
**Condition monitoring and diagnostics
of wind turbines —**

**Part 2:
Monitoring the drivetrain**

*Surveillance et diagnostic des éoliennes de production d'électricité —
Partie 2: Surveillance de la transmission*

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 108, *Mechanical vibration, shock and condition monitoring*, Subcommittee SC 5, *Condition monitoring and diagnostics of machine systems*.

A list of all parts in the ISO 16079 series can be found on the ISO website.

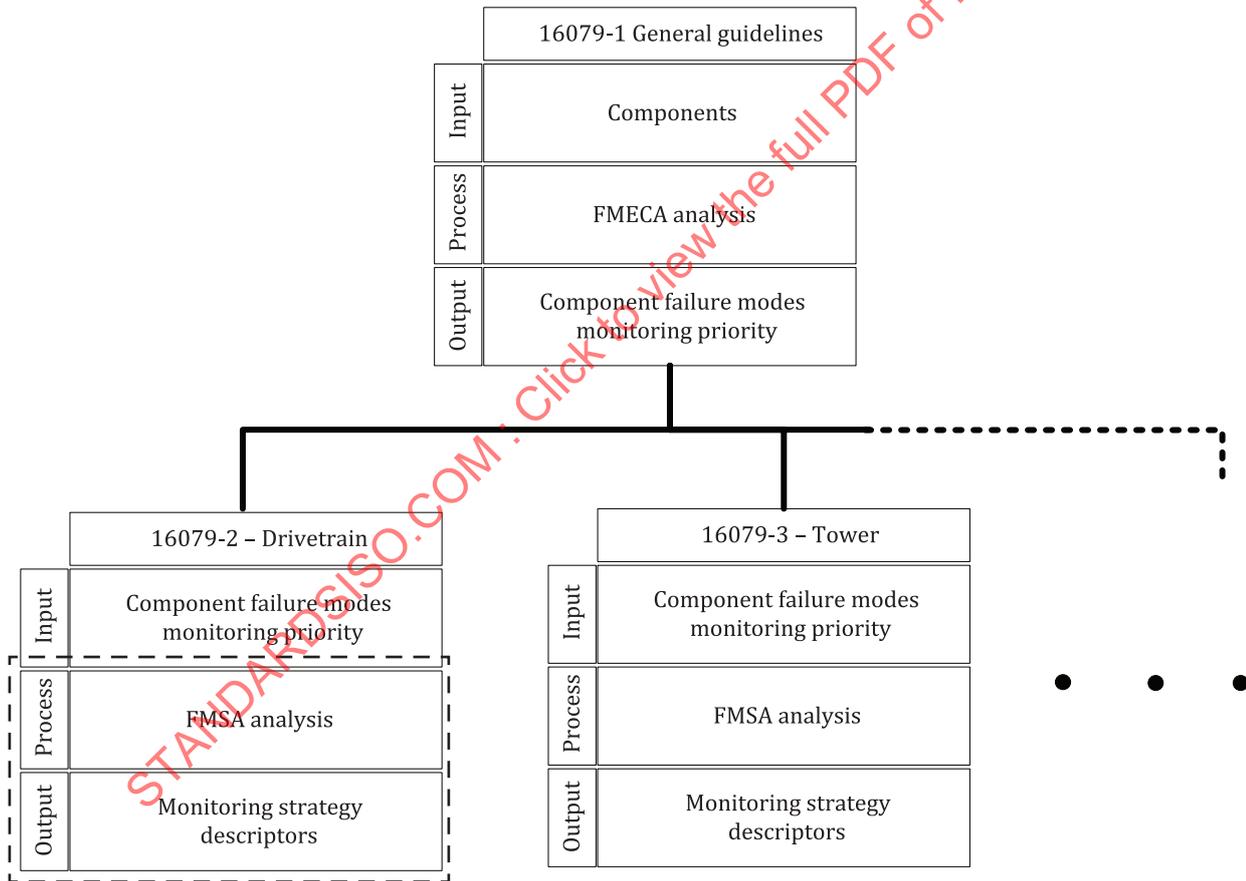
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Introduction

This document is the second step of the procedure for carrying out the CM and D application design phase according to the V-model of ISO 13379-1. In this step, the monitoring strategy for the drivetrain is defined, based upon the prioritized failure modes which were the outcome of the failure modes, effect and criticality analysis (FMECA) procedure performed according to ISO 16079-1 (see [Figure 1](#)).

According to the V-Model of ISO 13379-1 and ISO 16079-1, the steps described in this document are as follows:

- a) decide under which operating conditions the different faults can be best observed and specify the conditions under which the symptom is most likely to be observed;
- b) identify the symptoms that can serve in assessing the condition of the machine, and that are used for diagnostics;
- c) list the descriptors that are used to evaluate (recognize) the different symptoms;
- d) identify the necessary measurements and transducers from which the descriptors are derived or computed.



Key

dotted line scope of this document

Figure 1 — The relationship between this document and ISO 16079-1

In relation to the V-model, this document describes the two last steps of the application design phase of the condition monitoring system. This process shall ensure that data are available to support an

efficient process in the use phase of the condition monitoring system. The end goal of the “Use phase process” is minimizing wind turbine downtime through a risk assessment of a detected fault by means of remaining useful life (RUL) evaluation, and successive determination of maintenance timing. The criticality and risk assessment uses information from the FMECA analysis, but may also feed information back into an adjustment of the initial FMECA analysis (see [Figure 2](#)).

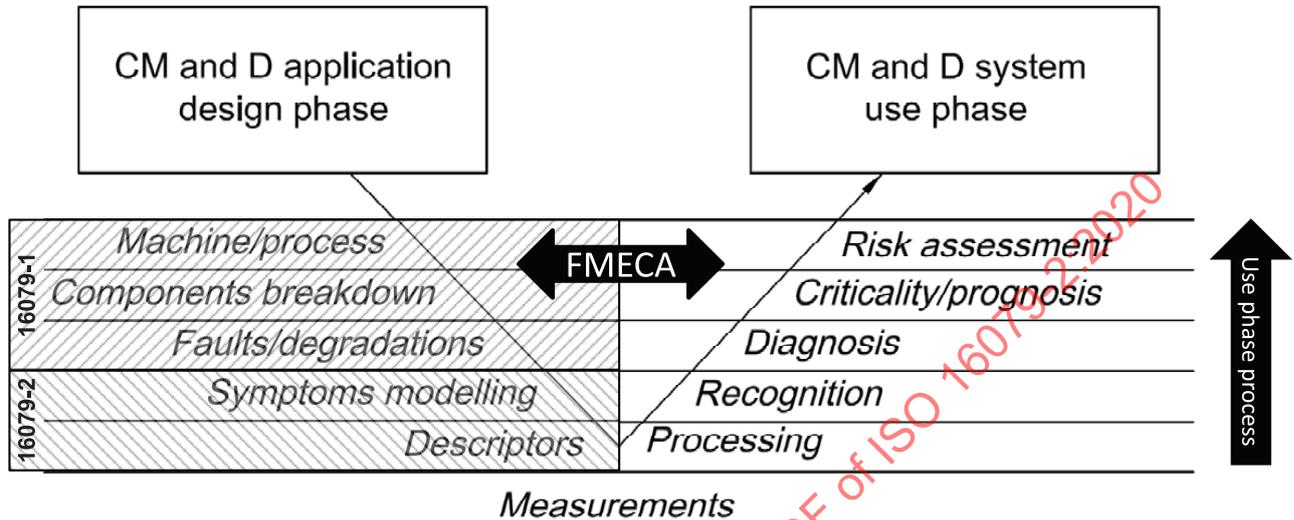


Figure 2 — Condition monitoring and diagnostics (CM and D) cycle: Design phase and use phase of the application on a machine

This document shows how to apply the results of an FMECA analysis made according to ISO 16079-1 by prescribing a methodology for making a failure mode symptoms analysis (FMSA) with the purpose of defining symptoms and related descriptors to detect a particular failure mode.

In order to implement the results of the FMSA, sections with guidelines for condition monitoring of wind turbines are provided, covering:

- 1) guidelines for descriptor measurements;
- 2) adapting to changes in operating conditions;
- 3) selection of transducers and transducer technology;
- 4) selection of transducer locations;
- 5) naming convention for identifying transducer locations and related descriptors;
- 6) evaluation criteria for descriptor measurements;
- 7) requirements to data for diagnosis;
- 8) prognosis and/or criticality assessment; and
- 9) review of the CM & D design:
 - a) assessment of effectiveness of the diagnostics system, and
 - b) cost benefit analysis.

[Figure 3](#) shows the relationship between the monitoring strategy, diagnostic strategy and maintenance strategy and how these important elements support the steps in the condition monitoring process. If the monitoring strategy, the diagnostic strategy, or both are based upon weak or missing data, it compromises the prognosis and the whole purpose of the condition monitoring process.

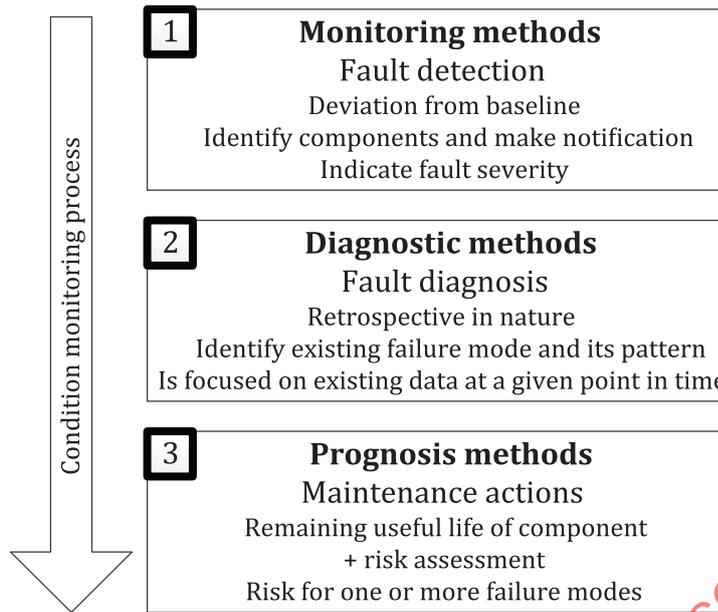


Figure 3 — Relationship between monitoring methods, diagnostic methods and prognosis methods

The selection of the monitoring method is to define where you measure, what you measure and how often you measure in order to provide data for:

- detecting the failure modes designated to be revealed by the condition monitoring system;
- assessing the severity of the present state of the fault;
- assessing the remaining useful lifetime of a certain component.

A weak point in the condition monitoring system setup (e.g. lack of transducers or bad transducer location, limitations in what can be measured, or too sparse data) affects the end goal of the condition monitoring process – the prognosis.

The choice of the diagnostic method is to provide enough data for:

- detailed analysis of a failure mode and identification of the root-cause;
- assessing the severity of the present state of the fault;
- assessing the remaining useful lifetime of a certain component.

