Handbook on Condition Monitoring of Wind Turbines

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Summary

This paper presents a handbook on condition monitoring of wind turbines, developed for power companies in Norway. The main objective of the handbook is aiding technicians in the technical condition assessment. The handbook, in Norwegian, contains separate chapters for all main wind turbine components. All chapters have a common structure describing the component itself, typical damages, condition monitoring methods, and a recommended condition monitoring programme. The key element is the specification of qualitative or quantitative criteria for the classification of the technical condition on component level. In addition, the handbook contains numerous pictures illustrating typical levels of degradation for the most important components.

Introduction

Since the early 1990's there has been an increasing focus on risk-based maintenance in the hydro power industry in Norway. A number of methods and tools have been developed in order to support risk-based strategies. A key element, and a fundamental tool, in such a risk-based approach is a handbook on condition monitoring of hydro power plants [1] developed by the Norwegian Electricity Industry Association (www.ebl.no) in a joint cooperation with power companies, manufacturers and consultants. It was first published in 1995, and updated in 2005.

In Norway, most of the wind farm owners are power companies with years of experience from establishing strategies and using tools for risk-based maintenance of hydro power plants. These power companies would also like to take responsibility for operation and maintenance of their wind farms after the warranty period using the same systematic approach they are familiar with from the hydro power industry.

A new project was therefore established as a joint cooperation between wind farm owners. The main objective of the project, running in the period 2006 – 2008, was to transfer technology, systems and experience from the hydro power industry to the wind power industry, by adjusting existing methods and tools, in order to develop a condition based maintenance system to optimise operational and maintenance cost and reduce downtime for wind power systems.

The main objective was reached through the following:

- a common designation system for wind turbines (by extending the Norwegian Electricity Industry Association coding system for hydro power plants to include wind turbines)
- a handbook on condition monitoring of wind turbines [2]
- a systematic approach for recording operational, failure and maintenance data and experiences
- recommendations related to how aspects regarding future operation and maintenance should be included in the negotiation and contract signing process with the manufacturer

This paper focuses on the part of the project concerning the handbook on condition monitoring of wind turbines.

Condition assessment and condition indicators

In general, the degradation of the technical condition of a component is a continuous process from an "as new" condition until failure as illustrated in Figure 1. Such curves are often denoted degradation curves, deterioration curves or lifetime curves.

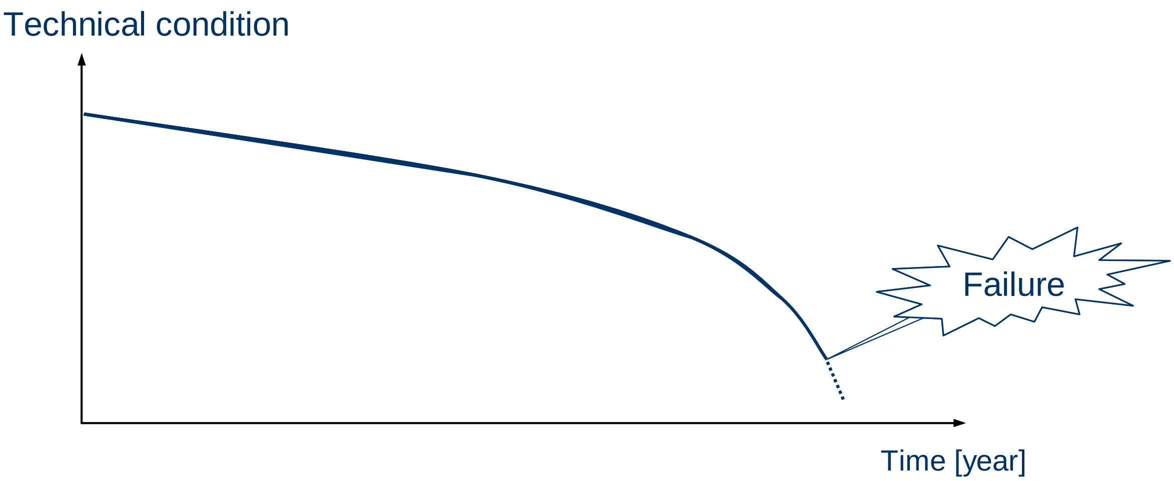


Figure 1   Generic continuous degradation of a component

Very few, if any, condition monitoring methods give a direct and accurate description of the actual technical condition of the component. The condition monitoring methods usually result in an *indication* of the components technical condition. Traditionally, power companies have also conducted condition monitoring using for instance visual inspections. Such methods will not give accurate knowledge of the exact position on a continuous degradation curve.

