Kurzfassung

Erweiterung des Umfangs von Condition Monitoring Systemen für Multi-MW und Offshore Windturbinen


Die hohen Erwartungen an die Verfügbarkeit, die mit der Anlagengröße steigende Wertekonzentration und die beschränkte Zugänglichkeit von Windenergieanlagen bilden zudem wichtige Argumente die Zustandsüberwachung auf weitere Anlagkomponenten ausdehnen. In dem vorliegenden Beitrag werden die grundlegenden Anforderungen an schwingungsbasierte CMS und ergänzende Methoden zur Verfeinerung der Triebstrangüberwachung beschrieben sowie ein Überblick über verschiedene mögliche Methoden gegeben, die auf die Zustandsüberwachung der Rotorblätter, des Turms und der Gründung abzielen.

Introduction

During the last years, the number of installations of vibration-based Condition Monitoring Systems (CMS) on wind turbines has increased significantly. According to AZT’s survey of CMS manufacturers from Europe and the U.S., almost 24,000 condition monitoring systems have been installed on wind turbines until 2012 (Figure 1). Thanks to the wide dissemination of the systems, knowledge about different failure modes, in particular their development and detection, has grown remarkably. Thus, in many cases condition changes can be detected at early stages, and this information is very valuable to plan the necessary maintenance and to prevent unexpected outages.

In order to establish one of the first quality standards for CMS, the Allianz Zentrum für Technik (AZT – a subsidiary of Allianz Global Corporate & Specialty AG) published a detailed technical catalog of requirements in 2003 [1]. These requirements have proven reliable as a basis for system assessments [2], and the systems have evidenced their usefulness in practice [3]. The requirements focus on the vibration-based monitoring of the mechanical drive train with shafts, bearings and gears. In addition, the tower vibrations and those induced by the rotor blades should be monitored via the low-frequency sensors installed at the drive train.

The high expectation of operational availability and the rising values of wind turbines, as well as their restricted accessibility, particularly of offshore turbines, provide important arguments for extending condition monitoring to other wind turbine components.

Different monitoring methods are currently in the testing phase or already commercially available. For example, monitoring has been designed for the rotor blades, the plant structure and the foundation. Moreover, in addition to the vibration magnitude, other parameters exist, which deliver condition-relevant information and can refine the vibration-based monitoring of the mechanical drive train components, such as temperatures, lube oil properties and oil particles.

The extension of condition monitoring presented in this paper is not to be understood as a requirement stipulated by insurers. Rather, it is meant to motivate planners, manufacturers and operators to consider the wide range of possibilities of condition monitoring, not only for the mechanical drive train, but also for other components of wind energy converters that are susceptible to failure. The methods discussed are...
Vibration-based condition monitoring of the mechanical drive train

Condition monitoring systems are meant to detect gradual changes in condition early and automatically. For this purpose, it is necessary to record the vibrations caused by the drive train at crucial points in the unit, and for the system to analyze and evaluate these by taking into account operating parameters that influence the vibrations.

In line with the main areas of damage and the available experience with comparable applications in other industrial branches, the scope of the condition monitoring initially was focused on the mechanical drive train.

Minimum scope of condition monitoring

The following key components form the minimum scope of condition monitoring in accordance with [1]:
- Rotor shaft and main bearing
- Gearbox with toothings and bearings
- Generator with bearings,
- Nacelle or tower vibrations

Furthermore, the nacelle and rotor shaft vibrations are to be utilized for the basic monitoring of the rotor and rotor blades. With the exception of the gearbox, the same scope of monitoring applies for direct-drive turbines.

Required vibration measuring points

The monitoring of the drive train vibrations is usually carried out by measuring the absolute vibrations at housings and structural components. Since not all components are fitted with separate sensors, the measuring points are suitably combined; this is done also due to economical reasons.

Wind energy converters with a three-point suspension of the rotor and planetary/spur gears require at least one sensor at the main bearing, three at the gearbox and two at the generator (T1 to T6 in Figure 2). For differently designed drive trains, the measuring positions should be adapted to the particular equipment configuration. For example, if a turbine has two main bearings, an additional sensor should be installed at the second main bearing. For turbines without a main gear, the required measuring points are confined to the rotor and generator bearings.

Irrespective of the type of drive train, the nacelle vibrations transversely and axially to the rotor axis are to be monitored (G1 and G2 in Figure 2). Given suitable sensors, the measurement of nacelle vibration can also be combined with sensors at the drive train.