The purpose of the prognosis is to make a prediction of remaining useful lifetime (RUL) of a component and assess the risk for related failure modes (secondary failure).

The maintenance action is based upon the data provided by the monitoring methods, the diagnostic methods and the prognosis methods, and on knowledge of maintenance history and alarm history. Therefore, it is very important that not only measured data are stored, but also information about earlier alarms, maintenance actions and identification of persons which have been involved with earlier alarm handling on the machine.

Condition monitoring and diagnostics of wind turbines —

Part 2: Monitoring the drivetrain

1 Scope

This document specifies the implementation of a condition monitoring system for wind turbines, with particular focus on monitoring of the drivetrain. Guidance for a practical implementation of the FMSA is provided, as well as guidance for specifying best practices and minimum recommendations regarding the condition monitoring system used for failure mode detection, diagnostics and prognostics of the direct drive and geared wind turbine drivetrain, including:

- a) main bearing(s);
- b) gearbox, if applicable; and
- c) generator (mechanical aspects).

This also includes subcomponents such as coupling and the lubrication system.

This document provides an overview of the important aspects of condition monitoring of wind turbines and makes references to other standards where in-depth information on the subjects is available.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 2041, *Mechanical vibration, shock and condition monitoring — Vocabulary*

ISO 13372, *Condition monitoring and diagnostics of machines — Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 2041 and ISO 13372 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <http://www.electropedia.org/>

3.1

time waveform

sampled vibration signal recorded from the transducer

Note 1 to entry: Time waveform recordings have a certain length in time and represent a parameter value at every instance during the recording of the time waveform.

4 Abbreviated terms

Table 1 gives the explanations of abbreviated terms used in this document

Table 1 — Abbreviated terms and their explanations

Abbreviation	Explanation
ETTF	Estimated time to failure.
FFT	Fast Fourier Transform.
FMECA	Failure modes, their effect and criticality analysis.
FMSA	Failure mode symptoms analysis.
IEPE	Integrated electronics piezoelectric. An accelerometer type using constant current supply. The abbreviation CCS (constant current source) is also used for this type of accelerometer.
IIoT	Industrial Internet of Things. Refers to a subcategory of the broader Internet of Things (IoT). Both concepts have the same main character of availability of intelligent and connected devices. The only difference between the two is their general usages. While IoT is most commonly used for consumer usage, IIoT is used for industrial purposes, such as manufacturing, supply chain monitoring and management systems.
MEMS	Micro electromechanical system. Applies to any sensor manufactured using microelectronic fabrication techniques. These techniques create mechanical sensing structures of microscopic size, typically on silicon. When coupled with microelectronic circuits, MEMS sensors can be used to measure physical parameters, such as acceleration.
n_{MP}	Monitoring priority number.
OPC	Open platform protocol. The purpose of OPC is to define an open common interface that is written once per device and then reused by any SCADA, HMI, or custom software packages. The OPC Foundation maintains the OPC standard, which has been adopted by IEC as the IEC 62541 series.
RUL	Remaining useful lifetime.
TCP/IP	Transmission control protocol/Internet protocol. The suite of two protocols, TCP and IP, used to interconnect network devices on the Internet.

5 Failure mode and symptoms analysis (FMSA)

5.1 General

The FMSA process is essentially an extension of the FMECA process with a focus on the symptoms produced by the identified and ranked possible failure modes that were the outcome of the FMECA analysis.

The FMSA methodology is designed to assist with the selection of monitoring techniques and strategies that provide the greatest sensitivity to detection and rate of change of a given symptom, thus maximizing the confidence level in the diagnosis and prognosis of each of the failure modes identified for each of the components of the wind turbine drivetrain.

Where the confidence in a technique's sensitivity and resulting diagnosis/prognosis accuracy is questionable, then the use of additional techniques for further correlation is recommended.

Refer to ISO 16079-1 which gives guidance on applying FMECA analysis to wind turbines.

5.2 The process of the FMSA analysis

The FMSA analysis shall be a team effort with participation of condition monitoring experts as well as participation of staff with an in-depth knowledge of the machine under analysis.

The essential elements of the FMSA process are:

- listing the components involved;
- listing the possible failure modes for each component;
- listing the effects of each failure mode;
- listing the causes of each failure mode;
- listing the symptoms produced by each failure mode;
- listing the most appropriate primary and feasible monitoring technique;
- listing the estimated frequency of monitoring – monitoring interval;
- listing the most appropriate correlation techniques. Increased diagnosis and prognosis confidence can be gained by using “correlation techniques” when monitored at a given frequency.

The FMSA analysis shall be performed for each component/failure mode, which can be prioritized by using the monitoring priority number (n_{MP}) of the FMECA analysis.

A practical approach is to use copies of [Table 2](#) to structure the FMSA process.

Refer to the example in [Annex B](#) which shows an FMSA analysis for the most common failure modes of the wind turbine drivetrain.

Table 2 — Template for implementation of the FMSA analysis

Component: <RDS-PP reference>	<descriptive name from FMECA analysis>		<short name according to IEC 61400-25-6>
Failure mode	<name of failure mode from FMECA analysis>		
Cause of failure mode	<What is the failure mode caused by>		
Effect of failure mode	<What is the effect of the failure mode. What happens>		
Monitoring priority number (n_{MP})	<monitoring priority number from the FMECA analysis>		
P-F Timescale	<Rough assessment>		
Symptom(s)	<describe the symptom(s) indicating the failure mode>		
Descriptors	<descriptor name>	<explanation>	
	<descriptor name>	<explanation>	
	
Primary monitoring technique	<describe detection method>		
Monitoring interval	<interval between successive descriptor measurements>		
Operational state bin parameter	<descriptor name> if more than one correlation parameter, add more rows to the table.		

6 Descriptors for fault detection

6.1 General

The FMSA process provides a list of potential fault indicators – the descriptors; this clause describes how some of those descriptors may be derived.

NOTE In some literature, the term “characteristic value” is used instead of “descriptor”.

The format of a descriptor is a single scalar value and a timestamp. This makes descriptors very suitable for long term trending against time. Changes in the measured value of descriptors are very easily detected and correlation between different descriptor values such as vibration-based values and

process parameters is straightforward. Any database historian can store descriptor values due to the simple format.

Regardless of the technique, the capability of a condition monitoring system relies upon the following basic elements: the number of sensors, the type of sensors, and the associated signal processing and simplification methods utilized to extract important information in the form of descriptors from the various signals and observations.

A symptom indicating a fault is expressed by the behaviour of one or more descriptors with respect to:

- presence,
- absence,
- increase or decrease,
- rate of change,
- location(s) of the change of descriptor,
- operating conditions.

The more selective the descriptors are, the more selective the symptoms, and therefore, the easier the diagnosis. The descriptor selectively reduces the number of fault hypotheses when inferring from symptoms to fault.

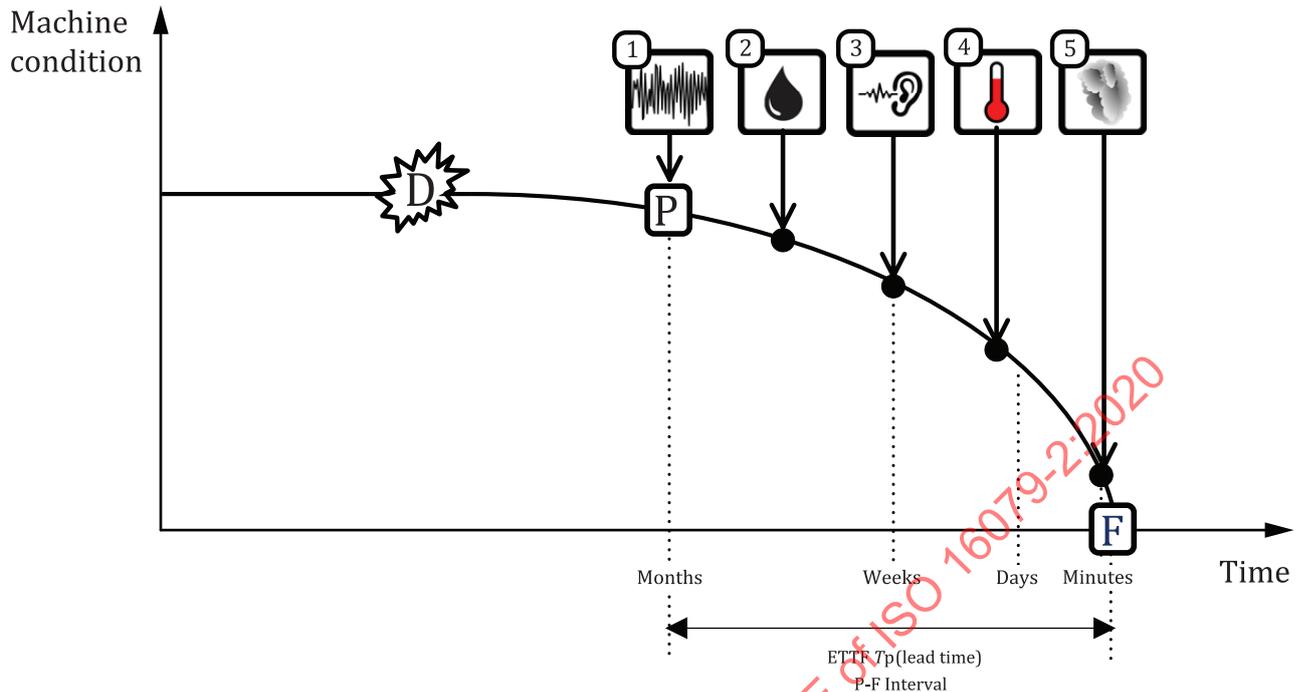
The number of descriptors which are defined shall be considered very carefully. It shall be ensured that each descriptor provides value and redundancy shall be avoided. The resources for performing the condition monitoring increase with the number of descriptors, as a result of the increased number of potential alarms due to statistical outliers.

6.2 Descriptor types

The descriptors are chosen based on the FMSA, which has provided a range of characteristics of specific faults. The most common descriptor types utilized for fault detection on the wind turbine drivetrain can be grouped as follows and derived from:

- process parameters,
- rotational speed,
- vibration signals,
- on-line oil analysis.

The most common types are descriptors based upon vibration. Descriptors derived from process parameters such as rotational speed, wind speed and actual power are often used for compensating vibration-based measurements with respect to varying operating conditions. On-line oil debris measurements are used for detecting ferrous or non-ferrous particles in the oil. [Figure 4](#) provides an example representation of the development of a mechanical failure.



Key

- D fault starts to develop
- P point where fault is detectable (potential failure)
- F point where functional failure occurs
- 1 point where increase in vibrations can be detected by advanced descriptors
- 2 point where mechanical wear particles can be detected by oil analysis
- 3 point where audible noise can be detected
- 4 point where temperature increase can be detected by temperature sensors
- 5 point where smoke can be detected by smell or visually

NOTE The example in the figure represents how a bearing failure would develop in most cases. Some gear faults can be detected earlier by oil analysis. The sequence of detection depends very much on the capabilities of the vibration monitoring system.