However, experience has shown that a practical solution is to categorise a component's continuous degradation into a limited number of possible condition states. In the handbook, the degradation of a component from commissioning to failure is simplified by categorizing the technical condition into four defined stages of degradation (states) as illustrated in Figure 2. The state definitions are based on a classification system originally introduced by ABB Energy in Norway [3], and later adopted by the Norwegian Electricity Industry Association [1].

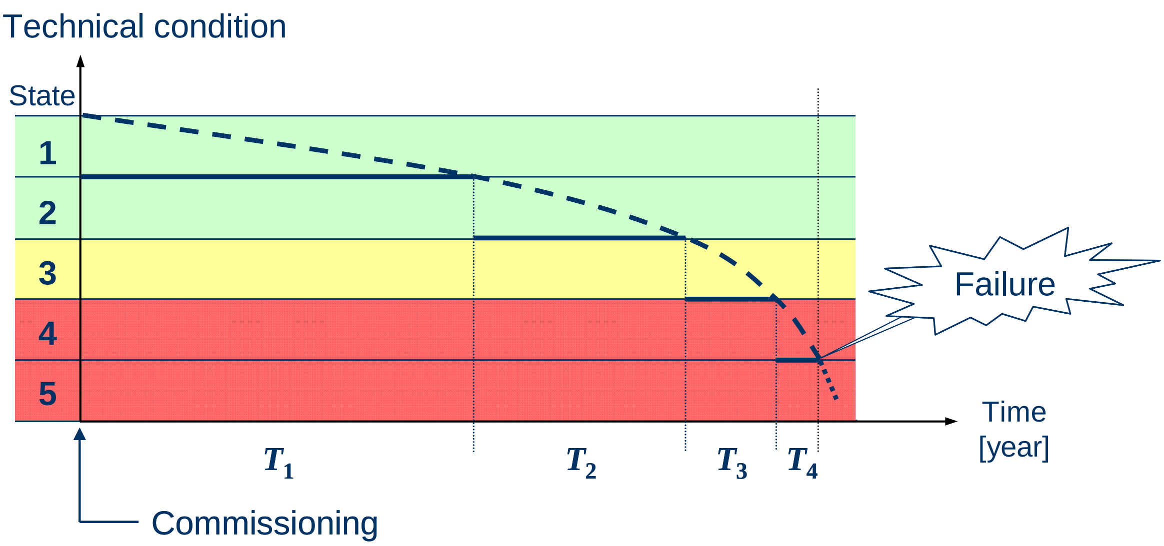


Figure 2   Simplified step-wise degradation curve

State 1 represents an "as good as new" condition (no degradation). State 2 represents a "normal" or "expected" degradation (wear and tear) that normally do not require any maintenance actions (incipient degradation). State 3 represents a condition that normally (sooner or later) would require some preventive maintenance action (severe degradation). State 4 represents a critical condition where maintenance actions should be taken immediately (critical degradation). In case of a failure, the component is in a fault state (state 5) that requires corrective maintenance. If no preventive maintenance is carried out, the technical condition of the component may run through all four states until failure occurs as illustrated in Figure 2.

These 5 state indexes (or health indexes) represent a quantification of a qualitative assessment of the component. A generic description of the 5 different technical condition state indexes, including possible maintenance actions, is summarised in Table 1.

Table 1 Generic description of technical condition state indexes

State	Description	Possible actions (depending on risk assessments)
1	No indication of degradation (the condition is "as good as new'")	No further actions.
2	Incipient degradation (the condition is noticeably worse than "as good as new")	No further actions. Condition may be subject to increased attention.
3	Severe degradation (the condition is considerably worse than "as good as new")	Actions may be conducted before further operation. Condition must be subject to increased attention.
4	Critical degradation (the condition is critical)	Corrective actions should be conducted before further operation.
5	Fault	Corrective actions must be conducted before further operation.

These 5 states can also be related to the more familiar 3 state traffic light analogy with green, yellow and red states. State 1 and 2 can be regarded as "green", state 3 can be regarded as "yellow", and state 4 and 5 can be regarded as "red" as indicated in Figure 2 and Table 1.

The time intervals T_1, T_2, T_3 and T_4 in Figure 2 represents the sojourn times in each of the first four states (the sojourn time in state 5 is of no relevance here).