To be able to jointly measure the very low frequency vibrations (rotor rotational frequency, tower vibrations), as well as the higher frequency structure-borne noise of the roller bearings, sensors with a large frequency and dynamic range are necessary. Depending on the rotational frequency of the rotor, a frequency range of approximately 0.1 Hz to 10 kHz (minim. 5 kHz) is sufficient. Special piezoelectric accelerometers can fulfill this requirement. Piezoresistive accelerometers, which can record accelerations of 0 Hz are also suitable for measuring in the lower frequency range. Due to the very low acceleration amplitudes in the lower frequency range, the measurement chain must be sufficiently sensitive.

For slowly rotating, large rotor bearings (e.g. slew bearings of single-bearing concepts), the monitoring of the relative radial or axial movements of the bearing rings or the shaft via displacement sensors is also possible (Figure 3). Appropriate sensors based on the eddy current or inductive principle, record both the relative vibrations and the quasi-static displacements with high resolution. The displacement amplitudes are dependent on the bearing clearance and the deformations that arise. This allows conclusions to be drawn about both wear (bearing clearance) and load (deformation). The displacement measurement also allows the detection of an increased clearance in the rotor blade bearings. The air gap in direct-drive generators can also be monitored via displacement measurement, and, depending on the design, an increase in the main bearing clearance can be detected with the same sensor.

In addition, the monitoring of relative displacement, as described above, should be conducted particularly if journal bearings are used instead of roller bearings. The pertinent principle of shaft vibration measurement is addressed in DIN ISO 10817-1 [5].

Analyses and frequency selective monitoring

From the sum of the drive train and nacelle vibrations, the vibration information relevant for the condition monitoring is to be extracted by means of suitable signal processing and analysis. The allocation of vibration components to machinery elements is carried out by means of frequency selective characteristics, which are defined on the basis of turbine-specific component kinematics. The following are to be taken into account:
– Excitation frequencies of rotor, drive train and gear toothing
– Defect frequencies of roller bearings
– Natural frequencies of tower and rotor

The frequency selective vibration characteristics are derived by Fourier-Transformation from amplitude spectra and envelope spectra. The monitoring of the other machine and nacelle vibrations requires various broadband vibration parameters from the raw and, when appropriate, from envelope time signals (Figure 4). The analysis methods marked as optional can be used as supplementary condition monitoring tools in order to increase the chances of early detection and the verification possibilities during the diagnosis.

Since the vibration behavior of a wind energy plant is strongly influenced by external and operational factors, the ability to monitor its condition is fraught with special difficulties when compared to most drive machines. As a rule, wind energy converters have a highly dynamic operating behavior with frequent performance and speed fluctuations (cf. [6]). This must receive special consideration during the analysis:

– The condition-dependent vibration changes must be separated from the normal operating-related vibration changes – for example, by means of operating-related classification.
– Speed fluctuations during the measuring process must be compensated using the order analysis (signal sampling according to actual rotational speed).

The frequency selective characteristics should be monitored as narrow-banded as possible and the center frequency should be adjusted to correspond to the actual rotation speed.

The threshold values must be defined in accordance with operating parameters that significantly influence vibrations, such as power, rotation speed or wind velocity.

### Extended drive train monitoring via additional parameters

#### Temperature monitoring

Temperature measurements are part of the standard instrumentation of the drive train, e.g. the temperature of the lubricant in the feed and return flow or the temperature of the generator’s stator winding. However, the temperatures are frequently monitored with absolute threshold values only, which means that gradual changes are detected only late or not at all.

**Temperature measurements of roller bearings**

If a local component is worn, the increase in friction has only minor influence on global temperature measurements, as with the lubricant temperature, for example. It is therefore recommended to additionally measure the local temperature at selected roller bearings. The temperature measurement should take place as close as possible to the stationary bearing ring to be able to detect a rise in temperature due to increased friction as early as possible. In the case of large rotor bearings, such as slew bearings (Figure 3), it is advisable to measure the temperature at several points of the circumference, as the position of the load zone changes in line with wind conditions.

**Temperature measurements at the generator**

The monitoring of temperatures of generator windings – typically a standard procedure – is important because of the operating limit of the insulation class used. Through the correlation of the winding temperature with the generator load and ambient temperature, it is possible to detect changes that point to potential errors. To be able to detect local errors in the stator winding, such as short circuits, it is necessary to measure the temperature at several predetermined points of the circumference and along the length of the winding. In the case of synchronous generators, where excitation is achieved via permanent magnets, additional temperature monitoring of the magnet material should be considered. This is because the remanence flux density of the magnets is reduced with rising temperatures, and excess temperatures can cause irreversible demagnetization.

#### Counting oil particles

During a process of wear or the development of damage, roller bearings and gears produce metallic abrasion and particles. The metallic particles that have entered the oil return flow can be recorded and automatically counted by means of special optical, inductive or eddy current detectors, if they are above a minimum size (i.e. bigger than 50 µm or 300 µm).