Figure 4 – Example representation of the development of a mechanical failure

6.3 Descriptors based on process parameters — Operational values

6.3.1 General

- a) Process parameters or operational values are most often values acquired from the wind turbine controller or by direct measurement using a transducer. It may be values such as temperature, pressure, load, voltage, wind speed, wind direction, pitch, active power and bearing temperatures.
- b) Such parameters are self-contained, in that they can be trended against each other and/or against time with no further processing. For these parameters, the pattern of change in value on a millisecond basis does not provide additional information over the inherent longer-term value.
- c) The value of the scalar measurement forms the descriptor. Process parameter descriptors can be used for the following:
 - Trend versus time, e.g. to visualize changes in bearing temperature.

- Correlation: trend vs. other descriptors to visualize any dependency between one or more descriptors.
- Operational state classification: for adapting the alarm evaluation of consecutive vibration measurements to the running conditions.

Examples of important process parameter descriptors include:

- **Active power:** this process parameter is important as it is proportional to the load on the wind turbine; in general, the stress on the components is higher when power production is high. Active power correlates also very well with the vibration level sensed on the components of the drivetrain. Active power is an important parameter for operational state classification.
- **Wind speed:** this process parameter also indicates the stress the wind turbine has been exposed to.
- **Temperature:** monitoring the temperature of a component is a very common condition monitoring method. Temperature monitoring is used to detect the presence of any potential failure related to temperature changes in the component. Temperature monitoring is used on components such as bearings, oil, and generator windings. Temperature monitoring provides information on the ongoing deterioration process in the component from excessive mechanical friction due to faulty bearings and gears, insufficient oil properties, and loose or bad electrical connections. However, temperature develops slowly and is not enough for early and precise fault detection. Furthermore, the measured temperature can also be influenced by the surroundings. Temperature is a valuable secondary source of information together with vibration monitoring.

6.3.2 Measurement of process parameter descriptors

Process parameters are usually provided by:

- 4-20 mA current loop signal: the 4-20 mA current loop is a common method of transmitting sensor information in many industrial process-monitoring applications. Transmitting sensor information via a current loop is particularly useful when the information must be sent to a remote location over long distances as the current loop is able to compensate for the voltage drop on the signal line. Many older wind turbine controllers can provide process parameters via a 4-20 mA output.
- Voltage: some controllers provide a voltage signal proportional to the process parameter. However, this is not as common as the 4-20 mA current loop and not suited for transmitting signals over long distances.
- Via LAN: process parameters may be acquired directly from the controller, or from the SCADA system via network protocols. High level protocols such as Modbus TCP/IP or OPC are very common. Some vendors have their own proprietary network protocols.

6.4 Measurement of rotational speed and descriptors based on rotational speed

6.4.1 General

Measurement of the rotational speed is important for compensating other descriptors for variation in the rotational speed of the turbine. Many descriptors used for indicating failure modes on the drivetrain are speed dependent. This means that they are not measured at a certain fixed frequency but are measured at a frequency which is a certain ratio to the running speed. Gearbox descriptors such as the vibration level at the tooth meshing frequencies are typical examples of speed dependent descriptors.

The raw speed signal can be stored as a time waveform, or as time stamps related to trigger points related to shaft position. ($1/\text{rev}$ or n/rev). This data can be used for further processing of rotational-speed-related descriptors and in detailed diagnostic investigations.

6.4.2 Measurement of rotational speed

It is important to select the correct sensor type and the correct number of sensors for the speed measurement.

- 1) Phase reference tachometer: usually inductive proximity switches or incremental encoders are used as a speed reference. In most cases (depending on the gear box transmission ratio), it is enough to only have one tachometer pulse per revolution at the high-speed shaft, as this facilitates both measuring the vibration magnitude and the phase of the vibration signal. Phase measurements are useful when it is needed to detect shaft related problems. For analysis of the low speed rotor, it is useful to have a separate phase reference on the low speed shaft for vibration vector analysis.
- 2) Incremental encoders, either on the high-speed shaft or input shaft, provide a phase and a more accurate speed measurement. If two incremental encoders are used, a torsional vibration measurement is possible.
- 3) Speed measurements from the turbine controller can only be used if the accuracy and resolution is sufficient. Insufficient resolution may lead to faults when doing speed dependent analysis.

6.5 Descriptors based on vibration

6.5.1 References to other standards

For more information on the content of this clause, refer to:

- ISO 5348,
- ISO 13373-1,
- ISO 13373-2,
- VDI 3832.

6.5.2 General

When using vibration data for condition monitoring, the raw signals from the vibration transducers contain a lot of information about the machine component. Unlike a traditional process parameter (e.g. a temperature), which is measured at a certain location, the raw signal from a vibration transducer can be further processed to extract several different descriptor types indicating the vibration level at the characteristic frequencies of the different machine components. Vibration is caused by the motion of the turbine components on either a macroscopic level (e.g. introduced by unbalance or misalignment) or a microscopic motion (e.g. introduced by impacting, fatiguing and friction).

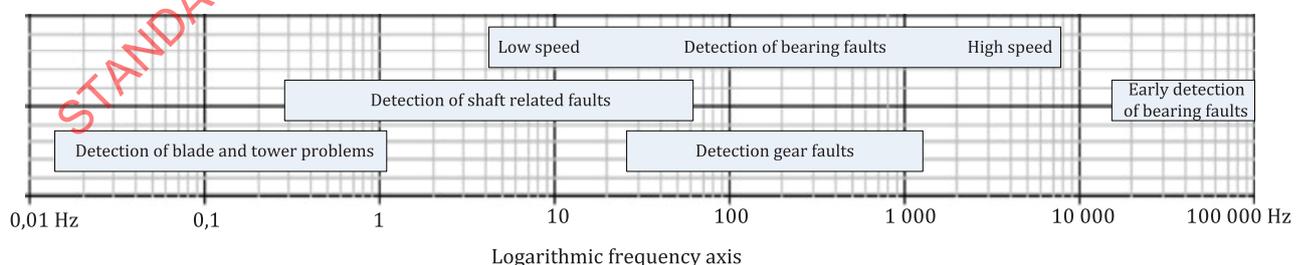


Figure 5 — Typical representation of frequency ranges for failure modes on a wind turbine

As an example, one descriptor can indicate if a bearing fault is present by measuring the vibration level at the outer ring of a certain bearing, another can indicate the vibration level at the shaft running speed and can indicate misalignment, unbalance or other shaft related faults. [Figure 5](#) indicates the need for different descriptor types in a wide frequency range for detecting vibration related failure modes on a wind turbine.

Vibration based descriptors are generated by the digital processing of the raw time waveform signal recorded by the vibration transducer; this can be done in three different ways:

- a) time domain-based descriptors;
- b) frequency domain-based narrowband descriptors;
- c) descriptors extracted from array measurements such as autospectra, envelope spectra, cepstra.

Each descriptor implementation has its advantages and drawbacks. There is basically no limit to how descriptors can be calculated; they all have one thing in common. That is, to convert complex information into a single descriptor value to be used for simple trending.

[Annex A](#) contains examples of the different descriptor types and clarifies the differences.

6.5.3 Measurement of vibration

When measuring vibration, it is important to select the correct physical parameter for the descriptor type:

- **Acceleration:** this is the parameter which is measured by the piezoelectric accelerometer. Acceleration measurements are weighted towards high frequency components and shall always be chosen when the frequency range of interest covers high frequencies. Accelerometers can measure at very low frequencies too, but acceleration signals do not emphasize low frequency components.
- **Velocity:** velocity measurements are most often obtained by electronic or digital integration of the acceleration signal. Velocity sensors which make a direct measurement of the velocity signal is available but are not so robust and have a limited frequency range. The RMS value of the velocity measurement is widely used for vibration severity measurements. This is because vibratory velocity is simply related to vibratory energy and is therefore a measure of the destructive effect of vibration.
- **Displacement:** the nature of mechanical systems is such that appreciable displacements only occur at low frequencies, therefore displacement measurements are of limited value in the general study of mechanical vibration. Displacement is often used as an indicator of unbalance or misalignment because relatively large displacements occur at the shaft rotation frequency. Descriptors based upon displacement values are normally measured by using a displacement sensor. Displacement values can also be obtained by double integration of the acceleration signal. However, double integration shall be used with much care as it requires a high dynamic range of the original acceleration signal in order not to be affected by the noise level of the measurement system. For measurement of absolute position in radial and axial direction, e.g. of main shaft, only a displacement sensor can be used.

The most common types of transducers for vibration measurements are IEPE type accelerometers and MEMS based accelerometers.

6.5.4 Transducers for vibration measurements

6.5.4.1 IEPE type accelerometers

It is recommended to use an IEPE type accelerometer, also sometimes referred to as line drive accelerometer or constant current source accelerometer (CCS). This transducer has a built-in integrated circuit with a charge to voltage converter. It requires an 18 V to 24 V DC power supply with constant current. This requirement for voltage supply is normally not a problem in a permanent installation such as in the wind turbine. The transducer sensitivity of an IEPE accelerometer is stated in $\text{mV}/(\text{m}/\text{s}^2)$ or mV/g .

If there is a need to measure velocity, it is common to integrate the output from the accelerometer in order to make a conversion to the velocity unit $\text{mV}/(\text{mm}/\text{s})$.

The IEPE type accelerometer has several properties which make it suitable for wind turbine monitoring:

- It has a wide amplitude and frequency range.

- It is robust. The environment where wind turbines operate can be unfriendly. Transducers are also sometimes subject to physical impacts during service and repair.
- It can operate in a temperature range from -40 °C to 100 °C . Wind turbines are located in all types of areas, from some of the warmest near equator to very cold in the mountains of the northern or southern hemisphere.
- It has a fast shock recovery. Transducers experience shock and overload during bursts of wind.
- It has a low cost.

The following shall be observed when selecting an accelerometer:

- a) The frequency range shall be linear in the range from 0,7 Hz to 10 kHz.
- b) The mounted resonance frequency shall be around 25 kHz to 30 kHz. The frequency range of the measuring system should generally cover frequencies from the lowest rotational frequency to up to 3,5 times the highest excitation frequency of interest. Typically, the highest excitation frequency is a tooth meshing frequency or a mechanical resonance caused by rolling element bearing faults. It is beneficial to have a measuring system covering the frequency range well above the transducer resonance frequency, as this enables very early detection of rolling element bearing defects. The lowest frequencies are around the rotor shaft rotational frequency. However, to keep transducer cost low, it is not required that the frequency range is linear down to 0,1 Hz. A linear roll of the transducer frequency characteristic is enough to ensure reliable relative measurements.
- c) Sensitivity shall be selected as appropriate to the frequencies of interest on different parts of the drivetrain. Commonly, $10,2\text{ mV}/(\text{m}/\text{s}^2)$ ($100\text{ mV}/\text{g}$) is used on the high and medium speed section and $50,9\text{ mV}/(\text{m}/\text{s}^2)$ ($500\text{ mV}/\text{g}$) is used on the slow speed section of the drivetrain. Sensitivity shall be verified by trial measurements before decision.
- d) The sensor shall have an allowable tolerance of max. $\pm 5\%$ of the calibration sensitivity.