Condition monitoring handbook structure

The handbook on condition monitoring of wind turbines covers the following components: blades, hub, pitch system, main shaft, bearings, couplings, yaw system, rotor brake, hydraulic system, gearbox, generator, frequency converter, transformer, cables, control system, spinner, nacelle, tower, foundation, earthing and lightning protection system, safety equipment, and wind measuring system.

Each of these components is described in separate chapters. All chapters have a common structure consisting of 4 sections: a component description, typical damages, condition monitoring methods, and a recommended condition monitoring programme. The following 4 sections in this paper detail these 4 sections in each handbook chapter.

Component description

This section gives a short description of the component. The component description starts with the main functions of the component, and continues with the most common technical solutions focusing on characteristics of importance for degradation, condition monitoring and maintenance.

Typical damages

This section gives a short description of the most common damages on the component. All damages, or failure mechanisms, are described in separate tables covering the following elements:

– causes
– possible consequences
– condition monitoring methods
– detection

Table 2 gives an example of a damage / failure mechanism for a gearbox.

Table 2 Gearbox, Tooth – Micropitting

Causes	– Mechanical wear – Impurities in the oil – Fatigue – Material defect – Manufacturing defect
Possible consequences	– Crack formation in tooth – Peeling
Condition monitoring methods	– Visual inspection (may include borescopy) – Oil analysis – Examination of oil filter – Magnetic particle collector – Wind turbine control system
Detection	– Visible signs of micropitting or pitting – Particle content in oil – Wear particles on magnet – Vibrations – Noise – Temperature increase

Condition monitoring methods

This section describes the most relevant condition monitoring methods that can be used to detect the typical damages on the component, and to diagnose the components technical condition. The section focuses on methods that can be used by the power company's own technicians, and that don't require any expert knowledge or tools, including both visual inspections and measurements. For some methods inspection forms and decision-support flowcharts are included.

One of the most important parts of the handbook is that each method description contains qualitative and/or quantitative criteria for the classification of the technical condition into one out of the four defined states.

The handbook should be applicable for a wide range of wind turbine components, covering different manufacturers, technical solutions, capacity, size, choice of material, etc. It is therefore in general very difficult to give quantified criteria (numerical values) for the different states. The criteria is therefore often given as qualitative criteria, or generic verbal descriptions as “No wear”, “Incipient wear”, “Severe corrosion”, etc.

Table 3 gives an example of criteria for visual inspection of micropitting and pitting in a gearbox.

Table 3 Gearbox, Tooth – Visual inspection (micropitting and pitting)

State	Criteria for state determination
1	No visible sign of wear, or run-in wear with polishing of tooth flanges. Micropitting on up to 10 % of tooth flange, typical in a corner or along the “bottom” of tooth flange [*Normally a run-in problem that doesn’t develop further*].
2	Micropitting on up to 50 % of the tooth flange. [*Normally a run-in problem that doesn’t develop further, but that should be kept under observation*]
3	Incipient pitting (small pits in the tooth flange), typical in combination with micropitting. [*Normally a run-in problem that doesn’t develop further, but that should be kept under observation*]. Heavily polluted magnetic particle collector.
4	Widespread pitting with peeling in larger areas. Very heavily polluted magnetic particle collector.

It is emphasised that in general the criteria given in the handbook are not absolute, and only indicative or guiding. The actual criteria may vary from one wind turbine to another depending on size, capacity, choice of material, etc. Each company may therefore define more exact criteria that are appropriate for their wind turbines.

A verbal description of a degraded state may not always be sufficient. Interpretation of the criteria may be different from one technician to another, e.g. how much corrosion is “severe corrosion”? Presenting pictures illustrating typical levels of degradation, i.e. different states, may therefore be a valuable supplement to the verbal criteria.

The handbook contains a large number of pictures illustrating the different levels of degradation for blades, bearings and gearboxes. Examples of such pictures are given in Figure 3 – Figure 6. These pictures are illustrating the same criteria as in Table 3.

Figure 3
Criteria and picture for Gearbox, Tooth – Micropitting, State 1:

“No visible sign of wear, or run-in wear with polishing of tooth flanges. Micropitting on up to 10 % of tooth flange, typical in a corner or along the “bottom” of tooth flange [*Normally a run-in problem that doesn’t develop further*].”