The increase of abrasion particles can be illustrated and evaluated in the form of a trend curve. Different systems also allow an analysis of the distribution of particle size (see [7]). Practical examples have shown that gradual wear processes can be identified through a rise in the number of particles, in some cases even before they are detected by means of a vibration analysis. However, this only applies to the components lubricated in the oil circulation system, and thus primarily to the gearbox.

Particle counting, as an additional monitoring parameter to the vibration analysis, allows a refined condition monitoring of the gearbox, particularly when it comes to components that are difficult to monitor (e.g. the planetary bearings). Since it is not possible to conclude the cause through the increase in particle numbers alone, a supplementary detailed vibration diagnosis and/or visual inspection (boroscopy) is necessary.

The counting of particles by itself does not allow complete condition monitoring of the mechanical drive train, as condition changes of the grease lubricated bearings (generator, main bearing), changes in the operating behavior of the gearbox and generator, or the vibration behavior of the wind turbine (tower and rotor vibrations) are not able to be detected.

#### Monitoring of the oil quality

During the past few years, additional sensors for monitoring the oil quality online have come onto the market, which serve to continuously evaluate oil aging. Inadmissible changes in the oil can in this way be detected and measured to help guarantee oil quality during operation. This serves to protect the lubricated components. Among the parameters analyzed are viscosity, relative humidity, dielectric constant and electrical conductivity.

In addition to information regarding fault conditions, which can cause accelerated aging of the oil (e.g. through moisture),...
the parameters allow conclusions to be drawn about potential wear processes of machine components (cf. [8]).

**Monitoring electrical characteristics** (generator, drives, lightning protection)

The fault diagnosis of generators and electrical drives by means of frequency analyses of current, voltage or power signals is a proven method. It is particularly suited for condition monitoring because no additional sensors have to be installed. Essentially, it only requires calculation capacity and suitable evaluation algorithms. Numerous theoretical and practical research works have been published on this subject over the past years. In spite of this, the electrical signature analysis for the online monitoring of wind generators is not yet widespread.

As wind energy converters are subject to extreme dynamic stress and are constantly exposed to power fluctuations and rotational changes, non-stationary processes are increasingly analyzed with the help of the Wavelet analysis instead of the Fourier analysis. For example [9,10], the evaluation of the power signal using the Wavelet analysis for detecting winding shorts or air-gap eccentricities (both as a result of imbalance and damage to bearings) is presented.

The research project MONGS [11,12] examines possibilities of identifying generator faults with the existing signals of the frequency converter. Depending on the fault, this process influences the control system in order to maintain the best possible energy production.

This applies to motors too, such as the pitch and azimuth drives, an electrical signature analysis could be used in order to detect signs of electrical and mechanical faults (also in the connected transmission gears). The components of a wind energy converter are, to a large extent, dependent on the correct functioning of the lightening and overvoltage protection concept. Since the strength and frequency of lightening strokes can negatively impact the lifespan of components and protection devices, counting and classifying all instances of lightening strokes and overvoltages can provide an information base necessary for early inspections and maintenance measures before damage arises. This serves to protect against consequential damage and promotes the availability of the facility.

**Rotor blade monitoring**

Wind loads and the rotation through the gravitational field cause high dynamic forces on rotor blades. As a result of turbulence and gusts, the blades are subject to different load spectra, as well as extreme loads. Moreover, environmental influences, such as extreme temperatures, UV radiation, salt, moisture, rain, hail, icing and lightning can negatively impact the condition of the blades and the operation of the turbine.

These different influences lead to the following relevant aspects regarding the monitoring of rotor blades:

- Detection of damage (e.g. cracks or delaminations)
- Detection of faulty condition (e.g. misalignment of nacelle or blades)

This offers the opportunity of optimizing the operational management and reducing the operating load.

- Recording the forces acting on the blades and classification of fatigue loads
- Load monitoring can be carried out by correlating the recorded measurement data with the blade load. This forms the basis to recognize unfavorable operating conditions with very high loads. In the long term, Life Cycle Monitoring can be established to verify the design assumptions and deduce information regarding the residual lifespan.

Different methods for monitoring rotor blades, currently available or still in the development phase, can be found in Table 1. Whether these methods can be used to detect early ice build-up if ice builds up on the blades and there is a risk of ice throw, the wind energy converter is to be shut down and not restarted while ice is present. Accurate detection methods may reduce the downtimes and thus increase the energy production when compared to indirect methods (e.g. via anemometer).

Table 1. Overview of various monitoring methods for motor blades.