6.5.4.2 MEMS based accelerometers

This type of accelerometer has all the same good physical properties as the IEPE accelerometer and it is even cheaper; the sensor can measure down to DC. The MEMS accelerometer requires a power supply of 6 V DC to 30 V DC.

Characteristics of a MEMS sensor compared to an IEPE accelerometer:

- MEMS sensors have a measurement range starting from DC. Can be used for static measurements such as inclination.
- MEMS sensors are available with a wide range of resonance frequencies. The cheapest MEMS sensors have the lowest resonance frequencies, e.g. a few kHz. More expensive types have a resonance frequency comparable with IEPE accelerometers.
- MEMS sensors have a higher noise level than IEPE accelerometers. IEPE accelerometers are considered better than MEMS for low level vibration measurements

However, technology is moving quickly, closing the specification gap between IEPE and MEMS accelerometers.

6.5.5 Vibration transducer mounting

Placement and mounting should consider the wide range of frequencies of interest, the frequent shock loads and the potential for high temperatures at the measurement positions. Rigid mounting should be ensured, particularly when high frequencies need to be measured, but also to withstand the shock loads.

The preferred method for attaching fixed transducers is a rigid mechanical fastening, which is commonly achieved by drilled and tapped holes in the transducer and the machine and joining the two

by a threaded stud. Stud mounting is good for transfer of high-frequency signals with little or no signal loss. The machine surface before mounting shall be smooth, flat and clean. Application of a light coat of silicone grease, or equivalent, to all mating surfaces is recommended to improve the transmissibility and accuracy of the response signal, especially at high frequencies. For new machines, the necessary preparation of measurement points should be provided by the manufacturer.

Where it is impractical or impossible to use a stud-mounted mechanical connection, cements are used to fasten a transducer mounting plate to the machine surface. The cement used shall be of the type that has high stiffness characteristics when cured. Resilient adhesives should not be used as they reduce the fidelity of the transmission of the signal. Measurement errors and frequency response are both influenced by the transducer fitting.

No matter which mounting method is applied, it is important that sensors are attached in an accessible location using a method which allows easy replacement. See [Clause 10](#) and Reference [19] for more in-depth information on transducers and their mounting.

6.6 Descriptors based on stress wave measurements

6.6.1 General

When impacting, fatiguing or friction events occur, stress waves are generated which propagate through the structure at the speed of sound within the metal. This produces ripples on the surface of the machine component.

Several techniques are available for the measurement of high frequency impacts through the use of stress waves generated by the impacts between moving parts and surface imperfections. These are variously known as ultrasound, shock pulse, acoustic emission or stress wave techniques. All detect the same types of signal but do so in different ways.

These techniques are particularly suitable for early detection of bearing failures, especially on low speed bearings, from which the defect signatures are often at similar frequencies to various component speeds, and so get swamped in the response to the motion of the machine.

Application: for early detection of bearing problems. A popular technique is to use the accelerometer resonance frequency for amplifying the stress wave signal, followed by an envelope analysis or peak detection using a bandpass filter spanning both sides of the resonance followed by either an envelope analysis or a peak detection algorithm.

Advantages: stress wave measurements are very sensitive to incipient indicators of bearing faults such as sub surface fissures, cracks or friction caused by missing lubrication. Stress waves are only generated at impact sites and are not caused by the bodily movement of the machine in response to shaft motion, unless an overload of some sort is occurring. They are also sensitive to subsurface fissures or cracks, and the effects of poor lubrication.

Disadvantages: the sensitivity is very dependent upon the transmission path. Due to the transmission path dependency, it is difficult to assess the severity of the fault, so it is not possible to standardize on acceptable or unacceptable levels in the signal. It is difficult to assess the type of fault and the location. The signals are vulnerable to noise due to flexure of the structure. Normally, there is no transmission path for this to reach the transducer, however if the transmission path is available the signal becomes very noisy. Stress wave sensors are very prone to noise created by all other types of impact, not necessarily coming from bearing damage.

6.6.2 Measurement of stress waves

The attenuation of the stress waves is frequency dependent, with the higher frequency components attenuating more rapidly than the lower frequency components as the measurement point is removed from the point of origin. This is especially true when stress wave packets must cross physical interfaces such as from shaft or inner race of a bearing to the observation point on the outer structure of the machine. Stress wave signals indicating bearing faults are detected in the frequency range of 15 kHz to 60 kHz.

Measurement methods are:

- a) Demodulation by envelope analysis. The bandpass filter for the envelope analysis shall be placed around the accelerometer resonance frequency. In this way, the accelerometer resonance is used to amplify the stress wave signals before analysis.
- b) Peak detection of the time waveform signal. This technique also uses measurements around the transducer resonance frequency. However, unlike the envelope method, the signal never passes through a low pass filter. Instead, the peak values are extracted from the signal.
- c) Direct analysis of the stress wave signal. As technology allows condition monitoring systems with analysis capabilities in the frequency range above 50 kHz, frequency analysis methods as applied in lower frequency ranges can be used.

6.6.3 Transducers for stress wave measurement

Accelerometers: the advantage of the accelerometer is that it responds to signals in a broad frequency range, which means that the primary energy from the stress waves initiated from impacting, fatiguing, and friction can be captured. The disadvantage is that the accelerometer also picks up all other signal from the machine.

Ultrasound transducers: this type of transducer applies to the frequency range above 20 kHz. This type of sensor is tuned to specific centre frequencies, e.g. 25 kHz. They only respond to the stress waves generated by the existence of a defect and do not pick up the normal bodily movement of the machine due to the rotation of the drivetrain. For more information on ultrasound transducers, refer to ISO 29821-1.

Acoustic emission sensors: acoustic emission sensors can measure stress waves in a higher frequency range than ordinary accelerometers and ultrasound transducers. The frequency range for acoustic emission is above 50 kHz and up to the MHz range. Transducers are based on piezoelectric crystals which are mostly undamped having very high sensitivity at the resonance. The acoustic emission sensors are sensitive to motion in any direction.

Strain gauges: this type of sensor is normally applied for structural loading of tower and blades and as such is outside the scope of this document.

6.6.4 Mounting of stress wave sensors

Stress waves propagate in all directions. Hence the selection of axial, vertical, or radial is not important. However, it is important that the sensor be placed near the load zone and as close to the initiation site as possible. The sensor can be an accelerometer or an ultrasound sensor. As the propagation of stress waves is critical to the passing of physical surfaces, it is important to take care when mounting the transducer; this applies especially to the ultrasound transducers which are sensitive only to a narrow frequency range.

6.7 Descriptors based on oil debris in lubricant oil

6.7.1 General

In the context of oil condition monitoring, it is important to distinguish between two different objectives.

Monitoring oil quality: oil quality monitoring is used to assess the quality of the oil to determine the need of an oil change. The parameters monitored are water content, viscosity, dielectric constant indicating oxidation of the oil and oil cleanliness level based on particle size distribution according to ISO 4406. The particle size measured to determine oil cleanliness is very small and shall not be confused with the particle sizes relevant for oil debris.

Monitoring oil debris content: oil debris (also often referred to as wear debris) content can indicate a developing fault in the mechanical components of the gearbox. The particle size to be detected is normally $>40\ \mu\text{m}$.

Although the quality of the oil eventually affects the components of the gearbox, this document is focused on detecting mechanical faults of the wind turbine drivetrain. Thus, only descriptors based upon debris content in the oil are included, as those descriptors can indicate a mechanical fault.

6.7.2 Oil debris descriptors

The most common failure modes of wind turbine gearboxes are bearing spall and gear teeth pitting which release metallic debris particles in the oil lubrication system. Monitoring of the particle concentration is thus well suited to provide an early indication and quantification of internal damage to bearings and gears of a wind turbine gearbox.

It has been found that the different wear behaviours show up in four debris features:

- a) concentration;
- b) size;
- c) morphology (characteristics such as shape, texture and colour); and
- d) composition.

Since debris concentration and size both increase by increasing of wear degree, they can reflect wear severity and wear rate. Concentration and size can be measured by an on-line oil debris sensor. In most cases, these sensors detect ferrous as well as non-ferrous particles. Oil particle morphology and composition need to be investigated off-line from an oil sample and can tell about the wear type and likely location of the fault. Thus, morphology and composition are not well suited for on-line monitoring.

Common on-line oil debris descriptors include:

- cumulative counts in bins according to particle size;
- cumulative mass;
- particle size: this is to express severity;
- short term rate of change of concentration on an hourly basis: this is to respond to a count rate of change sufficiently rapidly;
- long term rate of change of concentration on a daily basis: this is to maintain an average count rate under variable conditions of wind turbine operation.

The estimated damage propagation count rate is then set as a weighted average of the short- and long-term moving averages.

6.7.3 Oil debris sensors

The oil debris sensor type which is most widespread for condition monitoring of wind turbine gearboxes is usually an inductive device that installs in-line with the oil system in the gearbox. If there are several separated oil systems in the gearbox, an oil debris sensor is required for each. An oil debris sensor counts metallic particles resulting from pitting or spalling of bearings and gearwheels of the gearbox.

The sensor has a magnetic coil assembly and operates by monitoring the disturbance to an alternating magnetic field caused by the passage of particles through the magnetic coil assembly. Each time a particle passes through the sensor, an electrical pulse is generated which is counted.

An oil debris sensor can count ferrous as well as non-ferrous particles. The oil debris sensor usually groups the particle counts in several bins depending upon the particle size. The oil debris sensor is mounted in the dirty side of the oil filter.

7 Descriptor monitoring interval

7.1 Reference to other standards

For more information on the content of this clause, refer to:

- ISO 17359;
- ISO 13373-1.

7.2 Factors influencing the monitoring interval

The monitoring interval is the lapse of time between two subsequent measurements of a descriptor. The monitoring interval primarily depends on the following:

- the type of the failure mode to be detected;
- the type of the descriptors used for detection. Some descriptors are calculated by using processing methods, which are focussed on early detection of particular failure modes of a turbine component. These types of descriptors often indicate a fault several months before failure. Other descriptor types are focussed on assessing the severity of the overall vibration level of a turbine component. These types of descriptors indicate changes only weeks or days before failure;
- the typical rate of change of the failure mode, that is, if it normally develops in an exponential or linear fashion.

Figure 6 illustrates how the same failure mode is expressed in the trend using different descriptor types.

