Principles for condition-based maintenance of wind turbines

Adopted by the Expert Consulting Committee of the German Wind Energy Association (BWE e.V.) on 21st September 2007

Contents

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1. Purpose and objective of condition monitoring

The objective of condition-based maintenance (condition monitoring) of wind turbines is

- to determine the current technical status of the wind turbine,
- to detect and describe initial damage and,
- to help avoid secondary damage through early detection.

The result of the condition monitoring is documented in written form for use of the operator and contains necessary maintenance measures as well as recommendations concerning maintenance intervals.

2. Concept and condition monitoring intervals

The operator has to arrange for the inspection to be done. The inspection intervals comply with the installed capacity of the wind turbine and are defined as follows:

- wind turbine less than 300 kW: every 4 years
- wind turbine from 300 to 1500 kW: every 2 years
- wind turbine from 1500 kW: annually

The condition monitoring of wind turbines is carried out by a technical expert. The technical expert’s qualifications are described in a subsequent section.

The expert inspects the complete wind turbine and checks whether all requirements concerning

1. inspection requirements (see section 4)
2. maintenance measures (see section 5)
3. technical system management (see section 6)
4. periodic inspection (see section 7)

are fulfilled. Furthermore, the expert arranges or performs:

5. a drive train inspection (incl. oil level and vibration diagnostics) (see section 9.)
6. a rotor blade inspection (see section 9).

The technical expert writes a status report. The results are summarized in a form (see section 10).

3. The technical expert's qualifications

The condition-based maintenance of wind turbines according to the principles mentioned may only be performed by technical experts, who

- meet the "technical expert for wind turbines' qualifications" of the Expert Consulting Committee of the German Wind Energy Association (BWE e.V.).
- are members according to the "rules of procedure of the Expert Consulting Committee of the GWEA (BWE e.V.)".

4. Inspection requirements

The wind turbine must at the minimum have:

1. Appropriate access route.
2. All equipment necessary for operator protection (fall arrester, personal protective equipment).
3. The drive train kinematic data (a prerequisite for performing the vibration diagnostics).
4. Maintenance service manual.
5. Maintenance records and oil analyses.
6. If available: rotor blade maintenance history.
7. Operating instructions.
8. Building permission, type test or individual test.
9. Declaration of conformity.
10. Erection and installation records.
11. Commissioning record.
12. Maintenance contract.
13. Abridged works manager report according to section 7.

In his report the technical expert has to declare whether all requirements are fulfilled.

5. Maintenance requirements

The wind turbine has to be maintained. The following requirements are associated with the maintenance:

1. A maintenance contract has to be concluded with the manufacturer or a qualified maintenance company. The operator has to be qualified in case he wants to perform the complete or partial maintenance himself. Trained personnel have to be used for the maintenance.

2. The maintenance has to be performed according to the maintenance service manual, which has been verified by type testing. Additional or updated data may be used. Appropriate maintenance service manuals have to be kept for facilities with individual testing.
3. The maintenance intervals mentioned in the maintenance service manual and other documents must be followed. The maintenance has to be performed at least every six months.
4. The maintenance is to be comprehensively documented for the operator. Maintenance records have to be written according to the maintenance service manual.
5. At gearbox facilities oil samples have to be extracted and analysed during maintenance, at least annually.

The technical expert reviews the maintenance records and oil analyses. In his report he declares whether all requirements have been fulfilled since commissioning or since the last condition monitoring.

6. Technical control system requirements

A professional technical system management is a premise of condition monitoring. The technical system management requirements are the following:

1. **Permanent wind park monitoring**, preferably per remote inquiry. Realization and organization of emergency aid and troubleshooting.
2. **Organization and control of maintenance**: planning, commissioning and control of the maintenance, analysis of maintenance and operating records.
3. **Periodical systematic checks**: inspections (preferably monthly, at least quarterly) of the wind turbine, facility inspection and condition control.
4. **Facility survey,** survey of the relevant facility data (partially with serial numbers) and complete history of the wind turbine and its components by means of a database or register.
5. **If possible with the system management software: Recording of operating data (output, performance curves).**
6. **If possible with the system management software: Supervision of operating parameters (component and bearing temperatures, maximum output).**
7. **Documentation of error incidences and operational faults with cause analysis.**

The technical system management may be carried out by a specialist contractor or the operator. Parts of the system management may also be the responsibility of the manufacturer (e.g. no. 1 and 2).

