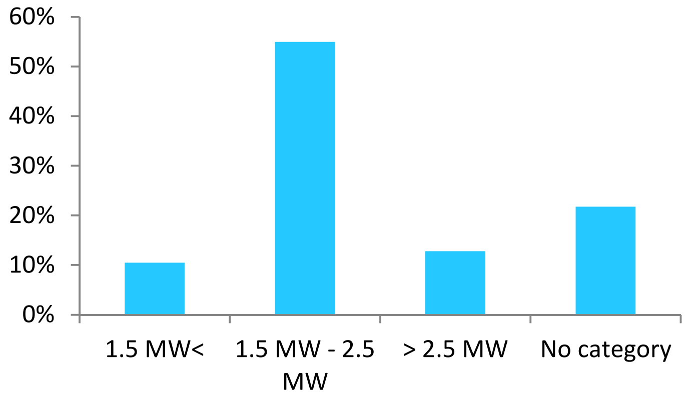


Figure 42: CMS-equipped wind-turbine fleet of which information was provided in the survey

All six operators that contributed to the survey apply vibration-based CMS for drivetrain monitoring. Three of them use SHM for the tower, while only one applies SHM for onshore foundations and offshore support structures. Concerning oil-based condition monitoring, only one operator reported the utilization of oil sensors for CMS proposes.

The suppliers of the CMS are summarized in Figure 43. The systems by SKF (in use at 4 out of 6 WTO) and by Brüel & Kjaer (in use at 3 of 6) are the solutions applied by most of the participating operators. In several cases, the WTO use CMS of different suppliers in their wind-turbine fleet.

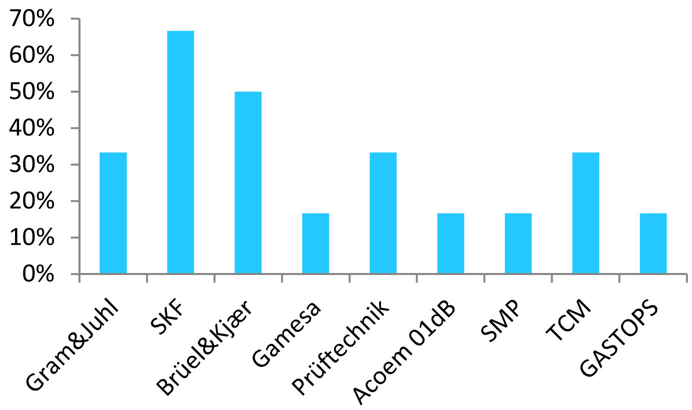


Figure 43: CMS systems in use at the six wind-turbine operators participating in the survey

Survey results: CMS utilization and experiences from the operators' perspective

According to the survey results, the main drivers for applying CMS from the operators' point of view are:

- minimizing the risk of severe damage / excessive repair cost (named by 5 WTO)
- performing cost effective maintenance (named by 4 WTO)
- CMS was standard-equipment of the purchased wind turbines (named by 3 WTO)

Other mentioned factors motivating the use of CMS include increased availability, extension of the wind turbine life span and improved capabilities for performing root-cause analysis and prognosis.

A large agreement is found in the way the CMS & SHM data processing and evaluation is carried out: The results of the survey indicate that all six WTO use the support of external condition-monitoring service centers for data evaluation and assessment. In three cases, an additional assessment is carried out in-house.

Experience with damage detection based on CMS was reported by half of the participating WTO, however only in a single case, a detailed assessment of the different vibration-analysis methods applied for drivetrain CMS could be provided. A second WTO also provided information about the usage of vibration methods and their suitability for diagnosis and residual life prognosis, but without ranking the systems' respective performance. Table 6 summarizes the responses obtained from these two WTO.

Table 6: Vibration-analysis methods in use and assessment of their suitability for fault diagnosis and residual life prognosis (X: indicated by one WTO, XX: indicated by two WTO)

Methods in use	Suitability for fault diagnosis	Suitability for residual-life prognosis
Variance	X	
Crest factor	XX	X
Kurtosis	XX	X
Frequency spectrum analysis	XX	XX
Envelope curve analysis	XX	XX
Cepstrum analysis	X	X

According to these responses, frequency spectrum analysis and envelope curve analysis are considered the most suitable methods for both fault diagnosis and residual-life prognosis, while also crest-factor and kurtosis based methods are considered valuable for diagnosis purposes.
With respect to CMS-data based residual life prognosis, one question in the survey was if such a prognosis of the remaining useful life of monitored components was based on quantitative methods or on subjective judgment of the condition-monitoring analysts.
Three of the participating operators stated that this was performed based on expert judgment. The other three were not certain about how residual life prognosis was carried out. None of the operators reported an analysis based on quantitative methods.

In order to assess the effectiveness of the different CMS in use, a question about their fault-detection performance, both with respect to the portion of faults detected, pre-warning time (P-F interval) and to false alarms, was included in the survey. The fact that only two of the operators could provide an assessment of these factors is an interesting

result in itself, suggesting that evaluations of CMS effectiveness have rarely been carried out so far.
All answers provided on the questions of CMS effectiveness were related to vibration-based systems for drivetrain monitoring. Interestingly, the responses showed a strong deviation: One stated that the CMS system provided numerous false alarms and that the system was able to identify only <25% of the faults leading to a failure. On the other hand, the second operator, having a larger CMS-equipped fleet, responded that their CMS detected >75% of the faults leading to a failure, while the number of false alarms was stated to be very different for CMS of different suppliers. Additional information about the faults detected by CMS in the different WT subassemblies can be found in Appendix 7.4.

Survey results: CMS utilization and experiences from the operators' perspective

Although the utilization of SCADA data for CMS is a topic of interest for the WTO, none of the WTO reported differences or benefits between the utilization of a standalone CMS or a SCADA-coupled CMS. Only two of the six operators use SCADA-system coupled CMS.

In regard to the cost benefits of CMS, one question of the survey was which types of CMS / SHM systems, according to the operators' experience, are cost effective (i.e. that the cost benefit over the turbine life exceeds the installation and monitoring expenses). Five out of six operators answered this question. The distribution of the results is summarized in Figure 44.

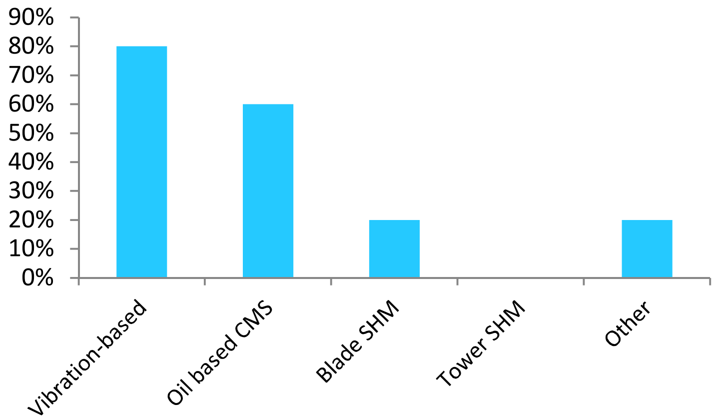


Figure 44: CMS and SHM systems considered to be cost-effective from the WTO point of view

The results show that vibration-based and oil-based CMS are considered the most cost effective approaches today. However, the list of components the operators would like the scope of CMS / SHM to be extended to in the future, see Table 7, shows that most of the WTO consider blades as important components to be monitored.

Table 7: WT components of interest for a future extension of the scope of CMS / SHM systems from the operators' perspective

Wind-turbine operator	Proposed extension of CMS and SHM systems
WTO 1	Blades, oil monitoring
WTO 2	Blades
WTO 3	Blades, tower, generator of direct-drive WT
WTO 4	Blades, offshore support structures
WTO 5	Blades, tower
WTO 6	n.a.

Finally, the survey asked for the main deficiencies and challenges in wind-turbine CM and SHM according the operators' experience. The responses obtained from the six participating wind-turbine operators are listed in the following:

Survey results: CMS utilization and experiences from the operators' perspective

- Interaction among wind turbine manufacturer, operator and CMS provider
- Fault detection based on alarms with high fault detection capability
- Implementation of CM in the maintenance strategies
- Completely functional CMS integrated with the SCADA
- Monitoring of remaining lifetime of failing components taking into account the future loading conditions (low wind or high wind)
- Development of industrial-scale monitoring for the blades
- Accurate monitoring of the low-speed shaft and main bearing
- Monitoring tower fatigue
- Analysis of data (highly detailed information requirements as an input for CMS)

6
Identified challenges and recommendations for future work

Based on the examination of literature, standards and web-based information, on the survey among wind-turbine operators and on a workshop with the VGB working group "Wind Energy", several key challenges related to condition monitoring and condition-based maintenance of wind turbines have been identified. Figure 45 summarizes these and assigns them to the three-step process of CMS utilization for condition-based maintenance, which was introduced in Section 1.2 (cf. Figure 3). In the following, the identified challenges are explained in more detail and recommendations are given on how to tackle them.