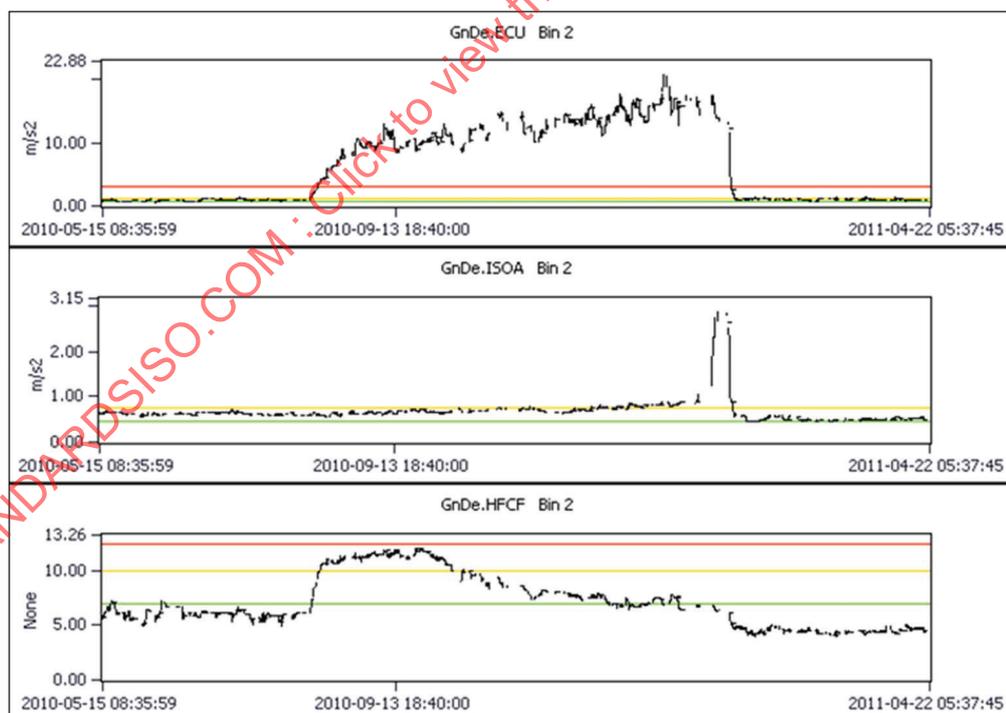


Figure 6 — The same bearing fault detected by three different descriptor types

NOTE The different descriptor types show 3 different lead times: a broadband envelope descriptor (GnDe.ECU), a descriptor based on ISO 10816-21 (GnDe.ISOA) and a descriptor based upon a Crest Factor (GnDe.HFCF). The sudden drop in vibration is due to exchange of the bearing.

Figure 6 illustrates that the choice of descriptor for fault detection is an important factor for estimating the remaining useful life and the measurement interval. The lead time indicated by the envelope (ECU)

and the crest factor descriptor (HF_{CF}) shows differences in months towards the ISO based descriptor. The rate of change of the ISO based descriptor shows that the selection of measurement interval is more critical for this parameter.

[Figure 6](#) also illustrates that the choice of parameters can be used to express the criticality of the fault. When the envelope and the crest-based descriptor starts to develop, the fault is far from critical. However, when the ISO based descriptor starts to change, repair shall be considered. When the overall vibration severity becomes unacceptable, the risk of failure is high and failure may be imminent.

Lead time can be influenced by factors such as operating conditions and number of starts and stops. It is therefore advisable to consider a measurement interval ensuring that descriptors are measured under all operating conditions and that a significant number of descriptor measurements are recorded between each start and stop of the turbine.

It is possible that different descriptor types require different measurement intervals. [Figure 6](#) illustrates for example that the descriptor relating to RMS vibration in the ISO band may be stored with very short intervals as it provides a good overview of the general condition of the turbine. Other more complex descriptors can provide long lead-times to failure and are perhaps only required once per month; however, in practice, most systems have little restrictions to storage capacity which allows storage more often. Storage of data several times per day increases the possibility of recording descriptors under various operating conditions. Averaging techniques such as exponential averaging or median filtering can then be applied to provide the representative values stored in the database server with hours interval.

8 Descriptor notification criteria

8.1 Reference to other standards

The following standards provide guidance for alarm and alert limits:

- ISO 10816-21,
- ISO 13373-1,
- ISO 13373-2,
- ANSI/AGMA 6000-B96 (R2002).

8.2 General

There are three factors which shall be considered when establishing notification criteria of descriptors measured on a wind turbine:

- a) descriptor/symptom magnitude,
- b) any significant change in descriptors, and
- c) rate of change of the descriptors.

Evaluation criteria are specified by a set of alarm and alert limits for each monitored descriptor. Typically, an alert and alarm are specified; however, it is acceptable to have more than two limits for this purpose. Instead of alarm, the terms “danger” or “trip” limits are also commonly used. In addition, some of the descriptors can also require lower thresholds instead of or as well as upper thresholds (e.g. tower natural frequency, or gearbox oil temperature):

- **Alert limit:** change in a descriptor value through this limit indicates the detection of a particular symptom relating to the condition of the machine has occurred. If correctly set, no immediate action is required; the symptom is now observed, and maintenance can be planned for the future (see also clause on prognosis below).

- **Alarm limit:** a continued change in a descriptor value exceeding this limit indicates a serious or even unacceptable increase in the level of a descriptor. If correctly set, the ALERT limit will have already triggered the planning of remedial action, which is now required in the short term.

When commissioning a new machine, the evaluations shall be made based on the vibration magnitude relative to some predetermined and agreed-upon permissible values. Once a machine has been commissioned and normal operating magnitudes have been determined, any evaluation is made not only based on the magnitudes, but also on the basis of any significant change that takes place.

8.3 Establishing descriptor alarm and alert limits for a new turbine

It is important that a turbine be monitored from the time of commissioning. As no vibration history exists for a new turbine, initial default alarm and alert limits must be established by using some agreed upon permissible values. Default alarm limits cannot be defined on all descriptors as many descriptor types show high variation from turbine to turbine. Time domain-based band pass descriptors covering a broad frequency range are good candidates for initial alarm limits as they show less variation and guidance for limits are covered by ISO standards.

EXAMPLES

- Initial alarm limits can be derived from ISO 10816-21 for RMS vibration; however, this covers only a small subset of possible descriptors. Limits for gearboxes can be derived from ANSI/AGMA 6000-B96 (R2002).
- Initial alarm and alert limits can be derived from limits which have been set on turbines of the same type. Limits for the new turbine can be calculated by considering average values and standard deviation of limits from other turbines.

8.4 Establishing alarm and alert limits for a turbine in normal operating condition

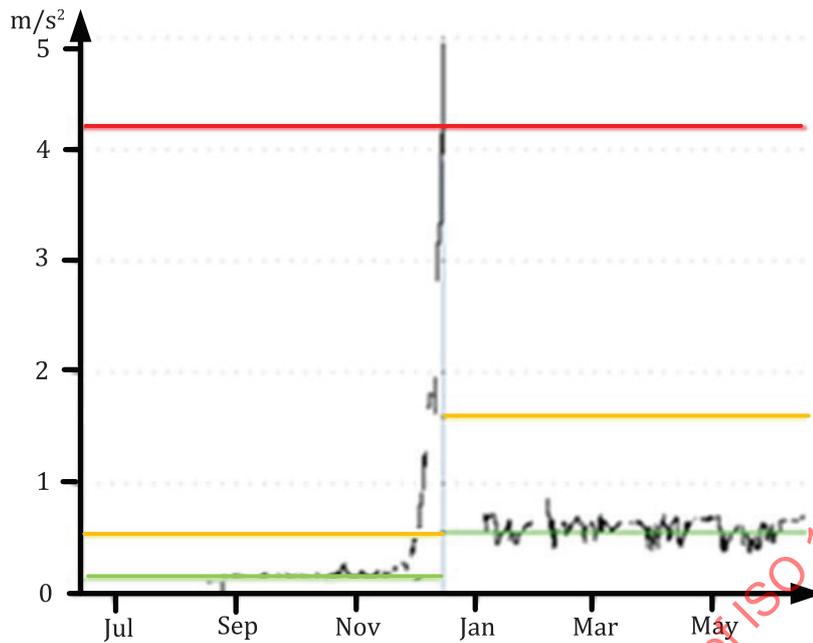
Once a machine has been commissioned and confirmed to be operating normally, alert levels are reassessed based on variation of the descriptor values seen in normal operation.

Alert limits shall be individual for each turbine and can be based on a statistical calculation of the recorded values for each individual symptom. It is important to set the alert limits as low as possible in order to get an early detection of incipient faults. However, descriptors relating to symptoms which only appear when a defect occurs can be extremely low when the machine is in its “as new” condition, in which case the alert level should be adjusted to a realistic value sufficiently above the noise floor to prevent nuisance alarms.

It happens sometimes that vibration levels show step changes where it is not possible to relate the increase in vibration to any change in the condition of a mechanical component. In such cases, the new vibration level shall be observed for a period of time before new alarm limits are set in order to ensure that the new level remains constant.

8.5 Establishing alert limits upon component change

If a turbine component is exchanged, e.g. a generator bearing or a coupling, it is very important that the alert limits be re-learned. Otherwise, important changes may go undetected (see [Figure 7](#)).



NOTE It is obvious that the alarm limits had to be re-learned. The differences in normal vibration levels before and after repair indicate that the repair was carried out badly.

Figure 7 — Example on trend before and after exchange of coupling on the high-speed shaft