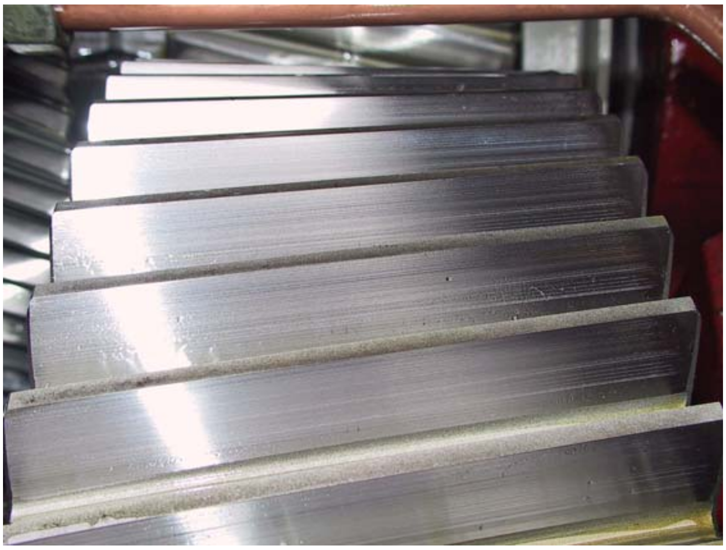


Figure 4
Criteria and picture for Gearbox, Tooth – Micropitting, State 2:

“Micropitting on up to 50 % of the tooth flange. [*Normally a run-in problem that doesn’t develop further, but that should be kept under observation*]”

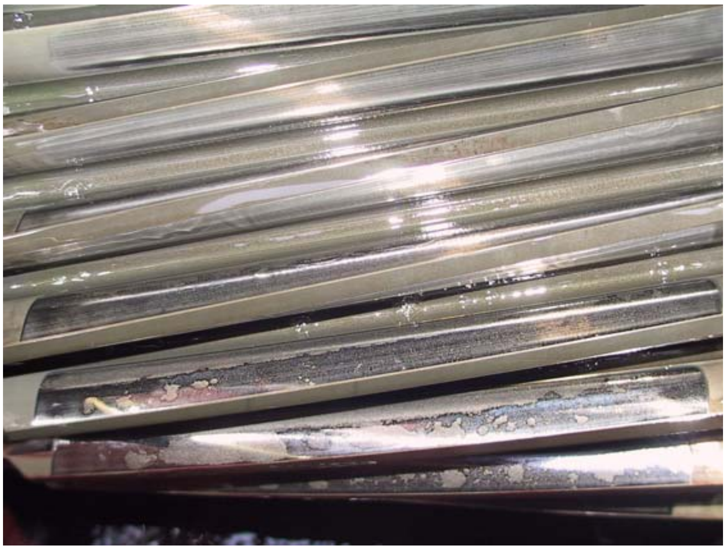
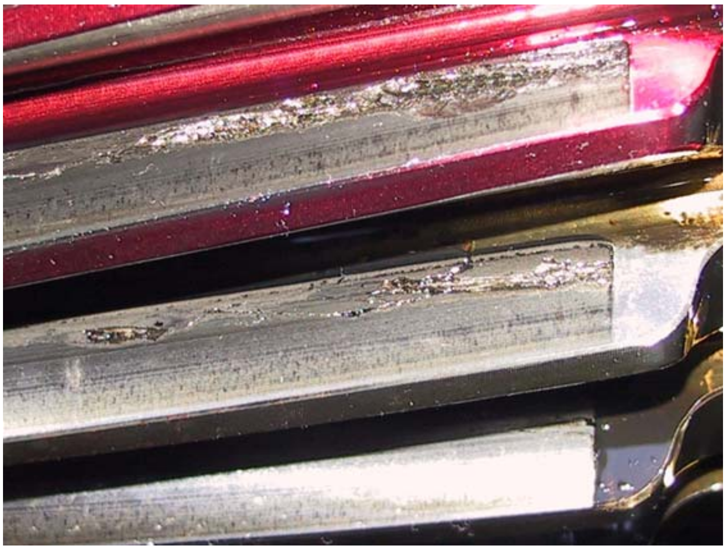


Figure 5
Criteria and picture for Gearbox, Tooth – Micropitting, State 3:

“Incipient pitting (small pits in the tooth flange), typical in combination with micropitting. [*Normally a run-in problem that doesn’t develop further, but that should be kept under observation*]. Heavily polluted magnetic particle collector.”