<table>
<thead>
<tr>
<th>Monitoring method</th>
<th>Sensor application</th>
<th>E.g.</th>
</tr>
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<tbody>
<tr>
<td>Evaluation of natural vibration behaviour</td>
<td>Acceleration sensors at selected blade positions or</td>
<td>[13]</td>
</tr>
<tr>
<td>(operational vibration analysis)</td>
<td>local strain measurement, for example by means of</td>
<td>[14]</td>
</tr>
<tr>
<td></td>
<td>classic strain gauges or optical strain gauges (Faser-Bragg-Gitter)</td>
<td></td>
</tr>
<tr>
<td>Evaluation of blade deflections</td>
<td>Measuring relative blade deflection, for example</td>
<td>[15]</td>
</tr>
<tr>
<td></td>
<td>by means of laser from the nacelle</td>
<td></td>
</tr>
<tr>
<td>Evaluation of local surface deformation</td>
<td>Distributed strain measurement, for example by means</td>
<td>[16]</td>
</tr>
<tr>
<td></td>
<td>of optical strain gauges (Faser-Bragg-Gitter)</td>
<td></td>
</tr>
<tr>
<td>Acoustic emission analysis (detection of</td>
<td>Distributed sensors to detect acoustic emissions from</td>
<td>[17]</td>
</tr>
<tr>
<td>high frequency structure-born noise for example,</td>
<td>the rotor blade (e.g. by means of Piezo-fibre sensors)</td>
<td></td>
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<td>subsequent to fibre breakage)</td>
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**Conclusions**

According to the market, vibration-based condition monitoring of drive train components in onshore wind turbines have shown a return on investment after two to four years. With CMS, necessary repairs can be planned for the low-wind season, reducing down times and secondary damage. The savings of one prevented serious damage could be equal to the cost of 20 or more condition monitoring systems. For example, a bearing failure, which results in extensive gearbox damage, can cost more than 100,000 euros, plus assembly and logistics costs. In comparison, a damaged bearing that is detected early by a CMS could be replaced for only several thousand euros. In the case of offshore installations, the potential savings from condition monitoring are even higher. Additionally, production losses can be re-
duced due to shorter duration of repairs. Therefore, vibration-based condition monitoring systems should be standard equipment for multi-MW and offshore turbines. As a result of the large investments required for these plants and the necessity for cost-optimized maintenance, detailed information on the condition of such facilities is becoming increasingly important. Moreover, the restricted accessibility of offshore plants constitutes an important justification for expanding the condition monitoring to wind energy plant structural components and a refinement to drive train monitoring with supplementary methods.

Table 2 shows an overview of the WEAs components with an allocation of the different monitoring methods considered in this paper. The crosses mark the components to be monitored by means of vibration-based CMS, according to [1]. The circles mark possible extensions. The filled-in circles represent extensions recommended for multi-MW and offshore turbines. The non-filled-in circles mark possible additional extensions, which have been determined to be of lower priority. The evaluation includes aspects such as the significance of the monitored components, practical experience of monitoring method (if any) and the limitation of the monitoring expenditure.

When implementing different monitoring methods, use of an integrated systems approach to reduce cost and improve signal communication is recommended. This also allows the multitude of signals available in the control system to be used for condition monitoring.

References

[1] Requirements for Condition Monitoring Systems for Wind Turbines, Summary of requirements according to Report 03.01.068 dated 27.03.2003, Allianz Zentrum für Technik GmbH.

Table 2. Overview of methods discussed. x = AZT requirements from [1], ∗ = recommended extension, o = additional possible extension
1: indirect via low-frequency nacelle/drive train vibrations, 2: air gap monitoring, 3: if oil lubrication, 4: at bearings, 3: distributed temperature measurement points

<table>
<thead>
<tr>
<th>Component</th>
<th>AZT Requirements accord [1]</th>
<th>Extended scope of CMS</th>
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<tbody>
<tr>
<td></td>
<td>Vibration</td>
<td>Displacement</td>
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<tr>
<td>Rotor blades</td>
<td>x</td>
<td>o</td>
</tr>
<tr>
<td>Pitch bearings</td>
<td>o</td>
<td></td>
</tr>
<tr>
<td>Rotor bearing</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>Gearbox</td>
<td>x</td>
<td>o</td>
</tr>
<tr>
<td></td>
<td>x</td>
<td>*</td>
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<tr>
<td>Interm. speed</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>High speed</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Generator bearings</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Direct driven</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Generator winding</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Direct driven</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Tower + Foundation</td>
<td>x</td>
<td>o</td>
</tr>
<tr>
<td>Electric drives</td>
<td>Pitch</td>
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<tr>
<td>Azimuth</td>
<td>o</td>
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