9 Handling changes in operating conditions — The operational state bin concept

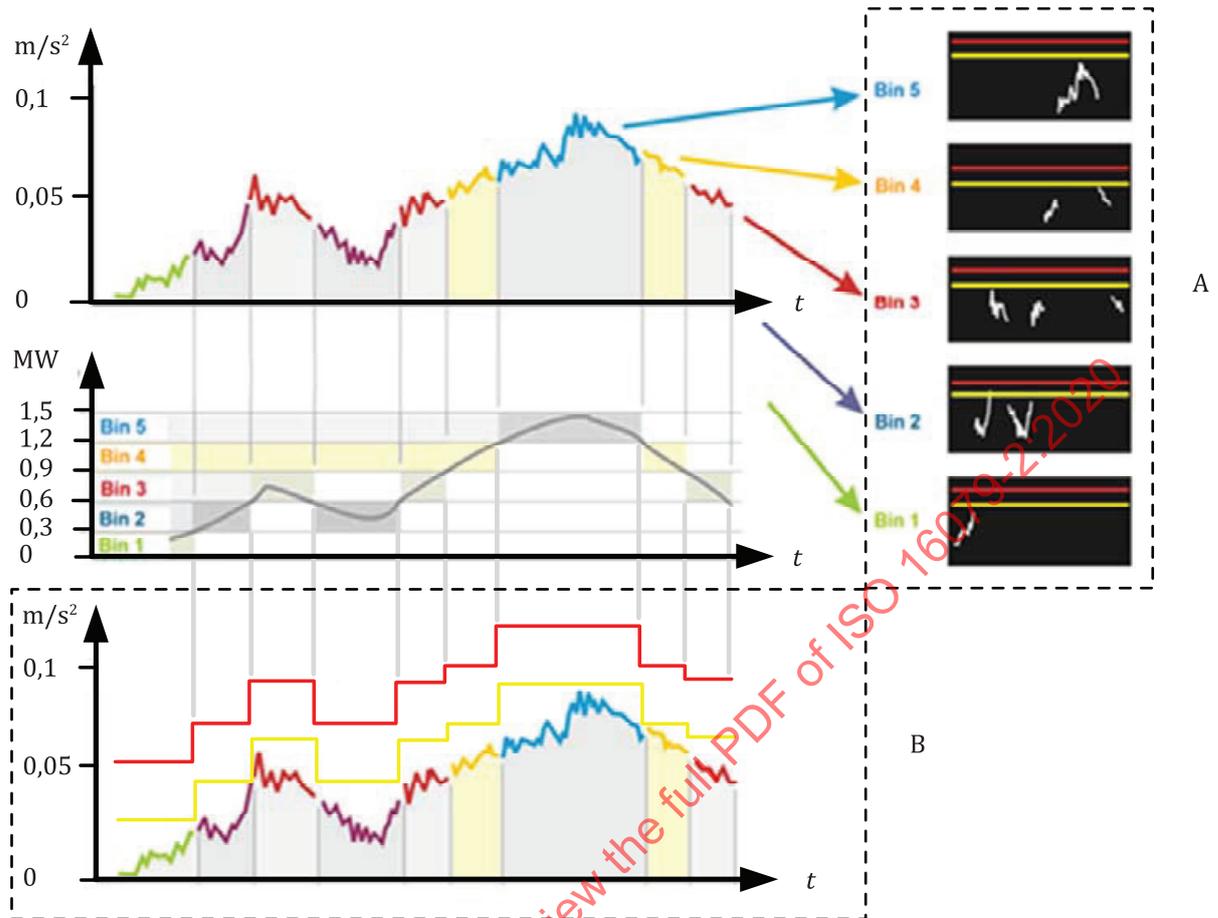
9.1 General

In order to describe the environment for a set of condition monitoring measurements, the operational state bin concept has been developed. A wind turbine operates in principle over a wide range of wind speeds causing a large variety of loads on the mechanical structures. An adaptive monitoring technique is often applied to secure a higher degree of reliability and repeatability of measurements used to detect developing faults in the full operating range, thus reducing the risk of triggering false alarms. In order to adapt to the varying operating conditions, data can be stored according to several operational states in multiple dimensions. The basic principle of condition monitoring is to observe the evolution of specific measured variables by comparing new measurements with previous ones. The effect of changes in operational conditions can be limited by comparing information belonging only to the same operational state.

9.2 Example of how to use active power as an operational state

Active power levels are used for the adaptive monitoring technique rather than the wind speed as the vibration level measured and the stress on the turbine components are found to be closely related to the active power production of the turbine. By using the active power level as the measurement trigger, it is also ensured that vibration measurements are recorded only when a wind turbine is producing active power.

Figure 8 illustrates two ways of adapting alarm limits to operational states of the turbine.



Key

- A adaptive monitoring using the power bin concept; data are stored in separate bins and evaluated towards a set of alarm limits defined for each bin
- B adaptive monitoring using process dependent alarm limits; for each defined process state a separate alarm limit is defined

Figure 8 — Two ways of implementing process dependent alarm limits

10 Transducer locations

10.1 Reference to other standards and guidelines

The following standards provide guidance for transducer locations:

- IEC 61400-25-6
- DNV-GL IV-4
- ISO 5348
- ISO 10816-21

10.2 Location of vibration transducers

The number of transducers for vibration monitoring of the drivetrain depends on the outcome of the FMSA analysis. Only sensors required to pick up the specified descriptors are necessary. The number of transducers and their positions shall be selected in such a way that all the meshing and defect/rotation

frequencies can be measured reliably. Under certain circumstances it can become necessary to perform trial measurements during operation to find out the optimal positions for the transducers.

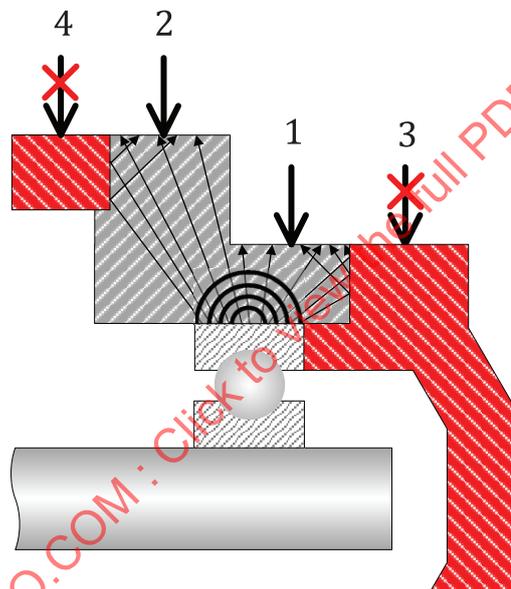
When selecting transducer positions, it is important to make sure that the vibration is transmitted directly from the origin of the condition relevant vibration to the transducer.

The following rules apply:

- a) Mount the transducer as close to the component as possible.
- b) Mount the transducer in the zone of highest load. That is, in the position and direction which predominantly shows the highest loads depending on operating conditions.
- c) Avoid transducer positions where the vibration signal must pass boundaries between materials before it is picked up by the accelerometer (see [Figure 9](#)).

However, sometimes it is necessary to mount transducers in locations where it is practically possible, or due to specifications from gearbox manufacturers or other component suppliers.

Reference [19] contains in-depth information about piezoelectric accelerometers.

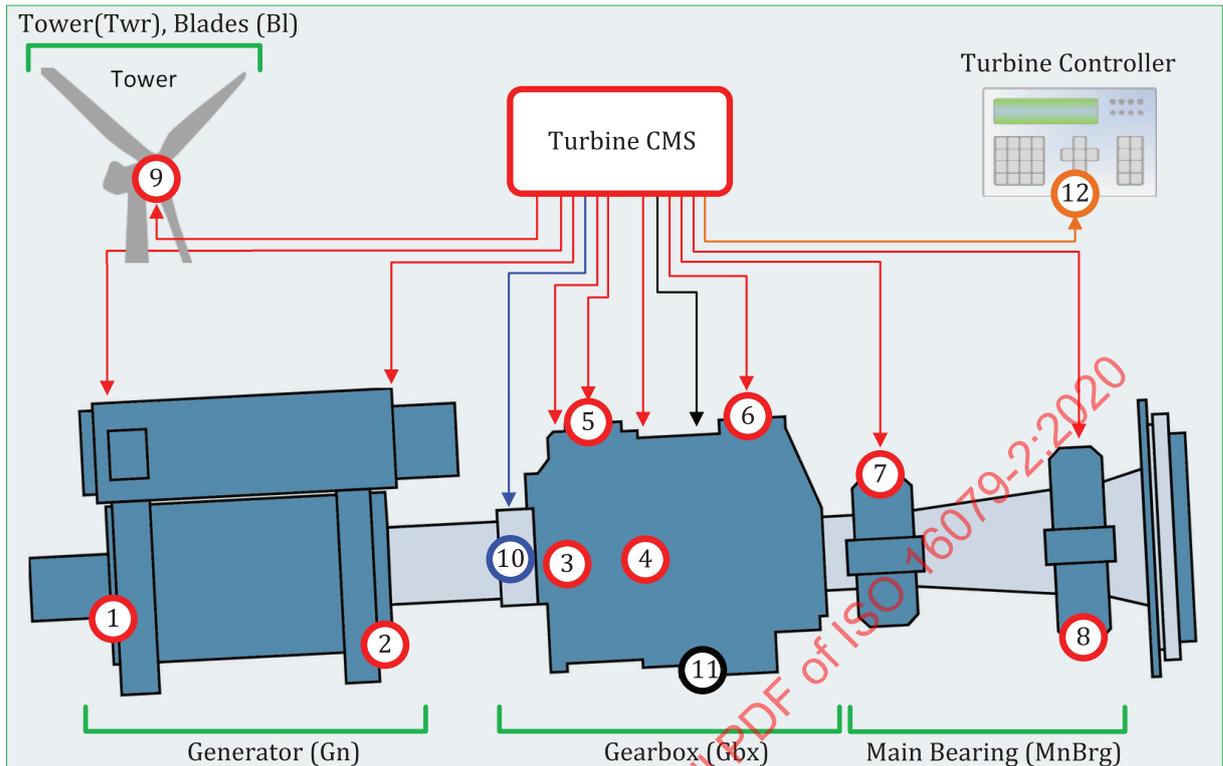


Key

- 1 direct transmission - recommended as point of measurement
- 2 direct transmission - recommended as point of measurement
- 3 boundary within transmission path - not recommended as point of measurement
- 4 boundary within transmission path - not recommended as point of measurement

Figure 9 — Vibration signal reflected and damped at boundaries between components and materials

[Figure 10](#) shows an example of mounting locations of accelerometers, speed sensor and an oil debris monitor on a turbine with a conventional gearbox with one planetary stage and two helical stages and two main bearings. This arrangement of the transducer positions can be transferred as appropriate to other gearbox types and drivetrain concepts. If necessary, additional transducers shall be installed.



Key

- Red circles 1-9: vibration sensor locations
- Blue circle 10: speed sensor (tacho) location
- Black circle 11: oil debris sensor
- Orange circle 12: import of process parameters from turbine controller

Figure 10 — Mounting locations of transducers on a turbine drivetrain

10.3 Location of stress wave transducers

Stress wave transducers shall be as close to the load zone as possible, e.g. like positions 7 and 8 in [Figure 10](#).

10.4 Location of oil debris sensors

An oil debris sensor is in general placed before the oil filter inlet. However, this may also be gearbox dependent and what is practically possible is that sometimes a secondary loop in the lubrication system is required.

10.5 Example of naming conventions and transducer locations

Since a wind park generally consists of many wind turbines, each of them equipped with several types of transducers, a convention for identifying a transducer is essential. In IEC 61400-25-6, a detailed wind turbine condition monitoring information model is defined. This standard also provides a systematic and easy interpretable syntax for naming of transducer locations and the descriptors measured at those locations. A few examples are given in [Table 3](#).

Table 3 — Transducer location and naming according to IEC 61400-25-6

No	Transducer location	Name according to IEC61400-25-6	Transducer type/Orientation
1	Generator non drive end	GnNDe-ACR	Accelerometer/radial direction
2	Generator drive end	GnDe-ACR	Accelerometer/radial direction
3	High-speed rear	GbxHssRr-ACR	Accelerometer/radial direction
4	High-speed front	GbxHssFr-ACR	Accelerometer/radial direction
5	Intermediate stage	GbxIss-ACR	Accelerometer/radial direction
6	1st planetary stage	Gbx1Ps-ACR	Accelerometer/radial direction
7	Main bearing rear	MnBrgRr-ACR MnBrgRr-SWR	Accelerometer/radial direction Stress wave sensor/radial direction
8	Main bearing front	MnBrgFr-ACR MnBrgFr-SWR	Accelerometer/radial direction Stress wave sensor/radial direction
9	Tower/nacelle	NacXdir-AC NacZDir-AC	Nacelle accelerometers
10	High-speed shaft	HssShf-MPR	Magnetic pickup/radial direction
11	Gearbox oil circuit	GbxOilFil-OD	Oil debris sensor located at the oil filter

11 Baseline — Initial recording of data for diagnosis at commissioning time

11.1 General

At commissioning time, it is recommended to make an initial recording of raw time waveforms on all relevant transducers on the turbine.