Figure 6
Criteria and picture for Gearbox, Tooth – Micropitting, State 4:

“Widespread pitting with peeling in larger areas. Very heavily polluted magnetic particle collector.”



All pictures are taken by

DANMARKS VINDMØLLEFORENING.

As long as there are no signs of degradation (i.e. state 1 and 2), no additional measurements are needed. If a severe degradation is indicated (i.e. state 3 and 4) additional measurements may be needed to verify the actual technical condition. These supplementary measurements may also require more expertise, for instance specialists from the manufacturer using more advanced condition monitoring methods and systems. A reduced measuring interval may also be needed, or repair should be conducted within a specified time. If state 5 is observed the component has already failed, but the failure was not yet recognised e.g. due to a hidden function. A generic decision support flowchart is presented in Figure 7.

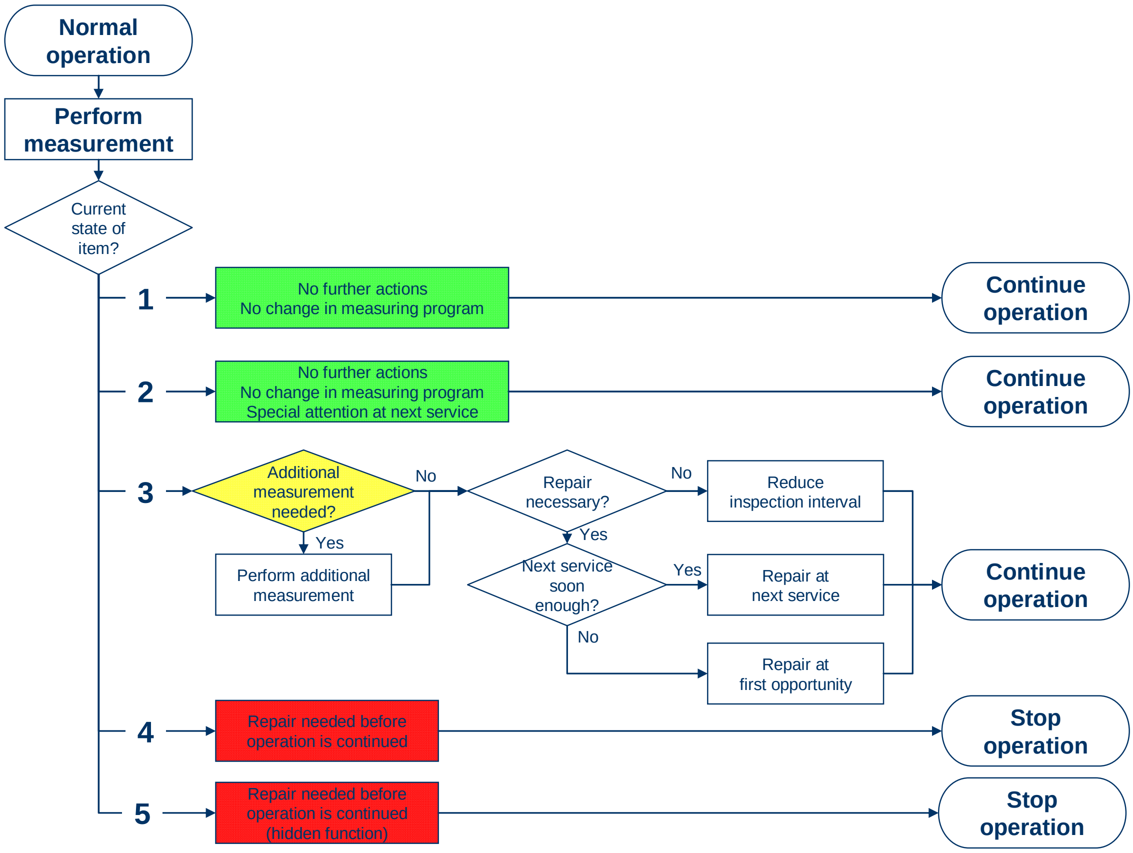


Figure 7 Generic decision support flow chart

Condition monitoring programme

Condition monitoring is often time consuming, demanding and expensive. It is therefore crucial to establish a strategy on which condition monitoring methods to implement, and to establish the appropriate measuring interval. The result of this strategy is a condition monitoring programme for the appropriate monitoring of the technical condition of the component.