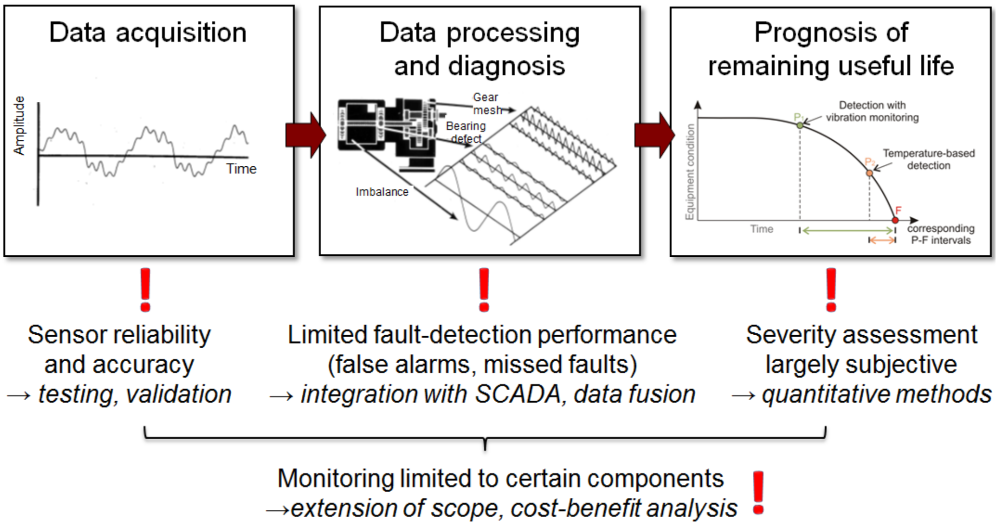


Figure 45: Overview of identified main challenges and solution approaches

One of the major challenges lies in the presently limited reliability and accuracy of both sensors and complete systems for condition monitoring. This is particularly the case for sensors for oil-based monitoring, for rotor-blade SHM systems, but also for certain fields of vibration-based monitoring such as drivetrains of direct-drive turbines or planetary gearboxes in geared turbines. It is worth noting that even in case of certified CMS, the certification covers factors such as instrumentation, system functionality, diagnosis methods and documentation, but it cannot guarantee a certain fault-detection performance. This is due to the fact that also other factors are influencing the detection capability, such as installation, configuration and adjustment of the system (e.g. of alarm thresholds), which must be carried out individually on every turbine type. Therefore, insufficient adjustment of CMS could reduce their fault-detection performance.
Both the suitability of sensors and the fault-detection capability of monitoring systems can be validated by means of testing under defined and repeatable conditions, using e.g. the test infrastructure at Fraunhofer IWES. This includes full-size rotor blade test rigs, the 10MW nacelle test stand «Dynalab« as well as a test center for offshore support structures and structural parts, and will be extended with a full-size main-shaft test bench and a test rig for assessment and validation of sensors for oil-based CMS in the near future (see Figure 46).

Figure 46: Test infrastructure at Fraunhofer IWES: (a) rotor-blade test rig, (b) dynamic nacelle test laboratory «Dynalab«, (c) main-shaft test stand, (d) test center for offshore support structures

Limited fault-detection performance of monitoring systems can cause frequent false alarms, but also missed faults which result in unforeseen failures. A general approach for achieving enhanced fault-detection performance is combining different sensors and monitoring systems. In the simplest case, this can be realized by coupling CMS and SCADA so that the CMS-data evaluation is supported with information about the turbine operation (e.g. active yaw). In a more advanced solution, it could mean the data fusion from multiple sensors and systems with different monitoring focus and capabilities. It is important to note that, as pointed out in Section 3.3, data fusion can enhance the fault-detection performance only if the strengths and limitations of the integrated methods are known. However, according to the literature and the survey results obtained in the present study, little quantitative information describing the detection performance of the different monitoring methods is available to date. Within the wind-power application, data fusion is still at an early development stage, and further R&D effort will be required to step from today’s first «combined« systems to high-certainty, data-fusion based condition-monitoring systems.

As indicated in Figure 45, another challenge is related to the severity assessment of detected faults, i.e. the prognosis of the remaining useful life, which determines the urgency of maintenance measures. In case of drivetrain CMS, this is typically performed based on subjective expert judgment. Quantitative approaches for CMS-data based residual-life prognosis should be further developed and tested in order to allow their implementation in commercial CMS.

Another challenge related to wind-turbine condition monitoring is that the monitoring is limited to certain components. Further R&D efforts are required to develop reliable monitoring solutions for those components, in which an early detection of faults can prevent costly damages or long downtimes. According to the survey among wind-turbine operators, there is a particularly strong interest in SHM for rotor blades. Other components named by the operators to be of interest for a future extension of the scope of CMS / SHM systems include towers, offshore support structures, generators in direct-drive turbines, low-speed shafts and main bearings. Another component for which an effective CMS would be highly desirable is the power converter, not only because of its high failure rates, but particularly because its failure is a common cause of fire in wind turbines (see e.g. [73]). Methods for condition monitoring of power converters are the subject of ongoing research in the Fraunhofer Innovationscluster «Leistungselektronik für regenerative Energieversorgung« [129].

Identified challenges and recommendations for future work

In view of the increasing variety of available condition-monitoring systems, it remains a complex task for project developers and wind-turbine operators to make the right choice among these. There is a broad agreement in the literature that vibration-based drivetrain CMS is cost effective on multi-MW turbines. However in general, the cost benefit of monitoring systems depends on a variety of factors, such as the turbine size, the reliability of the components of interest, the wind resource and the accessibility of the site.
A cost-benefit analysis using the relatively simple deterministic approach can provide a rough estimate of the value added by a CMS. However, as a basis for major investment decisions and to allow assessing also the risk associated with different strategies, a stochastic life-cycle cost analysis is recommendable. In any type of cost-benefit analysis, the failure rates of the components considered for monitoring should be taken into account. Another factor, which has a strong impact on the result and should therefore be included in the analysis, is the fault-detection performance of the monitoring system under consideration.

It can be concluded that quantitative information on the fault-detection performance of CMS is a prerequisite for both the implementation of effective data fusion and for a sound cost-benefit analysis. However, as stated above, the fault-detection performance (namely the detectability of different failure modes and the respective P-F interval) is mostly unknown.
Consequently this is a relevant field for future work: Bringing together historical CMS / SHM data (or diagnosis reports from condition-monitoring service providers), maintenance records and possibly inspection reports from a large fleet of turbines including a variety of monitoring systems, it should be investigated: Which failure modes were detected by means of the CMS or SHM systems? How sensitive was the monitoring system to the damage, i.e. how long before failure was a fault detected? How many false alarms were generated? But also: Which damages or failure modes were not detectable with today's instrumentation and diagnosis methods? Such a data-based, quantitative assessment of the condition-monitoring techniques and systems in use is considered being of high practical value, provided that it is performed on a sufficiently large data basis as it could e.g. be jointly provided by VGB-associated wind-turbine operators.

Finally, from the perspective of the wind-turbine operators, there is a clear interest in condition-monitoring approaches which are simpler and require less detailed turbine-specific information for diagnosis than the present commercially available CMS and SHM systems. In line with this, using SCADA signals for condition monitoring is considered very attractive, as a vast amount of signals is measured in the turbine for control purposes already. However, according to the results of this study, the typical 10min-averaged SCADA data is not suitable for standalone condition monitoring. This is not surprising in view of the information loss the 10min-averaging procedure is afflicted with. In contrast, it is expected that «real-time« SCADA-signals have a considerably higher information value, which could be used for the purpose of condition monitoring. In a recent VGB project, a so-called Asset Connection Box was developed. This is capable of providing wind-turbine operators with SCADA signals in a resolution of seconds. Investigating the potential of such high-resolution SCADA data for condition monitoring is considered another important subject for future work.

7 Appendix

7.1 Commercially available products for CMS and SHM of wind turbines

The following tables provide an overview of the commercially available CMS and SHM systems for wind turbines. The tables summarize the different types of products including vibration-based and oil-based CMS for the drivetrain as well as structural-health monitoring for rotor blades and support structures. The product list has been created based on information from [10], [43], [75], [83], [92], [130] and input from Allianz Center for Technology. The descriptions of the products are based on information collected from data sheets, product brochures and product-related websites and in discussions with the providing companies’ sales departments.

Products for vibration-based CMS for wind turbines

Company	Product	Type of product	Type of sensor	Description	Analysis method
ABS Consulting	Wind Turbine In-Service	Condition monitoring solution	Accelerometers	System performing multiple analysis based on inspections, vibration sensors and SCADA data to plan and carry out maintenance activities	Detection of faulty components by trend analysis identifying abnormal deviations; the system includes a maintenance inspection program to claim defects, problems or non-conformities
ACIDA GmbH	OMM System	Condition monitoring solution	Accelerometers, torque measurements	CMS with data-based management for components diagnosis	Vibration-based analysis combined with static and dynamic load analysis
ACOEM	OneProd Wind	Condition monitoring solution	Accelerometers, oil debris particle counter, generator rotational speed, supplied power, wind speed	System for vibration and oil particles analysis; the system allows diagnosis and early fault detection with remote access to all data; it uses trend analysis including an alarm system and indicates the turbine condition with a color code; the system allows the creation of reports in different formats	System is based on trend analysis and alarm system taking into account only data registered under similar conditions; a method to detect failure modes in difficult locations within the turbine is proposed to identify abnormal shocks and avoid false alarms
Bachmann	Omega-Guard	Condition monitoring solution	Accelerometers	Condition monitoring system for remote diagnostics with possibility to integrate further signals; color-based alarm system	Amplitude spectra analysis, envelope analysis, trend analysis and acoustic monitoring possible
Brüel & Kjaer	Brüel & Kjaer VibroSuite	Software	--	Software allowing diagnosis and alarm management; the system can be owned by the client for hosting, processing and analyzing data in-house; allows root-cause analysis and early fault detection	Vibration and acoustic emission analysis with time domain and FFT frequency analysis; additional temperature monitoring
	Brüel & Kjaer Vibro	Condition monitoring solution	Accelerometers, tachometer	Complete solution including monitoring system, a host-based alarm management and diagnostic software and data base; the system can be used as a turnkey solution, a customer-owned solution or a customer-owned solution with Brüel & Kjaer services	Time wave forms with high resolution are extracted from the sensors to carry out FFT frequency analysis

Products for vibration-based CMS for wind turbines (cont.)