- For initial diagnostic examination. As condition monitoring is based upon detecting differences in descriptors and symptoms, it is very important to know whether the turbine is in a good condition at the time when surveillance starts.
- For preserving a baseline (finger print) of the turbine. The baseline can be used as reference for all later time waveform recordings. In the case that a failure has not been detected, it is very important to be able to review whether there were any indications at the time when surveillance started.
- New baseline recording shall be made on component basis upon component exchange.
- Baseline recordings shall be stored until the turbine is de-commissioned.
- It is especially important that the baseline data be recorded during the rated operating conditions for the wind turbine.

It is recommended to accompany the baseline recording of raw time waveforms by a full set of descriptor values including process parameters indicating the turbine operating conditions.

11.2 Duration of time waveforms for baseline recording

As a guideline, the minimum duration of time waveforms for baseline data shall using [Formula \(1\)](#):

$$T_w = 10 (1/v_r) \quad (1)$$

where

T_w is the duration of the time waveform in (sec);

v_r is the shaft speed in (Hz).

This formula provides a good compromise between measurement time and the practical circumstances of recording the time waveform. The duration of the time waveform decides how high a resolution can be obtained by the frequency analysis. A time waveform of a longer duration enables analysis with a higher frequency resolution.

11.3 Repeatability and stability of time waveform recordings

For the purposes of repeatability and stability, it is necessary that there be no significant change of speed or load within the period of recording a time waveform. The amount of allowable variation should be definable within the condition monitoring system, and the system should automatically reject the recording if conditions vary by more than specified during the sampling period. Even where order tracking is used to compensate for changing speeds, the vibration of the machine can have been affected significantly, particularly if load was also changing.

Figure 11 shows stability criteria for the recording of time waveforms. Note that if a process descriptor such as power is used to trigger data collection, it should remain within the specified trigger range for the entire measurement duration and should not vary at a higher rate than specified in the measurement set up. If these conditions are not met the measurement shall be rejected

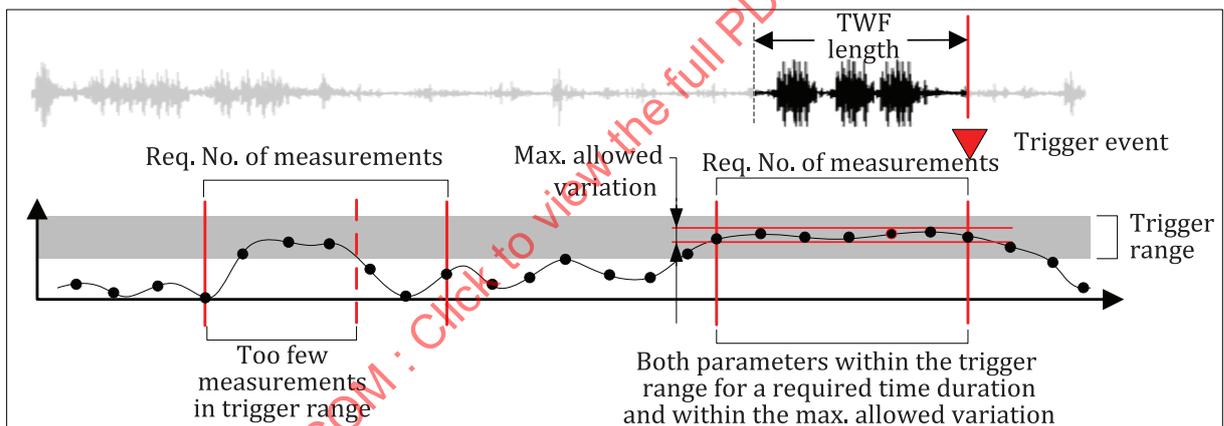


Figure 11 — Stability criteria for recording of time waveforms

11.4 Sampling rate of time waveform for baseline recording

The sampling rate is dependent upon the analysis frequency range required for the specific component. The analysis frequency range is the maximum frequency to be obtained of a spectral analysis. As a rule of thumb, the sampling frequency shall be 2,56 times the required analysis frequency range. The analysis frequency range is established from the frequencies of interest generated by the various components. That is, when making baseline measurements for a high-speed stage of the gearbox, an analysis frequency range of approximately 4 or 5 times the highest tooth mesh frequency of the gearbox shall be applied in order to allow for analysis of the higher harmonics of the tooth mesh frequencies and any related sidebands. For more information on this subject refer to ISO13373-2.

11.5 Initial check of the baseline data — Recommendations

- Perform a manual check of the time wave forms for impacts patterns to get a rapid and good indication of whether any failures are present.
- Perform a peer-to-peer comparison to other turbines of the same type.

12 Diagnosis of faults and their causes

12.1 Reference to other standards

For more information on the content of this clause, refer to:

- ISO 17359;
- ISO 13373-3.

12.2 General

Diagnosis is a retrospective process where existing data is used to assess the fault type and its causes and to assess the severity of the fault. The outcome of the diagnostic process shall be used as input to the prognostic process where the purpose is to estimate the remaining useful lifetime of a given component.

In order to support this process, a condition monitoring system shall provide information about the machine and be capable of recording data which shall be used for the diagnosis.

12.3 Component data

When vibration data is used for the diagnosis, kinematical data regarding the components of the machine shall be available, that is, data such as rotational speeds, number of teeth on gears, and characteristic frequencies of rolling element bearings.

When oil debris analysis is applied, data such as the oil path of the machine, oil flow rate and metal composition shall be available.

12.4 Raw-data time waveforms for detailed diagnosis

In order to make a detailed diagnosis without any constraints, recording of high-resolution raw time waveforms is recommended. Regular recording and long-time storage of time waveforms also enable a detailed analysis of unknown failure modes which may not have been detected by the descriptors configured for the monitoring process. New descriptors can be designed as an outcome of this process, thus allowing a continuous improvement of the monitoring system.

In order to support the detailed diagnosis, it is important to:

- record the speed reference signal along with the raw time waveforms from the vibration sensors. This allows order-based analysis of signals relating to any of the shafts in the gearbox by making angular resampling of the vibration signal. The recording of the speed reference signal shall have enough resolution to allow for resampling when performing order analysis. That is, it shall be possible to derive the time duration of one revolution;
- record a selection of process parameters such as active power, wind speed, pitch angle as time series or discrete values synchronous with the raw time waveforms.

Time waveforms shall be recorded synchronously in groups of channels as appropriate to the drivetrain layout (e.g. all the transducers on a gearbox). This allows investigation of simultaneous phenomena and correlation of events on all transducers mounted on the drivetrain.

The rules specified for duration and sampling rate of time waveforms for baseline recording apply also to recording of time waveforms for detailed diagnosis.

12.5 Regular recording

In order to facilitate a flexible and detailed diagnostic process, it is recommended to record time waveforms at certain time intervals from each transducer on the wind turbine.

The recording interval should depend on:

- component type and thereby the P-F interval – refer to FMSA analysis;
- networks bandwidth;
- storage capacity on the data server.

It is important that the CMS system be able to record time waveforms corresponding to the defined operational states for the wind turbine.

12.6 Recording on request

To support an ongoing diagnostic process, it shall be possible to request time waveforms on demand if additional data are required.

13 Prognosis

13.1 Reference to other standards

For more information on the content of this clause, refer to ISO 13381.

13.2 General

Prognosis is an important aspect of a condition monitoring system. In contrast to the diagnostic process, which is retrospective, the prognosis is focused on the future. In order to get the full benefits of a condition monitoring system, prognostic capabilities are required to predict the remaining useful life (RUL), RUL is the amount of time in terms of operating hours until the component causes loss of production due to functional failure. A functional failure does not necessarily mean the machine has failed catastrophically, but rather, it is no longer functioning in its intended state (e.g. production capacity).

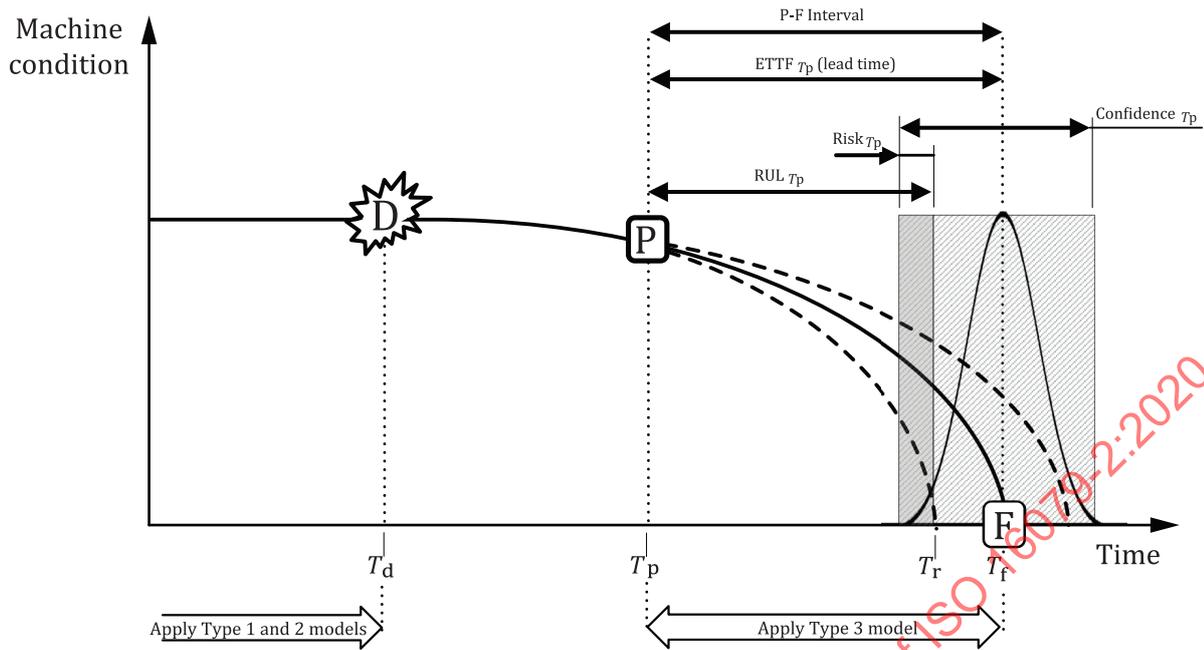
A reliable prognosis requires large amounts of data and reliable data collection from several sources. Such a requirement is very well supported by IIoT which provides well proven platforms for data collection and storage, thus enabling the user to have full focus on developing the prognostic methods.