This section therefore contains a recommended condition monitoring programme for the component, i.e. a recommendation of both methods and measuring intervals. The optimal measuring interval should be estimated by minimizing the cost of preventive maintenance and the expected cost of failures and reduced efficiency. The recommended intervals are often a little more conservative, and based on experience.

Table 4 gives an example of a recommended condition monitoring programme for a gearbox.

Table 4 Gearbox – Condition monitoring programme

Interval	Condition monitoring method
6 months, or on suspicion	Oil analysis
1 year	Visual inspection
1 year	Torque control on bolt connections
1 year	Function testing
When needed	Visual inspection using borescope
On suspicion	Vibration measurement
On suspicion on irregular wear	Examination of replaced oil filter
On suspicion on crack formation	NDT

It is emphasised that in general the recommended intervals given in the handbook are not absolute, and only indicative or guiding. The actual intervals may vary from one wind turbine to another depending on manufacturer, type of component, age, size, capacity, estimated risk, etc. Each company may adjust the recommended intervals to be more appropriate for their wind turbines. An important premise when using condition monitoring is also that the interval should be adjusted based on the technical condition of the component. This implies that the intervals should be reduced when the probability for (or consequence of) failure is increasing.

Residual lifetime estimation

An important tool in long term planning is residual lifetime estimation. In case of a continuous degradation, the technical condition of the component may run through all four states until failure occurs as illustrated in Figure 2. This can be regarded as a Markov process.

Time series of state indexes from condition monitoring of a large number of wind turbines, e.g. all wind turbine in a wind farm, can be used to estimate expected values for the sojourn times T_1, T_2, T_3 and T_4 in Figure 2. These parameters can be estimated using classical methods such as maximum likelihood or least square methods. If data is scarce, expert judgements can also be added to establish good estimates for the sojourn times. In more advanced models the sojourn times may also be modelled as probability distributions.

Once good estimates for the sojourn times are established, existing lifetime prediction models, together with expert judgements, operational statistics, expected stress, and knowledge of the current technical condition, can be used to estimate expected residual lifetime, failure probabilities, optimal inspection intervals, etc.

A Bayesian approach for the estimation of sojourn time distribution parameters has been presented in [4]. The advantage of using a Bayesian approach is that both data and expert judgement can be used as source of information. It is also shown how censored data from a condition monitoring programme can be utilized. It is described how the data must be processed in order to provide the required input for parameter estimation. The paper also contains examples that illustrate how the approach can be applied in practice.

From the mid 1990's, many power companies in Norway have used the hydro power handbooks and the classification system described in Table 1. They have established long time series with results from condition monitoring, and are now looking into residual lifetime estimation as explained in the paper. For wind farms, with a large number of equal units and more frequent condition monitoring than in hydro power, such tools may be of even higher value.

Summary and conclusions

The main objective of the handbook on condition monitoring of wind turbines is aiding maintenance planners in establishing a well founded condition monitoring programme, and aiding technicians in the technical condition assessment of the wind turbines.

The handbook describes the most common condition monitoring methods, gives recommendations on the intervals between measurements, and defines criteria for the assessment of the technical condition of the components.

A simple rule for condition based maintenance is that when a component has reached state 3, a preventive maintenance action to avoid a possible failure should, based on a risk assessment, usually be planned and finally carried out (short term planning), i.e. the handbook gives the criteria for when to initiate preventive actions.

A more advance level of use is to perform trend analysis on the time series of recorded states in order to plan maintenance or replacement a long time in advance, i.e. long term planning based on estimated residual lifetime.

A systematic and uniform execution of the methods and assessment of the technical condition, combined with a quantification of the results, can therefore identify both short term and long term changes in the components technical condition. The handbook may therefore aid in prioritising components and allocating maintenance resources.

The handbook may also serve as a valuable reference in the education of younger technicians, and as a reference in establishing a common understanding among all technicians in the company on how to actually assess the technical condition of components in wind turbines.

It is emphasised that this handbook on condition monitoring should not replace the manufacturer's service manual. The service manual gives detailed information about bolt connections, oil-levels, etc. that need to be checked, and the recommended intervals ("what to do, and when to do it"). The handbook is a valuable supplement to the service manual focusing on possible damages/failures, and how to discover degradation before failure.

To our knowledge, this is the first handbook on condition monitoring of wind turbines developed in a joint collaboration between several power companies. We are convinced that such handbooks may be useful also for non-Norwegian wind farm owners. This handbook may therefore serve as a good starting point for a manufacturer-independent handbook in English.

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