Company	Product	Type of product	Type of sensor	Description	Analysis method
DMT	Windsafe	Condition monitoring solution	Accelerometers, acoustic emission sensors	Automation platform for vibration analysis and condition monitoring; can be integrated with the control unit	Based on the measurement of acoustic emissions, vibrations and shock impulses, amplitude spectral analysis, envelope analysis and order analysis is possible
EC Systems KAStrion project	VIBstudio WIND	Condition monitoring solution	Accelerometers	System performs data analysis, storage and data selection; an automated generation of analysis and thresholds is performed by the software including an alarm system; the system allows storing long-time signals improving the frequency resolution	Based on the machine kinematics during the system configuration, a reduction in the implementation and launching of diagnostics is achieved; reference periods are used to gather data to configure the machine operational states
Eickhoff GmbH	E-GOMS	Condition monitoring solution	Accelerometers, acoustic emission sensor, tachometer	Condition monitoring system with alarm system included	Vibration signal analysis with alarm system for fault detection
FAG Industrial Services GmbH	WiPro	Condition monitoring solution	Accelerometers, sensors for temperature, pressure, displacement, speed, force	Early warning system for fault detection; online measurements with remote access; system can be used in three models including full service, costumer specific training of employees, partial or full monitoring of turbines by the wind farm operator	Measurement value for vibration and RMS, peak to peak, crest factor analysis; Speed-dependent tracking of frequency bands in RMS demodulation including speed-variable alarm level; the system also offers the possibility to integrate oil quality and particle content indicators as well as stationary torque measurements
Gamesa Eolica	SMP-8C	Condition monitoring solution	Accelerometers	Predictive maintenance system for early fault detection; can be integrated within the control system	Vibration analysis based on 8 measurement points
GE Energy and Bently Nevada	Ascent	Software	--	Software storing and analyzing the vibration data from measurement instruments and devices; system allows viewing spectra, waveforms and trends including band alarms; system generates reports in one data base	Accelerometers are used to perform frequency and time domain analysis e.g. averaged crest factor, envelope and FFT analysis; software comprises a large library of bearings and their associated fault frequencies

Products for vibration-based CMS for wind turbines (cont.)

Company	Product	Type of product	Type of sensor	Description	Analysis method
GE Energy and Bently Nevada	ADAPT.wind	Condition monitoring solution	Accelerometer, oil debris particle counter	Monitoring solution including transducers, monitor units and software with centralized management; system can be integrated with the SCADA system; system has alarm, diagnostic, analytic and reporting capabilities for monitoring and trending with high resolution	Analysis based on the planetary cumulative impulse detection algorithm to detect and trend the passage of debris particles through the planetary gearbox; a dynamic energy index (DIE) is used for spectral energy calculations and early fault detection
	Condition Based Maintenance System (CBM)	Software	--	Monitoring and diagnostics of drivetrain parameters such as vibration and temperature based on ADAPT.wind; used only for 1.5 MW wind turbines	Alarming system based on the vibration signals; GE Monitoring and Diagnostics performs the analysis, issues a report and recommends the course of action
	System.1	Dashboard	--	Provides a secure user access for monitoring equipment; interface and support of the workflow	System applies analytics to instrumentation and software alarms to help users to easily identify faulty conditions in their equipment and instrumentation
Gfm mbH	Peakanalyzer	Condition monitoring solution	Accelerometers, tachometer	Vibration analysis with included alarm system; particle counter can be installed with the system	Analysis of vibration signals with envelope, spectra and order analysis
Gram & Juhl A/S	TCM (Turbine Condition Monitoring)	Condition monitoring solution	Accelerometers	System provides diagnosis based on alarms and fault signatures; takes into account the type of turbine and offers an online ticket system with a customer portal	System is based on health indicators which comprise a numbering system to signalize an alert; chronological timeline is aligned with the turbine health indications; system delivers status and recommended actions in regard to the condition of the turbine
Hainzl	HAICMON	Condition monitoring solution	Accelerometers	System provides a very flexible approach in selection of sensors and monitoring hardware based on a Condition Monitoring Unit (CMU); performs data acquisition and local intermediate storage	System performs time-domain analysis (e.g. minimum, maximum, RMS, crest factor), and frequency-domain analysis (e.g. envelope analysis, cepstrum) to identify faulty components

Products for vibration-based CMS for wind turbines (cont.)

Company	Product	Type of product	Type of sensor	Description	Analysis method
ICONICS	Wind AnalytiX	Software	--	Web-based diagnosis system based on energy inefficiencies to provide fault-cause analysis for improving maintenance activities	System allows analysis of the system performance, load profiles, weather data analysis and system benchmarking; creates automatic reports based on date, time, value, alert or on demand
IsTec GmbH	WKA-COMOS	Condition monitoring solution	Accelerometers	CMS for diagnosis based on time-frequency methods to select the most relevant and predominant peaks in the frequency domain	Time and frequency domain analysis, amplitude spectrum, envelope analysis, RMS values, crest factor, kurtosis, etc.
Mita-Teknik	WP4086	Condition monitoring solution	Accelerometers	System based on vibration analysis; alarms set for both time and frequency domains based on predefined thresholds; operational parameters recorded alongside with vibration signals/spectra and complete integration with SCADA systems	System performs real-time sample calculation and storage of vibration signals and operating conditions; analysis in the time and frequency domain, complemented with an alarm system and additional storage of raw data
Moventas	Condition Management System (CMaS)	Condition monitoring solution	Accelerometers, sensors for temperature, pressure, rotational, speed, oil condition and wear debris	Integral system to monitor temperature, vibration, load, pressure, speed, oil aging and oil particle count; mobile interface available	Gearbox condition monitoring based on vibration and oil particles analysis; fault detection in the cooling system or lubrication system based on temperature analysis and oil analysis; detection of misalignment and friction problems by vibration analysis, of wear by means of particle counters; torque and rotational speed measurements provide details about the operating conditions
National Instruments	Distributed Condition Monitoring System	Data acquisition system	--	System possesses 16 channels for accelerometers, 4 for proximity sensors, 8 for tachometers; offers additionally the measurement of various signals e.g. temperature, strain and voltage	System consists of a Field Programmable Gate array for signal processing, data logging, control and regulation; integration of analysis functions of LabVIEW possible to perform vibration analysis including spectra analysis, order analysis among others

Products for vibration-based CMS for wind turbines (cont.)

Company	Product	Type of product	Type of sensor	Description	Analysis method
Nordex	CMS	Condition monitoring solution	Accelerometers	Fingerprint approach; actual values automatically compared by frequency, envelope and order analysis, with the reference values stored in the system	Time-domain based on initial 'fingerprint'; Comparison of the ideal and actual situation to identify differences
NRG Systems	TurbinePhD (Predictive Health Monitoring)	Condition monitoring solution	Accelerometers	Vibration analysis tool based on a color system to indicate the severity of a developing fault	Vibration in the time and frequency domain for fault identification; system performs a prognosis of the monitored components to plan maintenance and reduce downtime; residual life prognosis based on a physics-of-failure model
OrtoSens - Advanced Wind Turbine Monitoring	OrtoSens	Condition monitoring solution	Acoustic emission sensors	Condition monitoring method based on the human auditory perception; system detects abnormal vibration with high sensitivity	System identifies interference patterns that are related to damage or worn elements within the drivetrain; system uses Auditory Perceptual Pulse analysis (APPA)
Prüftechnik	VIBGUARD	Condition monitoring solution	Accelerometers, tachometer	CMS for diagnosis with alarm management system and capability for gearbox modeling	Analysis is performed with two time signals or envelope curve analysis; registers up to 8 characteristic overall values, such vibration severity and bearing condition
Romax Technology Ltd. and Gram & Juhl	InSight intelligent Diagnostic System (iDS)	Software	--	Software integrating CMS and SCADA data to perform analysis and create predictive life models; analysis is hardware independent	Failure analysis and drivetrain lifetime models for prognosis; system provides data analysis of CMS, SCADA, maintenance logs, lubrication analysis data
Siemens	SIPLUS CMS4000	Condition monitoring solution	Dependent on the application	Condition monitoring tool to perform machine diagnosis; monitoring of analogue and binary signals can be performed including the recording of high dynamic processes with a sampling rate over 40kHz	System uses software called X-Tools for data treatment, visualization and evaluation of data; includes analysis in the frequency domain

Products for vibration-based CMS for wind turbines (cont.)