The works manager has to provide the technical expert with an abridged report, in which he provides the following information since commissioning or since the last condition monitoring:

1. Proof of commissioning, maintenance and servicing activities.

2. List of all maintenance and repair activities.
3. Records of periodic checks (inspections) by the system management.
4. If possible, evaluation of operating data.
5. Information on the development of the maximum component temperature.
6. List of failure events (error lists, frequency) with information on cause and repair.

The technical expert checks the system manager’s report and, if necessary, requests and checks additional documents. In his report the technical expert declares whether all requirements on the system management are fulfilled since commissioning or since the last condition monitoring.

With agreement, operating data collected may be transferred to the expert and analyzed by him for

- fault reports with error codes, beginning and end of the operational fault in digital form,
- time series of the operation data, e.g. 10-minutes data of the wind turbine with the most important operational data (wind speed, RPM, capacity, temperature),
- list of error codes.

7. Periodic inspection requirements

Within the framework of condition-based maintenance, the operator has to arrange periodic inspections according to planning permission requirements and the type approval. Inspection periods must be adhered to (every two years, with a maintenance contract every four years during the first 12 years of operation). These maintenance intervals are listed in the type approval and the valid expert’s report.

The periodic inspection is performed following the “Principles of the Periodic Inspection of Wind Turbines” of the Expert Consulting Committee of the German Wind Energy Association (BWE) in their latest version. All requirements placed on the expert, the scope of testing and other details are managed by this document.

Periodic inspection requirements are:

1. adherence to the maintenance intervals in accordance with the type approval,
2. scope of complete wind turbine inspection according to the “Principles of the Periodic Inspection of Wind Turbines“ of the Expert Consulting Committee advisory of the German Wind Energy Association (BWE),
3. procedures according to the “Principles of the Periodic Inspection of Wind Turbines“ of the Expert Consulting Committee of the German Wind Energy Association (BWE),
4. completion of the maintenance required in the last inspection report.

The last inspection report on the periodic inspection is to be made available to the technical expert (for condition monitoring). He checks the adherence to an interval since the last periodic inspection and the completion of recommended maintenance in the inspection report. The results of this inspection report are used in his evaluation.

The condition-based monitoring may coincide with periodic inspection.

8. Condition monitoring of the drive train

One focus of condition monitoring is checking the drive train. The condition report must include the results of the visual check, the vibration diagnostics and an oil analyses performed by a reputed laboratory. Any initial damage or irregularities found are to be rated with regard to their possible affect on the service life of plant components. Corrective maintenance requirements are to be fully described and recommendations made for a maintenance date.

The drive train must be fully examined by the technical expert. The scope and the type of inspection are to be taken from the following table 1.

component to be checked	type of inspection and checkpoints	inspection period		
		yearly	every 2 years	every 4 years
hub	cracks, paintwork, corrosion	from 1500 kW	300 to <1500 kW	< 300 kW
drive shaft slow side	cracks, paintwork, corrosion, slipping clamping ring	from 1500 kW	300 to <1500 kW	< 300 kW
bolted joint shaft – hub	corrosion, crack, mounting torque	from 1500 kW	300 to <1500 kW	< 300 kW
spindle	cracks, paintwork	from 1500 kW	300 to <1500 kW	< 300 kW
rotor bearing	noise, leakage, greasing, sump pan, lightning protection system, shaft nut	from 1500 kW	300 to <1500 kW	< 300 kW
gearbox	noise, visual gear teeth wear, chipping, scuffing, micropitting, gear-tooth contact pattern, head assembly (spur gears, planetary stages), deposits.	from 1500 kW	300 to <1500 kW	< 300 kW
complete drive train	vibration analysis: collection of vibration data through periodic or permanent measurement at defined points of the housing. Data analysis through expert service provider.	from 1500 kW	300 to <1500 kW	< 300 kW

component to be checked	type of inspection and checkpoints	inspection period		
		yearly	**every 2 years**	**every 4 years**
oil supply	condition, function and cooling properties (temperature difference). Visual oil level check, condition, frothing formation, mud), accumulation, strainer fouling, oil pump function, exchanger noise; oil analysis through specialist laboratory	from 1500 kW	300 to <1500 kW	< 300 kW
coupling and brake	visual function control, alignment and wear when stopped and with an stroboscope when in service	from 1500 kW	300 to < 1500 kW	< 300 kW
torque converter bearing	condition of rubber bearing, movement, mounting position	from 1500 kW	300 to <1500 kW	< 300 kW
generator (high-speed) gearbox wind turbine	Bearing noises, leaks, fastening at machine footing, grounding, junction box, grind rings, brush wear abrasion, vibration, alignment	from 1500 kW	300 to <1500 kW	< 300 kW
generator (low-speed) wind turbine without gearbox	check for cracks, corrosion, air gap, bolts, insulation	from 1500 kW	300 to <1500 kW	< 300 kW
temperature behaviour	check of maximum bearing and oil temperatures if supported by production management software	from 1500 kW	300 to <1500 kW	< 300 kW

table 1: scope of drive train inspection

All necessary inspection equipment must be supplied by the technical expert or equipment operator.