Company	Product	Type of product	Type of sensor	Description	Analysis method
SKF	WindCon 3.0	Condition monitoring solution	Accelerometers, tachometer	Lubrication, blade and gearbox oil systems can be remotely monitored through SKF @ptitude observer software; WindCon 3.0 collects, analyzes and compiles operating data that can be configured to suit management, operators or maintenance engineers	FFT frequency domain analysis, envelope analysis, time-domain analysis, can be coupled with oil and blade monitoring techniques
SwanTech	Swanguard	Condition monitoring solution	Acoustic emission sensors	CMS for diagnosis of the drivetrain based on acoustic emissions and high frequency analysis	Stress wave analysis
Winergy	Condition Diagnostics System (CDS)	Condition monitoring solution	Accelerometers, oil debris particle counter	System analyzes signatures in selected operating states e.g. vibration levels, load and oil to establish baselines, enables trending and comparison, gives diagnostics, forecasts and recommendations for corrective action; automatic fault identification	Deviations from baseline are associated with potential faulty signatures which are collected and stored to be further used to define a deviation by fault symptom strength; results are used to predict fault development generating an automatic diagnosis report with recommendation

Products for oil-based CMS for wind turbines

Company	Product	Type of product	Description and analysis method
Argo Hytos	LubCos H2O	Sensor	Sensor delivers information about lubricant temperature and water saturation; humidity measurements
	LubCos H2O plus II	Sensor	Monitoring of oil quality based on oil electrical parameters; oil quality, oil humidity and temperature
	LubCos Visplus	Sensor	Oil properties sensor measuring viscosity, dielectric constant and temperature
Bosch Rexroth	Particle Monitor and Water Content Sensor	Sensor	Sensor technology to measure water content and particles in oil
CJC	Oil Contamination Monitor	Sensor	Measurement of oil quality based on particle content; measures according to ISO 4406:1999
CMC Instruments GmbH	WearSens	Sensor	Measurement of the conductivity to monitor oil quality; dielectric constant and temperature also obtainable
Eaton	CSM 01 - Contamination Sensor Monitor	Sensor	Used as a stationary or mobile condition monitoring system; analysis of the amount and size of solid contamination in hydraulic and lubrication fluids
FAG	Wear Debris Check	Sensor	Monitoring the amount of particles in oil; differentiation into ferrous and non-ferrous metals; detection of particles: ferrous > 50 microns, non-ferrous > 150 microns
	Wear Debris Check (MkII)	Sensor	Detection and classification of wear in bearings, cages and gears; quantity of ferrous / non-ferrous particles and size indication
GasTOPS	MetalSCAN Debris Monitor	Sensor	Online measurement of particles for different sizes of metallic particles (ferrous and non-ferrous), minimum detectable: 50 microns
HYDAC International	AquaSensor AS1000	Sensor	Sensor delivers information about lubricant temperature and water saturation
	HYDACLab	Sensor	Monitoring of oil quality based on oil electrical parameters including temperature
	Contamination Sensor CS1000 series	Sensor	Monitoring of oil quality based on particle counting; measurement of contamination level based on ISO 4406
	Metallic Contamination Sensor MCS 1000 Series	Sensor	Permanent monitoring system for wear debris; solid contamination level, ferrous particles > 70 microns, nonferrous particles > 200 microns
Lubrigard	Dielectric Sensor	Sensor	Measurement of oil quality based on dielectric constant and measurements
Macom Technologies Ltd	TechAlert 10 TechAlert 20	Sensor	Inductive sensor to count and size ferrous and non-ferrous debris in circulating oil systems; inductive or magnetic oil debris particle counter

Products for oil-based CMS for wind turbines (cont.)

Company	Product	Type of product	Description and analysis method
Measurement Specialties	Fluid Property Sensor	Sensor	Measurement of different oil parameters; monitoring of viscosity, density, dielectric constant and temperature of the oil
Pall Industrial Manufacturing (Pall Europe Ltd)	PCM200	Sensor	Fluid cleanliness monitor reports test data in real-time; can be permanently installed or portable
Pall Corporation	Pall Water Sensor WS10	Sensor	Sensor delivers information about lubricant temperature and water saturation; returns the water content information in percent saturation
Parker Kittiwake	ANALEXrs Online Sensor Suite	Condition monitoring solution	Combined module with different sensors to monitor the oil condition and particle content; measurement of ferrous debris, oil quality index scale, relative humidity
	Oil Condition Sensor	Sensor	Detects changes caused by water and acid levels with a dielectric sensing technology completed with smart algorithms to provide trend analysis
	Moisture sensor	Sensor	Online measurement of relative humidity in the oil with additional temperature measurements
	Total ferrous debris sensors	Sensor	Online measurement of wear debris density; ferrous density (ppm)
	Metallic wear debris sensor	Sensor	Online measurement of wear debris. Quantity of ferrous and non-ferrous metals
Poseidon Systems	SmartMon-Oil	Sensor	Monitoring of oil quality based on oil electrical parameters; indication of water contamination, additive depletion, soot level, incorrect fluid
Smith Industries	Inductive Debris Monitor	Sensor	Measurement of ferrous and non-ferrous metallic debris; minimum detectable particle size: 50 microns
Spectro INC	Fluid Scan Q1100	Sensor	Offline measurement of different oil properties; measurement of water content, TAN, oil oxidation
Tan Delta	Oil Quality Sensor	Sensor	Monitoring of oil temperature, oxidization, TAN,TBN, viscosity, water content, soot by means of oil quality index to quantify oil degradation
Vickers Tedeco	Quantitative Debris Monitor (QDM)	Sensor	Measurement of wear debris; creates a magnetic flux field, which detects the presence of debris

Products for SHM of wind-turbine rotor blades

Company	Product	Type of product	Type of sensor	Description and analysis method
Baumer	Vision-System ZHDM series	Sensor	Laser-based sensors	Measurement of the blade deflection and torsion for individual pitch control; additional ice detection capability
	Strain sensors DSRT series	Sensor	Strain gauges for load monitoring	Measurement of blade strain
Bosch Rexroth (IGUS ITS GmbH)	BLADEcontrol	Condition monitoring solution	Accelerometers	Accelerometers bonded to the blades; hub unit transfers data wirelessly to nacelle; blades assessed by comparing spectra with those stored for reference conditions; measurement and analysis data stored centrally, blade condition displayed using a web browser
FiberSensing	FS2500	Condition monitoring solution	Fiber optic strain	BraggSCOPE measurement unit designed for industrial environments to interrogate up to 4 Fiber Bragg Grating sensors; acceleration, tilt, displacement, strain, temperature and pressure measurable
FOS4X	Fos4IceDetection	Condition monitoring solution	Accelerometers, bending moment	Ice detection system based on fiber optic measurements; 2D acceleration measurements with optional bending moment measurements
	Fos4blade R&D	Condition monitoring solution	Sensor net installation	Strain measurements for rotor blades with optical fiber sensors; used for blade validation e.g. measurement of flutter at the blade tip
	Fos4Blade	Condition monitoring solution	Fiber optic strain sensor	Measurement of dynamic loads on rotor blades; strain measurement at the blade root and optional vibration measurements; analysis of parameters e.g. maximal loading, blade bending moment, hub moment, order analysis for blade monitoring
HBM	Deflection sensor	Sensor	Force transducer, inclination sensors	Measurement of blade deflection by a glass fiber reinforced string extended along the blade; information recorded by two orthogonal force transducers to estimate deflection; correlation of blade amplitude movement with inclination at measuring point of the sensor
LM Wind Power	LM Blade Monitoring System	Condition monitoring solution	Fiber optic sensor	System measures strain based on sensors embedded in the rotor blade, which is determined for calculating the absolute torque in the blade; system offers a data processing software for costumer use
Moog Insensys Ltd.	RMS (Rotor Monitoring System)	Condition monitoring solution	Fiber optic strain sensor	Load measuring system for installation in turbine hub; can be designed-in during turbine manufacture or retrofitted; monitors blade icing, imbalance, damage and lightning strikes

Products for SHM of wind-turbine rotor blades (cont.)

Company	Product	Type of product	Type of sensor	Description and analysis method
Pepperl+Fuchs	Inclination-acceleration sensor F99	Sensor	Inclination angle measurement sensor	Measurement of the inclination in two orthogonal directions
SCAIME	SCAIME Condition Monitoring Solutions	Condition monitoring solution	Fiber optic sensor	Analysis of strain to define the condition of the blade; system possesses an integrated remote server and an alarm system based on the blade loading which can be used as input for pitch control; system performs an estimation of residual life and includes an ice detection monitoring system
SKF	SKF Blade Monitoring System	Condition monitoring solution	Laser-based sensors	Measurement of the rotor condition by monitoring the blade deflection (system under development)
Wölfel	SHM.Blade + IDD.Blade	Condition monitoring solution	Structural noise, acceleration and temperature sensors	SHM.Blade detects structural changes in the blade based on a reference condition; IDD.Blade detects ice formation on the blade; learning phase required

Products for SHM of wind-turbine support structures

Company	Product	Type of product	Description and analysis method
Baumer	GAM900S	Condition monitoring solution	Monitoring of tower vibration and shocks; monitoring of the vibration with alarm triggering system
HBM	Optical fiber strain sensors and optical rosette	Sensor	Bragg-Gitter sensors for strain measurement on the blades, tower, offshore support structures; proportional method based on the correlation between vibration velocity and maximum dynamic strain
Hermos	Hermos-IAB Condition-Monitoring-System	Condition monitoring solution	Monitoring of the foundation for onshore wind turbines; movement of the foundation in vertical and horizontal direction
preusser-messtechnik GmbH	StrainBUSter and strain gauges	Sensor and data acquisition system	Strain gauges sensor and data acquisition system supplier for tower monitoring; strain measurements for post-analysis
SCAIME	SCAIME Condition Monitoring Solutions	Condition monitoring solution	Monitoring of deformations and oscillation by sensors measuring bending moments at different tower heights; monitoring of the foundation is based on calculations of loads, soil pressure and grouting
Strainstall	Crackfirst	Sensor	Fatigue sensor for welded joints in the tower and support structure; record of cumulative fatigue damage based on crack presence and expansion
Zensor	PermaZEN	Sensor	Sensor for corrosion monitoring on offshore support structures
	Zensor foundation monitoring	Condition monitoring solution	Integrated, autonomous system for monitoring offshore wind-turbine support structures: monitoring of corrosion activity, grout condition, displacements and deformations, dynamic behavior (natural frequencies, damping etc.) of structures and components, stresses and strains, cathodic protection, dissolved species, oxygen levels in air, temperatures and pressures; all data is continuously collected and translated into periodic reports and alarm signals

7.2
Standards and guidelines related to condition monitoring

Standard, guideline	Title, subject	Wind-power specific	Not wind-power specific
FGW Instandhaltungs-richtlinie TR7	TR7: Instandhaltung von Kraftwerken für Erneuerbare Energien (Maintenance of power plants for renewable energy)	x	
GL-IV-4	GL Guideline for the Certification of Condition Monitoring Systems for Wind Turbines, GL-IV-4, Edition 2013	x	
IEC61400-25-6	Wind turbines - Logical node classes and data classes for CM	x	
ISO 10816 (DIN)	Mechanical vibration - Evaluation of machine vibration by measurements on non-rotating parts		x
ISO 10816-21	Mechanical vibration - Evaluation of machine vibration by measurements on non-rotating parts - Part 21: Horizontal axis wind turbines with gearbox; based on VDI 3834	x	
ISO 13372	Condition monitoring and diagnostics of machines - vocabulary		x
ISO 13373-1 (DIN)	Vibration condition monitoring - General procedures		x
ISO 13373-2 (DIN)	Condition monitoring and diagnostics of machines - Vibration condition monitoring - Part 2: Processing, analysis and presentation of vibration data		x
ISO 13374	Condition monitoring and diagnostics of machines - Data processing, communication and presentation		
ISO 13379-1	Condition monitoring and diagnostics - General procedures		x
ISO 13381-1: 2004-11	Condition monitoring and diagnostics of machines - Prognostics - Part 1: General guidelines		x
ISO 17359:2011-09 (DIN)	Condition monitoring and diagnostics of machines - General guidelines		x
ISO 7919 (DIN)	Mechanical vibration - Evaluation of machine vibration by measurements on rotating shafts		
ISO/DIS 13379-2	Condition monitoring and diagnostics of machines - Data interpretation and diagnostics techniques - Part 2: Data-driven applications		x
ISO/CD 16079-1/2	Condition monitoring and diagnostics of wind turbines - Part 1: General guidelines, Part 2: Monitoring the drivetrain	x	

Standard, guideline	Title, subject	Wind-power specific	Not wind-power specific
VDI 3832	Measurement of structure-borne sound of rolling element bearings in machines and plants for evaluation of condition		x
VDI 3834 Part 1	Measurement and evaluation of the mechanical vibration of wind energy turbines and their components – Part 1: Onshore wind energy turbines with gears (Note: not for condition monitoring, but vibration assessment)	x	
VDI 3839	Instructions on measuring and interpreting the vibration of machines		x
VDI 3841	Vibration monitoring of machinery - Necessary measurements		x
VDI 4550	Darstellung von Analyseergebnissen in der Schwingungstechnik (under preparation)		x
VDI 4551	Strukturüberwachung und Beurteilung von Windenergieanlagen und Plattformen (under preparation)	x	

7.3 Questionnaire used within the survey on user-experiences with respect to wind-turbine CMS and SHM

Questions:

1a) What is the (approx.) number of wind turbines in your fleet equipped with online condition-monitoring systems (CMS) or online structural-health monitoring (SHM) systems?

Answer:
__ turbines rated <1.5MW,
__ turbines 1.5 MW … 2.5 MW,
__ turbines rated >2.5 MW

1b) Please specify roughly the portion of the different drive-train topologies in your turbine fleet:

Answer: __% direct-drive, __% hybrid concept, __% classical geared concept

2) Which components of the wind turbines in your fleet are monitored by means of online-CMS or online-SHM systems?

Answer:
( ) drive-train (main bearing, gearbox bearings and gears, generator bearings)
( ) rotor-blades
( ) tower
( ) foundation (onshore)
( ) support structure (offshore)
( ) others (which?)

3) CMS / SHM systems of which types and brands do you use in your wind-turbine fleet? Which are your experiences with each of these with respect to fault-detection capability? (In case of different monitoring systems used, please provide the answers for each of them.)

System 1

Manufacturer/brand:	
Monitored wind-turbine component:	
Type of monitoring system (e.g. vibration-CMS, particle counter for gearbox oil, …):	
Detection certainty with respect to false alarms (A: no false alarms,…, E: many false alarms):	
Detection certainty with respect to fault-detection capability (1: no missed faults, 2: 75%…95% of faults detected, 3: 50%...<75% of faults detected, 4: 25%...<50% of faults detected, 5: <25% of faults detected):	
Average length of the P-F interval (for illustration, see Figure 1):	

System 2
…

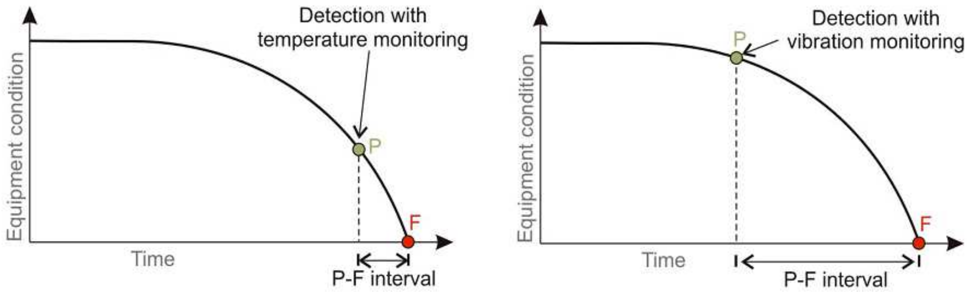


Figure 1: Intervals between detection of a potential failure (initiating fault) P and functional failure F (causing turbine standstill) for vibration-based vs. temperature-based condition monitoring of bearings

4) Which types of sensors are used by the CMS / SHM systems installed in your fleet and in which positions are these installed? (In case of different monitoring systems used, please provide the answers for each of these.)

Answer:

System 1
CMS / SHM system:
Type of sensor:
Sensor position(s):

System 2
…

5a) Which type of faults did you already identify in the following components by using CMS /SHM?

Monitoring approach	**Mechanical drivetrain**		
	Main shaft, main bearing	Gearbox (gears, shafts, bearings)	Lubrication system
Vibration-based			
Oil-based			
SCADA-based			
Other:			

Monitoring approach	**Electro-mechanical / electrical components**		
	Generator assembly	Frequency converter	Transformer
Vibration-based			
Oil-based			
SCADA-based			
Thermography			
Other:			

Monitoring approach	Structural components			
	Blades	Tower	Foundation (onshore)	Support structure (offshore)
Vibration-based				
SCADA-based				
Displacement-based				
Strain-gauge-based				
Modal analysis				
Laser-based				
Thermography				
Acoustic emission				
Other:				

5b) Did you use a combination of the previous or additional approaches? If yes, which ones?

Answer:( ) no ( ) yes (which?)

6a) Are the CMS / SHM systems used in your fleet standalone systems without coupling to the SCADA or do these utilize SCADA signals? (In case of several monitoring systems in use, please answer for each of these.)

Answer: ( ) standalone CMS / SHM ( ) CMS / SHM coupled to SCADA

6b) In case you have both standalone and SCADA-coupled systems in use, have you observed differences in their fault-detection capabilities?

Answer:( ) no ( ) yes (which?)

/) The CMS / SHM data processing and evaluation is carried out:

Answer: ( ) by an external condition-monitoring service center ( ) in-house

8) In the evaluation process of your CMS / SHM data, is the prognosis of the remaining useful life of the monitored component based on quantitative methods or on subjective judgment of the CM analysts?

Answer: ( ) quantitative methods, ( ) subjective expert judgment, ( ) don’t know

9) According to your experience, how well does the real component condition found during inspection in the field match with the CMS-based condition assessment? (In case of different monitoring systems in use, please provide an answer for each of these.)

Answer (1: excellent, 2: good, 3: satisfactory, 4: acceptable, 5: poor):

10) From your experience, which analysis methods are used in your vibration-based CMS (1: used always,…, 5: not used)? How effective are these methods for fault diagnosis and residual-life prognosis (1: excellent, …, 5: poor)?

Analysis method	Usage*	Suitability for fault diagnosis	Suitability for residual-life prognosis
Analysis in the time domain			
Time-domain averaging			
Autocorrelation			
Analysis by means of parameters			
Variance			
Crest factor			
Kurtosis			
Analysis in the frequency domain			
Frequency analysis			
Envelope curve analysis			
Order analysis			
Cepstrum analysis			
Pre-whitening			
Cyclo-coherence analysis			
Spectral kurtosis			
Kurtogram-based filtering			
Time-frequency methods			
Short-term Fourier Transform (STFT) analysis			
Wavelet analysis			
Wigner-Wille distribution			
Other			
…			

*NA: Not applicable, UN: unknown

11) Which analysis software do you apply for processing and evaluating CMS / SHM data?

12) What is your primary motivation for using CMS in your wind-turbine fleet?