This may include:

- flexible endoscope with the possibility for digital documentation
- electronic stethoscope
- infrared temperature gauge
- appropriate vibration measuring system (appropriate sensors, preferably 8-channel but at least 4-channel data logger for data acquisition and evaluation unit)
- alternatively, a diagnostics service from a competent supplier.

The complete kinematics data are required for the drive train vibration measurement. These are:

- type of gearbox with sectional drawing,
- number of teeth of all gears and pinions,

- damage frequency of all integrated gearbox bearings, generator and the main bearing,
- nominal rotation speed or speed range of the drive,
- all kinematic data of external exciters (e.g. pump type, pump vane rotation speed, pumping rotation speed).

A continuous monitoring system using online measurement does not replace the visual control.

The following is required for the vibration measurement of the drive train:

Vibration of the generator casing:

The measurement of the vibration is preferably measured at the generator casing within a short distance to the shaft bearings using acceleration sensors. The sensor selection has to fulfil the mentioned frequency characteristics requirements. The mounting of sensors must be by gluing or bolting (manufacturer's approval necessary). The acceptability of using permanent magnets to mount the sensors must be checked.

The measuring device must comply with the loading direction of the particular rolling bearings. For gearboxes this is the radial direction of tooth engagement; for the generator and the rotor bearings it is the direction of greatest loading, usually vertical. The bearings in front of or behind a coupling are to also be measured in the axial direction.

Shaft vibration:

The measurement of the vibration is to be taken with displacement sensors placed in the proximity of the rolling bearing to be tested. The measurement direction must follow the loading direction of the particular rolling bearings. For gearboxes this is the radial direction of tooth engagement; for the generator and the rotor bearings it is the direction of greatest loading, usually vertical. Axial bearings are also to be measured in the axial direction.

Measurement parameters:

The position of the sensors has to be documented. If necessary the measuring points should be marked. For data acquisition the drive has to be run under representative conditions, at least at partial load operation.

The data acquisition should be taken simultaneously in order to be able to clearly associate the data with any anomalies that occur during testing. In practice data acquisition in groups will suffice, preferably with an 8-channel or at least a 4-channel measuring system.

The spectrum should be able to reach from 0 Hz up to three times the highest gear mesh frequency. The accelerometer signal, used for envelopes formation, should be available within a range above the highest sinusoidal excitation, usually the highest gear mesh frequency, up to 15 kHz. It is often advisable to use the range from 2 up to 15 kHz. The formation of spectrum and envelope spectrum should be produced from the same time stamped data set. The resolution of spectrum and envelope spectrum should be at least 0.1 Hz.

This results in the following minimum data acquisition requirements:

Measuring range of the measuring section:	0.1 Hz	up to	15 kHz
Linearity of measuring section to 3 dB:	0.1 Hz	up to	three times the highest gear mesh frequency
Sampling rate:	> 36 kHz		
Anti-aliasing filter:	15 kHz		
Testing period:	> 10 s		

The rotational frequency (see section 8) and the generator capacity are recorded along with the vibration data. This is recorded as an additional channel. For this purpose a reference mark has to be installed at the fastest shaft for detecting the RPM. Alternatively, existing components like the coupling pins may be used. The rotation speed measurement can be made with optic, inductive or other appropriate sensors.

Formation of spectra, envelope spectra, order spectra and envelope order spectra:

The spectra are built from the time signal up to the required frequency range by using FFT (fast Fourier transformation). The FFT parameters are to be adjusted so that the required resolution (at least 0.1 Hz) is achieved. The usage of an appropriate window function, e.g. Hanning, is advisable.

The envelope spectra are built from the envelope of the high-pass filtered time signal. As a limit frequency for high-pass filtering of 2 kHz is advisable for most applications; in individual cases a different limit frequency may be necessary. Envelope formation can be done by means of refraction or another appropriate method. The FFT parameters are to be adjusted in order to achieve the required resolution. The rectangle window function has to be used.