Answer:( ) minimizing the risk of severe damage / excessive repair costs

( ) cost-effective maintenance
( ) reduced insurance cost
( ) CMS was standard-equipment of purchased wind turbines
( ) legal / regulatory requirements
( ) other (which?)

13) According to your experience, which types of wind-turbine CMS / SHM systems are cost effective (i.e. the cost benefit over the turbine life exceeds the installation and monitoring expenses)?

Answer: ( ) vibration-based drivetrain CMS
( ) oil-based CMS (please specify the type)

( ) rotor-blade SHM (please specify the type)
( ) tower SHM (please specify the type)
( ) other (please specify)

14) Which are the key deficiencies / challenges in wind-turbine CM and SHM according to your experience? (In case different CMS and/or SHM systems are applied in your fleet, please give an answer for each of them.)

15) To which wind-turbine components should the scope of CMS /SHM be extended in the future?

7.4
Additional survey results

Table 8: Overview of the faults detected in wind-turbine components by means of different condition- monitoring approaches

Mechanical drivetrain

Monitoring approach	Main shaft, main bearing	Gearbox (gears, shafts, bearings)	Lubrication system
Vibration based	XXX	XXX	X
Oil-based	XX	XX	X
SCADA based	X	X	XX
Others	X		

Electro-mechanical/Electrical components

Monitoring approach	Generator assembly	Frequency converter	Transformer
Vibration based	XXX		
Oil-based			X
SCADA based	X	X	X
Thermography	X	X	X
Others	X	X	X

Structural components

Monitoring approach	Blades	Tower	Foundation (onshore)	Support structure (offshore)
Vibration based	XX			
SCADA-based				
Displacement-based		X	X	
Strain-based				
Modal based				
Laser based				
Thermography	X			
Acoustic emissions				
Others	X	X	X	

Note: Every X represents one operator which stated successful fault detection for this component and monitoring approach.

8 Bibliography

[1] P. Svoboda, "Betriebskosten als Werttreiber von Windenergieanlagen – aktueller Stand und Entwicklungen," *Energiewirtschaftliche Tagesfragen,* vol. 5, 2013.

[2] BVG Associates, "Offshore wind: Industry's journey to £100/MWh," 2013.

[3] Y. Feng, P. Tavner and H. Long, "Early Experiences of UK Round 1 Offshore Wind Farms," *Proceedings of the Institution of Civil Engineers - Energy,* vol. 163, no. 4, pp. 167-181, 2010.

[4] Deutsches Institut für Normung, DIN EN 13306: Maintenance - Maintenance Terminology, 2010.

[5] H. Bloch and F. Geitner, Machinery failure analysis and troubleshooting, Houston, Texas: Gulf Publishing Company, 1983.

[6] R. Ahmad and S. Kamaruddin, "An overview of time-based and condition-based maintenance in industrial application," *Computers & Industrial Engineering,* pp. 135-149, 2012.

[7] A. Jardine, D. Lin and D. Banjevic, "A review on machinery diagnostics and prognostics implementing condition-based maintenance," *Mechanical Systems and Signal Processing,* vol. 20, p. 1483–1510, 2006.

[8] T. Gellermann and J. Kolerus, "Schwingungsbeurteilung und Diagnostik von Windenergieanlagen im Spiegel von Normen und Richtlinien," in *VDI-Fachtagung Schwingungen von Windenergieanlagen*, Bremen, 2014.

[9] K. Fischer, "Maintenance Management of Wind Power Systems by means of Reliability-Centred Maintenance and Condition-Monitoring Systems," Chalmers University of Technology, Gothenburg, 2012.

[10] W. Yang, P. Tavner, C. Crabtree, Y. Feng and Y. Qiu, "Wind turbine condition monitoring: technical and commercial challenges," *Wind Energy,* vol. 17, pp. 673-693, 2014.

[11] T. Gellermann, "Extension of the scope of Condition Monitoring Systems for multi-MW and offshore wind turbines," Allianz Global Corporate & Specialty, ARC-AZT-05/2012, 2012.

[12] T. Gellermann and G. Walter, "Anforderungen an Condition Monitoring Systeme für Windenergieanlagen (Requirements for Condition Monitoring Systems in Wind Turbines)," Allianz Zentrum für Technik, 2003.

[13] GL Renewables Certification, Guideline for the Certification of Condition Monitoring Systems for Wind turbines, Hamburg: GL Renewables Certification, 2013.

[14] SKF Reliability Systems, "Vibration Diagnostic Guide," 2000. [Online]. Available: www.skf.com.

[15] ISO - International Organization for Standardization, "ISO 13373-1: Zustandsüberwachung und -diagnostik von Maschinen Schwingungs-Zustandsüberwachung Teil 1: Allgemeine Anleitung," DIN Deutsches Institut für Normung e.V, 2002.

[16] International Electrotechnical Commision IEC, ISO 61400-25-6: Communication for monitoring and control of wind power plants - Logical node classes and data classes for condition monitoring, Geneva: International Electrotechnical Commision IEC, 2010.

[17] B. Heintz, "Optimierung und Standardisierung der Analyse und Diagnose von Schäden am Antriebsstrang von Windkraftanlagen," Kaiserslautern, Germany, 2010.

[18] SKF, "Aptitude Observer," 2012. [Online]. Available: www.skf.com/binary/30-16339/CM-P8-10253-3-EN-SKF-Aptitude-Observer-data-sheet.pdf. [Accessed November 2014].

[19] C. Molina, Contributions to the analysis of vibration and acoustic emissions for the condition monitoring of epicyclic gearboxes, Aachen: RWTH Aachen University, 2010.

[20] T. Gellermann, "Extension of the scope of condition monitoring systems for multi-Megawatt and offshore wind turbines," in *VGB Conference "Maintenance of wind power plants*", Hamburg, 2013.

[21] Verein Deutscher Ingenieure e.V., VDI 3834: Messung und Beurteilung der mechanischen Schwingungen von Windenergieanlagen und deren Komponenten, Düsseldorf: Verein Deutscher Ingenieure e.V., 2009.

[22] ISO, ISO 10816-21 Mechanical vibration - Evaluation of machine vibration by measurements on non-rotating parts - Part 21: Horizontal axis wind turbines with gearbox, ISO, 2014.

[23] ISO, ISO 13379-1 Condition monitoring and diagnostics of machines — Data interpretation and diagnostics techniques – General guidelines, 2012.

[24] Z. Hameed, Y. S. Hong, Y. M. Cho, S. H. Ahn and C. K. Song, "Condition monitoring and fault detection of wind turbines and related algorithms: A review," *Renewable & Sustainable Energy Review,* vol. 13, pp. 1-39, 2009.

[25] F. Garcia Marquez, A. Mark Tobias, J. Pinar Pérez and M. Papaelias, "Condition monitoring of wind turbines: Techniques and methods," *Renewable Energy,* vol. 46, pp. 169-178, 2012.

[26] S. Sheng, "Wind Turbine Gearbox Condition Monitoring Round Robin Study - Vibration Analysis," National Renewable Energy Laboratory, Colorado, USA, 2012.

[27] D. Siegel, W. Zhao, E. Lapira, M. AbuAli and J. Lee, "A comparative study on vibration-based condition monitoring algorithms for wind turbine drive trains," *Wind Energy,* vol. 17, no. 5, pp. 695-714, 2014.

[28] C. Andersson, "Efficient fault detection & fault diagnosis on +4000 wind turbines using vibration monitoring," in *Presentation at COWEC*, Berlin, Germany, 2013.

[29] E. Bechhoefer and M. Kingsley, "A review of time synchronous average algorithms," in *Annual Conference of the Prognostics and Health Management Society*, San Diego, USA, 2009.

[30] H. Luo, C. Hatch, M. Kalb, J. Hanna, A. Weiss and S. Sheng, "Effective and accurate approaches for wind turbine gearbox condition monitoring," *Wind Energy,* vol. 17, pp. 715-728, 2013.

[31] P. McFadden, "Detecting fatigue cracks in gear by amplitude and phase modulation of the meshing vibration," *ASME Journal of Vibration, Acoustic, Stress, and Reliablity in Design,* vol. 108, pp. 165-170, 1986.

[32] E. Becker, "Telemonitoring of wind turbines - for your condition-based maintenance," *Magazine "Antriebstechnik",* May 2008.

[33] N. Wismer, "Application note: Gearbox Analysis using Cepstrum Analysis and Comp Liftering," Brüel & Kjaer, Denmark, 1994.

[34] DIN Deutsches Institut für Normung e.V., ISO 13373-2:Zustandsüberwachung und -diagnostik von Maschinen - Schwingungs-Zustandsüberwachung - Teil 2: Verarbeitung, Analyse und Darstellung von Schwingungsmesswerten, Berlin: DIN, 2005.

[35] Brüel & Kjær Vibro GmbH, "Brüel & Kjaer Vibro," 2014. [Online]. Available: http://www.bkvibro.com/measurement-techniques/envelope-analysis.html. [Accessed November 2014].

[36] S. Watson, B. Xiang, W. Yang, P. Tavner and C. Crabtree, "Condition Monitoring of the Power Output of Wind Turbine Generators Using Wavelets," *IEEE Transactions on Energy Conversion,* vol. 25, no. 3, pp. 715-721, 2010.

[37] W. Wang and P. McFadden, "Application of wavelets to gearbox vibration signals for fault detection," *Journal of Sound and Vibration,* pp. 927-939, 1996.

[38] C. Chen, C. Sun, Y. Zhang and N. Wang, "Fault diagnosis for large-scale wind turbine rolling bearing using stress wave and wavelet analysis," in *Electrical Machines and Systems*, Nanjing, 2005.

[39] Y. Zhang and X. Liu, "The fault vibration signal analysis of wind turbine gearbox based on wavelet transform," in *2nd International Conference on Measurement, Information and Control*, Harbin, China, 2013.

[40] I. Hochmannova, F. Fomi Wamba and L. J, *Anwendung von Zeit-Frequenz-Methoden für drehzahl-variable und niedertourige Windenergieanlagen,* 2013.

[41] R. Hyers, J. McGowan, K. Sullivan, J. Manwell and B. Syrett, "Condition monitoring and prognosis of utility scale wind turbines," *Energy Materials,* vol. 3, pp. 187-203.

[42] R. Wirth, "Möglichkeiten und Grenzen des Condition-Monitoring an Triebsträngen in Windenergieanlagen (Potential and limitations of condition monitoring in the drivetrains of wind turbines)," in *Antriebsstränge in Windenergieanlagen*, Essen, 2012.

[43] J. Zhu, D. He and E. Bechhoefer, "Survey of Lubrication Oil Condition Monitoring, Diagnostics, and Prognostics Techniques and Systems," *Journal of Chemical Science and Technology,* vol. 2, no. 3, pp. 100-115, 2013.

[44] B. Jacobson, Rheology and Elastohydrodynamic Lubrication, Nieuwegein, The Netherlands: Elsevier, 1991.

[45] E. Zaretsky, STLE Life Factors for Rolling Bearings, Society of Tribologists and Lubrication Engineers (STLE), 1992.

[46] M. Moon, "How clean are your lubricants?," *Trends in Food Science & Technology,* vol. 84, pp. 74-88, 2007.

[47] D. K. Roveti, "Choosing a humidity sensor: A review of three technologies," *Sensors,* 2001.

[48] J. Ukonsaari and H. Moller, "Oil Cleanliness in Wind Power Gearboxes," ELFORSK, Stockholm, 2012.

[49] J. Stover, "The Road Map to Effective Contamination Control in Wind Turbines," in *Wind Turbine Condition Monitoring Workshop*, Golden, Colorado, USA, 2011.

[50] T. Stalin, "Oil quality management," in *IQPC Drive Train Conference*, 2013.

[51] A. Toms, "Oil debris monitoring: Part of an effective gearbox monitoring strategy," in *69th STLE annual meeting and exhibition*, Lake Buena Vista, 2014.

[52] A. Carey and A. Hayzen, "The Dielectric Constant and Oil Analysis," Machinery Lubrication - Noria Corporation, 2014. [Online]. Available: http://www.machinerylubrication.com/Read/226/dielectric-constant-oil-analysis. [Accessed April 2014].

[53] Y. Dingxin, . Z. Xiaofei, H. Zheng and Y. Yongmin, "Oil Contamination Monitoring Based on Dielectric Constant Measurement," in *International Conference on Measuring Technology and Mechatronics Automation*, Zhangjiajie, 2009.

[54] L. Yu-mei , C. Xiao-ning, Q. Cheng-hui, S. Jian, L. Hong-qi and G. Lei, "Engine Lubricant Warning System Based on the Dielectric Constant," in *9th International Conference on Electronic Measurement & Instruments*, Beijing, China, 2009.

[55] D. C. Ash, M. J. Joyce, C. Barnes, C. J. Booth and A. D. Jefferies, "Viscosity Measurement of Industrial Oils Using the Droplet Quartz Crystal Microbalance," *Meas. Sci. Technol.,* vol. 14, pp. 1955-1962, 2003.

[56] T. Meindorf, "Condition Monitoring Facetten moderner, umfassender Zustandsüberwachung und ihr Kundennutzen," in *Ölsensoren-Symposium 2013*, Brannenburg, 2013.

[57] H. Brachmann, "20 Jahre Partikelmesstechnik eine Retrospektive," in *OilDoc Ölsensoren Sympoisum*, Brannenburg, 2013.

[58] K. Mikulan, "Bottle sampling versus online monitoring," in *69th STLE annual meeting and exhibition*, Lake Buena Vista, 2014.

[59] A. Wilburn, "Wind turbine tribology - a field perspective," in *69th STLE annual meeting and exhibition*, Lake buena vista, 2014.

[60] E. Loannides, E. Beghini, G. Bergling, J. Wuttkowski and B. Jacobson, "Cleanliness and its importance to bearing performance," *Lubrication Engineering,* pp. 657-663, 1992.

[61] K. Fischer, F. Besnard and L. Bertling, "Reliability-Centered Maintenance for Wind Turbines Based on Statistical Analysis and Practical Experience," *IEEE Transactions on Energy Conversion,* vol. 27, no. 1, March 2012.

[62] S. Sheng, "Investigation of oil conditioning, real-time monitoring and oil sample analysis for wind turbine gearboxes," in *AWEA Project Performance and Reliability Workshop*, San Diego, 2011.

[63] J. Zhu, J. Yoon, D. He and E. Bechhoefer, "Online particle-contaminated lubrication oil condition monitoring and remaining useful life prediction for wind turbines," *Wind Energy,* vol. 17, 2014.

[64] M. Zundel, "Ölüberwachung und Condition Monitoring an Hauptgetrieben von Windenergieanlagen," in *OilDoc Windkraft Symposium*, Brannenburg, 2011.

[65] D. Coronado and C. Kupferschmidt, "Assessment and Validation of Oil Sensor Systems for On-line Oil Condition Monitoring of Wind Turbine Gearboxes," in *2nd International Conference on System-Integrated Intelligence: Challenges for Product and Production* , Bremen, 2014.

[66] D. Mba and R. Rao, "Development of acoustic emission technology for condition monitoring and diagnosis of rotating machines," *The Shock and Vibration Digest,* vol. 38, no. 1, 2006.

[67] D. Lekou, "From laboratory to field measurements for wind turbine condition monitoring," in *WINDFORCE*, Bremerhaven, 2013.

[68] D. Board, *Stress wave analysis provides early detection of lubrication problems,* 2003.

[69] J. Wei and J. McCarty , "Acoustic emission evaluation of composite wind turbine blades during fatigue testing," *Wind engineering,* vol. 17, no. 6, pp. 266-274, 1993.

[70] S. Sheng, F. Oyague and S. Butterfield, "Investigation of Various Wind Turbine Drive Train Condition Monitoring Techniques," Golden, CO, USA, 2010.

[71] C. Tan and D. Mba, "Correlation between acoustic emission activity and asperity contact during meshing of spur gears under partial elastohydrodynamic lubration," *Tribology letters,* pp. 63-67, 2005.

[72] R. Raja Hamzah and D. Mba, "The influence of operating condition on acoustic emission generation during meshing of helical and spur gear," *Tribology International,* pp. 3-14, 2009.

[73] B. Anjar, M. Dalberg and M. Uppsäll, "Feasibility study of thermal condition monitoring and condition based maintenance in wind turbines," Elforsk, Stockholm, 2011.

[74] M. Ralph, "The continuing story of power plant thermography," Inframation, 2009.

[75] C. Crabtree, D. Zappala, P. Tavner and S. Hogg, "Electrical Fault Detection Using Mechanical Signals," in *Proceedings of EWEA 2014*, Barcelona, Spain, 2014.

[76] D. S. Dolan and . P. Lehn, "Real-time turbine emulator suitable for power quality and dynamic control studies," in *International Conference on Power Systems Transients*, 2005.

[77] W. Yang, P. Tavner and M. Wilkinson, "Wind turbine condition monitoring and fault diagnosis using both mechanical and electrical signatures," in *International Conference on Advanced Intelligent Mechatronics*, Xi'an, 2008.

[78] X. Gong and W. Qiao, "Current-based online bearing fault diagnosis for direct-drive wind turbines via spectrum analysis and impulse detection," in *Power Electronics and Machines in Wind Applications (PEMWA)*, Denver, 2012.

[79] X. Gong and W. Qiao, "Imbalance fault detection of direct drive wind turbine using generator current signals," *IEEE Transaction on Energy Conversion,* vol. 27, no. 2, pp. 468-476, 2012.

[80] X. Gong and W. Qiao, "Bearing fault diagnosis for direct-drive wind turbines via current-demodulated signals," *IEEE Transactions on Industrial Electronics,* vol. 60, no. 8, 2013.

[81] S. Gregoire and K. De Bauw, "Advanced Condition Monitoring of Wind Turbines for Early Warning and Diagnostic of Deviating Behavior: Promising First Results," in *Proceedings of the Renewable Energy World Conference & Expo Europe, 3-5 June 2014*, Cologne, Germany, 2014.

[82] C. Crabtree, Y. Feng and P. Tavner, "Detecting Incipient Wind Turbine Gearbox Failure: A Signal Analysis Method for Online Condition Monitoring," *Scientific Proceedings of the European Wind Energy Conference 2010, Warsaw,* 2010.

[83] C. Crabtree, D. Zappala and P. Tavner, "Survey of commercially available condition monitoring systems for wind turbines," Durham University School of Engineering and Computing Science and the SUPERGEN Wind Energy Technologies Consortium, Durham, 2014.

[84] Global Lightning Protection Services A/S, "Global Lightning Protection Services," 2014. [Online]. Available: www.global-lightning.com. [Accessed 30 November 2014].

[85] Hainzl, [Online]. Available: http://hainzl.lets-go.technology/en/produkte/condition-monitoring-systems_cat_207. [Accessed 30 November 2014].