The order spectra and envelope order spectra are displayed just as the spectrum and envelope spectrum. The time signal has to be re-sampled to the actual RPM signal beforehand by using the recorded RPM signal. If necessary, filters can be used in this step.

The vibration diagnostics for wind turbines without gearboxes (direct driven, slow-speed generators) is restricted to the main bearings.

9. Condition control of the rotor blades

The rotor blades are to be checked in detail and their condition is to be documented. Irregularities and damages are to be detected and a recommended repair date specified. The rotor blades are checked in detail by the technical expert. Scope and type of inspection are taken from the following table 2. The inspection periods comply with the wind turbine’s installed capacity.

component to be checked	**type of inspection and checkpoints**	**inspection period**	
		every 2 years	**every 4 years**
blade body	visual control of cracks, air pockets, delamination, drainage, protective film and erosion of the leading edge, lightning protection system, spark gap	from 300 kW	< 300 kW

	documentation of blade pitch angle	from 300 kW	< 300 kW
flow elements	turbo rills, vortex generators, micro swirl prong bands, gurney flaps	from 300 kW	< 300 kW
	stall stripes	from 300 kW	< 300 kW
visible profile accuracy	characteristics of the trailing edge, light reflection	from 300 kW	< 300 kW
blade inner	If technically possible, the blade should be checked from the inside. It is important that the area is stable enough. delamination, bars : cracks, finish of web adhesion	from 300 kW	< 300 kW
blade sealing to hub	oil in the blade, lightning protection system within the blade	from 300 kW	< 300 kW
extender	corrosion, bolts, weld seams	from 300 kW	< 300 kW
wind turbines tip stall mechanism	play, grime, adjustment, crack, guide tube, damping plate, index pins, bolts and cross bolts, function	from 300 kW	< 300 kW
wind turbines blade pitch adjusting device	bearings, grease condition, play in mechanism, leaks, gear tooth contact pattern, connecting rod, oil in the blade	from 300 kW	< 300 kW
wind turbines blade pitch adjusting cylinder	leaks, mechanical stops, blade adjustment locking device	from 300 kW	< 300 kW
wind turbines pitch return element	function, tighten the accumulators	from 300 kW	< 300 kW
wind turbines pitch electrical cabinet	tighten within hub	from 300 kW	< 300 kW
cable twist protection	function optional insulation test	from 300 kW	< 300 kW

table 2: scope of blade inspection

10. Report

The technical expert provides an accurate comprehensive report on the condition of the wind turbine in which all results are documented.

Initial damages and irregularities found are to be rated with regard to the possible affect on the service life of plant components (when possible and meaningful).

Corrective maintenance requirements and recommendations for a maintenance date are to be noted. In case the repair date cannot be fixed because of initial damage, another inspection of the affected component is to be arraigned.

The report includes a form in accordance with section 13 which acts as proof of the inspection, merges the essential results, and may e.g. be provided to an insurance company.

11. Final remark

The condition-based maintenance principles were generated in co-operation with Gothaer Allgemeine Versicherung AG and the members of the Expert Consulting Committee of the German Wind Energy Association (BWE e.V.). The BWE thanks Gothaer Allgemeine Versicherung AG for the co-operation.

The principles shall be regularly updated according to the state of knowledge in consultation with the persons concerned.

Osnabrück, September 21st, 2007.

12. Sample final report

Final results of the condition-based maintenance of a wind turbine for insurance purposes

wind turbine: __________________ **location:** ______________________________

type: _________________________

serial number: ________________

operator: ______________________ **technical expert:** _____________________

The technical expert ______________ performed a complete condition-based inspection on the above mentioned wind turbine, on ___________ (date) in accordance with the "Principles for condition-based maintenance of wind turbines" [1]. The results are described within report no. _____ from ________ (date).

The main results are:

1. The Inspection prerequisites according to [1], section 5 are fulfilled. yes O no O

2. The **maintenance** requirements for the wind turbine according to [1] section 6 are fulfilled. yes O no O

3. The **control system** requirements for the wind turbine according to [1], section 7 are fulfilled. yes O no O

4. The **periodic inspection** requirements for the wind turbine according to [1], section 8 are fulfilled. yes O no O

5. The **drive train inspection** according [1], section 9

   results: initial damage present. yes O no O

   Maintenance requirements of the drive train are described as follows and include recommendations for maintenance dates: ________________________

   ____

6. The **rotor blade test** according [1], section 10

   results: initial damage present. yes O no O

   Maintenance requirements of the rotor blade are described as follows and include recommendations for maintenance dates: _____________________________

   ____

   date, signature