[86] Wölfel, [Online]. Available: www.woelfel.de/en/engineering-services/wind-energy/measurement-of-vibrations. [Accessed 30 November 2014].

[87] Bosch Rexroth, 2014. [Online]. Available: www.boschrexroth.com/en/xc/industries/renewable-energies/wind-energy/products-and-solutions/condition-monitoring-systems/condition-monitoring-systems. [Accessed 30 November 2014].

[88] Moog, [Online]. Available: www.moog.de/maerkte/energie/windenergieanlagen. [Accessed 30 November 2014].

[89] R. Hill, V. Peters, J. Stinebaugh and P. Veers, "Wind Turbine Reliability Database Update," Albuquerque, New Mexico, and Livermore, California, USA, 2009.

[90] D. Hartman, "Analysis of wind turbine blade failure modes," in *Presentation at Composites & Polycon 2006*, St. Louis, Missouri, USA, 2006.

[91] D. Tilch, "Condition monitoring of rotor blades for damages, ice, overload," in *Poster presented at EWEA 2011*, Brussels, Belgium, 2011.

[92] R. Rolfes, S. Tsiapoki and M. Häckell, "Sensing solutions for assessing and monitoring wind turbines," in *Sensor Technologies for Civil Infrastructures - Applications in Structural Health Monitoring*, M. Wang, J. Lynch and H. Sohn, Eds., Woodhead Publishing, 2014, pp. 565-604.

[93] D. Tilch and D. Brenner, "Early damage detection on rotor blades of wind turbines," in *Presentation at COWEC 2013*, Berlin, 2013.

[94] C. Boller, F.-K. Chang and Y. Fujino, Encyclopedia of Structural Health Monitoring, Chichester, West Sussex, U.K.: John Wiley, 2009.

[95] Fos4X, "Fiber optic measuring the load on the rotor blade," 2015. [Online]. Available: www.fos4x.de/fos4blade. [Accessed January 2015].

[96] H. Timmerman, "SKF WindCon - Condition Monitoring System for Wind Turbines," in *Presentation at the New Zealand Wind Energy Conference 2009*, 2009.

[97] C. Gill, "SKF Service Division," in *Presentation at the SKF Capital Markets Day*, 2011.

[98] R. Rolfes, J. Lynch, W. Gerasch, G. Haake, J. Reetz and S. Zerbst, "Ganzheitliches Dimensionierungskonzept für OWEA-Tragstrukturen anhand von Messungen im Offshore-Testfeld alpha ventus," Leibniz Universität Hannover, Hannover, 2012.

[99] M. Hassanzadeh, "Cracks in onshore wind power foundations: Causes and consequences," Elforsk, Stockholm, Sweden, 2012.

[100] J.-S. Chou and W.-T. Tu, "Failure analysis and risk management of a collapsed large wind turbine tower," *Engineering Failure Analysis,* vol. 18, no. 1, pp. 295-313, 2011.

[101] S. Lachmann, Dissertation: Kontinuierliches Monitoring zur Schädigungsverfolgung an Tragstrukturen von Windenergieanlagen, Bochum: Ruhr Universität Bochum, 2014.

[102] R. Soman, P. Malinowski and W. Ostachowicz, "Neutral axis tracking for damage detection in wind turbine towers," in *Poster presented at EWEA 2014*, Barcelona, Spain, 2014.

[103] G. De Sitter, W. Weijtjens, Y. Van Ingelgem, D. De Wilde, K. Verlinden, S. Millis and C. Devriendt, "Foundation monitoring systems: Analysis of 2 years of monitoring at the north sea," in *Poster presented at EWEA 2014*, Barcelona, Spain, 2014.

[104] M. e. a. Veljkovic, "High-strength tower in steel for wind turbines (HISTWIN)," European Union, Luxemburg, 2012.

[105] M. Currie, M. Saafi, C. Tachtatzis and F. Quail, "Structural health monitoring for wind turbine foundations," *Proceedings of the ICE - Energy,* vol. 166, no. 4, pp. 162-169, 2013.

[106] M. Ozbek and D. Rixen, "Operational modal analysis of a 2.5 MW wind turbine using optical measurement techniques and strain gauges," *Wind Energy,* vol. 16, no. 3, pp. 367-381, 2013.

[107] M. Ozbek, F. Meng and D. Rixen, "Challenges in testing and monitoring the in-operation vibration characteristics of wind turbines," *Mechanical Systems and Signal Processing,* vol. 41, p. 649–666, 2013.

[108] Institut für Angewandte Bauforschung Weimar gGmbH, "Innovations," 2014. [Online]. Available: http://www.iab-weimar.de/de/forschung/innovationen/82-condition-monitoring-system.

[109] A. Czyzewski, "Wind energy gets serial," *The Engineer,* 2012.

[110] Bundesamt für Seeschifffahrt und Hydrographie (BSH), "Konstruktive Ausführung von Offshore-Windenergieanlagen / Design of Offshore Wind Turbines," BSH, Hamburg, 2007.

[111] P. Faulkner and M. Hassell, "Structural health monitoring systems on offshore wind turbine structures," in *Proceedings of EWEA 2013*, Vienna, Austria, 2013.

[112] C. Kupferschmidt, I. Koprek, M. Strach, M. Hohmann and H. Huhn, "Offshore-taugliche Sensorik und Messtechnik für das Condition Monitoring einer schwimmenden Windkraftanlage am Beispiel von HiPRwind," in *Aachener Kolloquium für Instandhaltung, Diagnose und Anlagenüberwachung (AKIDA)*, Aachen, 2012.

[113] C. Kupferschmidt, M. Strach, H. Huhn and F. Vorpahl, "Offshore wind structures," in *Handbook of technical diagnosis - Fundamentals and application to structures and systems*, Berlin, Springer, 2013, pp. 505-518.

[114] R. Rohrmann, S. Said, W. Schmid, S. Thöns, S. Bicker and W. Rücker, "Results from monitoring and assessment of offshore wind turbines," in *8th International Conference on Structural Dynamics*, Leuven, 2011.

[115] I. Koprek, "Messkampagne zur Strukturüberwachung und Validierung der numerischen Modelle," in *Optimierung aufgelöster Gründungstrukturen für Offshore Windenergieanlagen (OWOWin)*, Bremerhaven, Germany, 2010.

[116] M. Wilkinson, B. Darnell, T. van Delft and K. Harman, "Comparison of methods for wind turbine condition monitoring with SCADA data," in *Proceedings of EWEA 2013*, Vienna, Austria, 2013.

[117] M. Wilkinson, B. Darnell, T. van Delft and K. Harman, "Comparison of methods for wind turbine condition monitoring with SCADA data," *IET Renewable Power Generation,* vol. 8, no. 4, p. 390–397, 2014.

[118] M. Schlechtingen and I. Ferreira Santos, "Comparative analysis of neural network and regression based condition monitoring approaches for wind turbine fault detection," *Mechanical Systems and Signal Processing,* vol. 25, p. 1849–1875, 2011.

[119] K. Abdusamad, D. Gao and E. Muljadi, "A Condition Monitoring System for Wind Turbine Generator Temperature by Applying Multiple Linear Regression Model," in *Proceedings of the 2013 North American Power Symposium (NAPS)*, Manhattan, Kansas, USA, 2013.

[120] P. Dempsey and S. Sheng, "Investigation of data fusion applied to health monitoring of wind turbine drivetrain components," *Wind Energy,* vol. 16, p. 479–489, 2013.

[121] D. Brenner and D. Tilch, "Gesamtheitliche Datenanalyse beim Condition Monitoring von Windenergieanlagen," in *Conference paper at VDI Fachtagung Schwingungen von Windenergieanlagen / VDI-Berichte 2200*, Bremen, Germany, 2013.

[122] J. Xing and K. Hoei, "Condition based turbine maintenance," 2010. [Online]. Available: www.windsystemsmag.com. [Accessed November 2014].

[123] S. Faulstich and B. Hahn, "Comparison of different wind turbine concepts due to their effects on reliability," Kassel, Germany, 2009.

[124] R. Wolff, "Life-Cycle-Management: Zustandsüberwachung von Windenergieanlagen," in *Conference paper at the 4th VDI Fachtagung Schwingungen von Windenergieanlagen, VDI-Berichte*, Bremen, Germany, 2013.

[125] R. Bellens and P. Chemweno, "Business case for condition based maintenance of wind turbine gearboxes.," Katholieke Universiteit Leuven, Leuven, 2010.

[126] A. VanHorenbeek, "Information-based maintenance optimization with focus on predictive maintenance," Heverlee, Belgium, 2013.

[127] A. VanHorenbeek, J. VanOstaeyen, J. Duflou and L. Pintelon, "Quantifying the added value of an imperfectly performing condition monitoring system—Application to a wind turbine gearbox," *Reliability Engineering and System Safety,* vol. 111, pp. 45-57, 2013.

[128] F. Besnard and L. Bertling, "An Approach for Condition-Based Maintenance Optimization Applied to Wind Turbine Blades," *IEEE Transactions on Sustainable Energy,* vol. 1, no. 2, pp. 77-83, 2010.

[129] Fraunhofer IWES, "Zuverlässige Leistungselektronik für Windenergieanlagen (Reliable power electronics for wind turbines)," 2014. [Online]. Available: www.power4re.de.

[130] C. Crabtree , "Condition Monitoring Techniques for Wind Turbines," Durham University, Durham, 2011.