Prognostic methods can be categorized by the type of information and method used for the prognosis:

- **Type I: Time-to-failure data based.** This is based upon reliability techniques using methods like Weibull analysis where probability of failure is obtained from failure histories of a high number of samples or laboratory testing. It estimates the life of an average component operating under average conditions and applies to components of the same type.
- **Type II: Stress based.** This considers environmental stresses such as temperature, load, speed, number of starts and stops. Methods under this category estimate the life of an average component under given usage conditions.
- **Type III: Condition based.** Uses measures of performance and condition to estimate RUL for a given component. The degradation is measured in terms of the value of one or more descriptors. This information can be used to narrow down the uncertainty of the RUL predictions initially based upon the reliability-based estimate.

Type I and Type II prognostic models can be categorized as physics based or model-based methods and Type III prognostic models as data driven models.

A hybrid prognostic approach can be made up as a combination of reliability (whole population) estimates and condition-based estimates. Emphasis changes from the former to the latter during the life of an individual component.



Key

- D fault starts to develop
- P point where fault is detectable (Potential failure)
- F point where functional failure occurs
- T_d time when fault starts to develop; until T_d , physics based models for RUL estimation are applied - the reliability approach
- T_p time when potential failure can be detected
- T_f time when functional failure occurs; between T_p and T_f data driven models for RUL estimation are applied
- T_r indicates the defined risk zone for the RUL assessment taking the confidence of the ETTF assessment into account
- P-F this is the interval between the detection of a potential fault and functional failure
- RUL remaining useful lifetime defined as a function of accepted confidence level indicated by the grey square, and the risk

Figure 12 — Illustration of the key concept of RUL

13.3 Type I — Failure data-based prognostics — Statistically based

Traditional approaches to reliability estimation are based on the distribution of event records of a population of identical units. One of the most common models for estimating machine reliability is the Weibull distribution due to its ability of making statistics using historical event data, e.g. replacement/failure times of a number of similar units. It estimates the life of an average component operating under average conditions and applies to components of the same type. These kinds of methods have a large uncertainty for a given specific unit.

In relation to [Figure 12](#) showing the definition of RUL, the reliability model can be used on the flat piece of the curve before any faults start to develop, illustrated as point D. Here it can serve as a useful tool in estimating the cost of future maintenance when looking some years ahead to support budget planning. This assumes that many identical units are available in the fleet.

The reliability model cannot be used to establish an accurate RUL once a fault has occurred. In this case, the data driven approach shall be used.

13.4 Type II — Stress based prognostics — Model based

The disadvantage of a pure reliability-based approach is that the operating conditions are not considered. The failure distribution for the reliability approach provides a failure distribution for typical components under typical conditions. The class of methods for stress-based prognostics takes the operating conditions into consideration by expecting that components operating under harsh conditions are expected to have a shorter lifetime than components operating under mild conditions.

These models use prior observations of variables such as power production, torque, temperature, and the response variable, which is usually the failure time, to predict the life of a component.

The stress based prognostic method is based on gathering event data, e.g. replacement/failure times of historical units. Some models also include simulations of the wind turbine under previous operating conditions to establish a more realistic estimate of expected lifetime. However, these approaches only provide general or average estimates for the entire population of identical units operating under identical operating conditions to facilitate time-based maintenance intervals. In relation to [Figure 12](#), showing the definition of RUL, the reliability model can be used on the flat piece of the curve before any faults starts to develop illustrated as point D. Here it can serve as a useful tool in estimating the cost of future maintenance when looking some years ahead to support budget planning. This assumes that many identical units are available in the fleet.

The stress based prognostic model cannot be used to establish an accurate RUL once a fault has occurred. In this case, the data driven approach shall be used.

13.5 Type III — Data-driven method — Condition based

This approach is used once it has been identified that a fault is developing and where it is located. Consider [Figure 12](#), which illustrates the key concept of RUL estimation. At T_p (time when potential failure can be detected) a prediction is made of “estimated time to failure” (ETTF). Once the ETTF has been generated, the next question is to decide when to carry out the corrective maintenance actions taking into account the confidence of the ETTF. The critical point is the confidence of the estimated lifetime, ideally the time chosen for the maintenance action that shall avoid equipment failure and at the same time maximize the useful life of the component. This is an exercise in risk management, and the established RUL is a compromise between those two factors. The confidence of assessing ETTF is highly component and failure mode dependent.

Estimating the RUL is supported by having a set of descriptors where some are efficient in detecting the fault and others provide value in estimating the severity of the fault. Operating conditions of the turbine after the fault has been detected shall also be considered in order to assess the RUL. Long experience of a diagnostic engineer is indispensable in making these assessments. Once the assessments have been established, the process can be handled by less experienced engineers or even automated to a certain degree.

It is recommended to make new assessments of ETTF at regular intervals in order to use the latest information to increase the confidence of the estimation and even prolong the RUL estimation. This prolongs component lifetime and may be used to postpone a repair action until it is most convenient.

14 Review of the condition monitoring and diagnosis system design

14.1 Reference to other standards

For more information on the content of this clause, refer to:

- ISO 13379-1;
- ISO 16079-1;
- the ISO 18436 series.

14.2 General

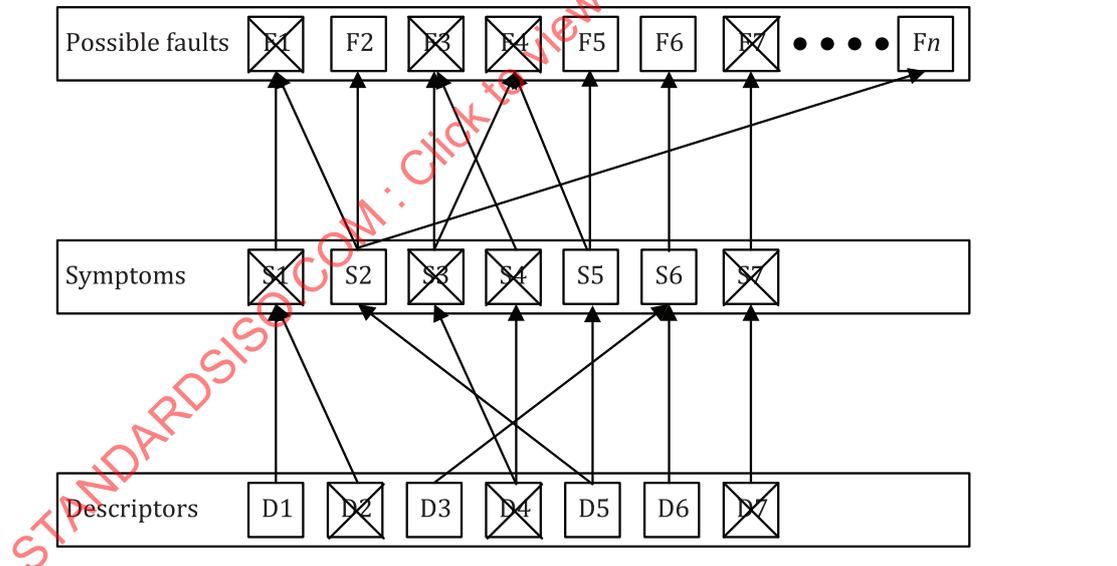
The objective of the FMECA recommended by ISO 16079-1 and the guidelines for selecting component failure mode detection and diagnostic methods in this guideline is to emphasize the issues of:

- a) cost;
- b) detection capability;
- c) complexity of monitoring system and methods; and
- d) available resources and skill level of staff in the monitoring body

versus the benefit of minimizing the lost production from the wind turbine. The result of the FMECA analysis can be used to assess the effectiveness of the monitoring system and make a cost benefit analysis.

14.3 Assessment of effectiveness of the condition monitoring system

The effectiveness of the CM system can be assessed by using the outcome of the FMECA analysis. The FMECA analysis provides a monitoring priority number, n_{MP_rel} , for each of the failure modes which have been investigated during the FMECA analysis. The n_{MP_rel} expresses the criticality of each of the failure modes as well how beneficial it is to detect and monitor. n_{MP_rel} reflects the viewpoint that a correct assessment of a failure mode brings most value to the investment in a condition monitoring system. Therefore, it is most beneficial to prioritize the monitoring of failure modes which are the easiest to detect with simple means and which match the training level of the surveillance staff. Trying to detect non-trivial failure modes will often lead to many false alarms causing expensive and wasted service visits leading to increased service costs.



- Key**
- | | |
|-----------------------------|---|
| An uncrossed box indicates: | A crossed box indicates: |
| D a descriptor | D a descriptor is not present, not able to be measured by CMS |
| S a symptom | S a symptom not verified, not enough descriptors |
| F a possible fault | F a fault is not diagnosed due to missing symptoms |

NOTE Each fault can be diagnosed only if its symptoms, and thus the descriptors used to evaluate these symptoms, are available.

Figure 13 — Example of faults/symptoms/descriptors relationship

[Figure 13](#) illustrates how only a selection of possible faults can be detected if not all descriptors are measured. Some descriptors can require a difficult measurement technique, an expensive sensor or be difficult to detect if it is only occurring frequently under certain conditions.

Based on the relationship between the summations of the FMECA monitoring priority numbers for all failure modes vs. the monitoring priority numbers for the selected failure modes, a factor expressing the effectiveness of the CM system can be calculated. See [Formula \(2\)](#).

$$E = \frac{\sum_{D_F} n_{MP_rel}}{\sum_F n_{MP_rel}} \quad (2)$$

where

- E is the effectiveness;
- F is the possible failure modes obtained from FMECA;
- D_F is the diagnosable set of failure modes, a subset of F ;
- n_{MP_rel} is the monitoring priority number for failure mode obtained from FMECA.

The monitoring priority number includes (see ISO 16079-1):

- a) failure rate (included in criticality factor f_{CR});
- b) consequential damage (included in criticality factor f_{CR});
- c) secondary damage (included in criticality factor f_{CR});
- d) loss of production (included in criticality factor f_{CR});
- e) failure mode priority - diagnostic reliability (included in failure mode priority f_{FMP}).

14.4 Cost benefit analysis

14.4.1 General

In order to quantify the potential cost benefit for the condition monitoring activity, it is necessary to consider the criticality of the equipment, the failure modes and the mitigating actions which can be taken.

This clause provides two methods for quantifying the potential cost benefit:

- a) a simple model which is based only on turbine downtime and lost revenue;
- b) a more advanced model which requires more information gathering as it in addition to the downtime costs also requires knowledge of repair costs and cost of logistics required to make the repair.

14.4.2 Simple model

This model compares the lost revenue when a run-to-failure strategy is used, with the lost revenue when a condition monitoring system is used to plan a change of a component before it fails. This model requires a minimum of information which can be deducted from the data of most condition monitoring systems. See [Formula \(3\)](#).

$$DTS = [(DT - RD) ADR] \quad (3)$$

where

- DTS* is the downtime savings obtained if service is carried out before a component fault develops into functional failure of the component;
- DT* is the downtime which can be expected when a fault develops without being detected by a condition monitoring system (run-to-failure);
- RD* is the number of days (replacement days) it takes to change the component when a planned change can be carried out before the component fault develops into functional failure of the component;
- ADR* is the average daily revenue per wind turbine generator (WTG).

14.4.3 Advanced model

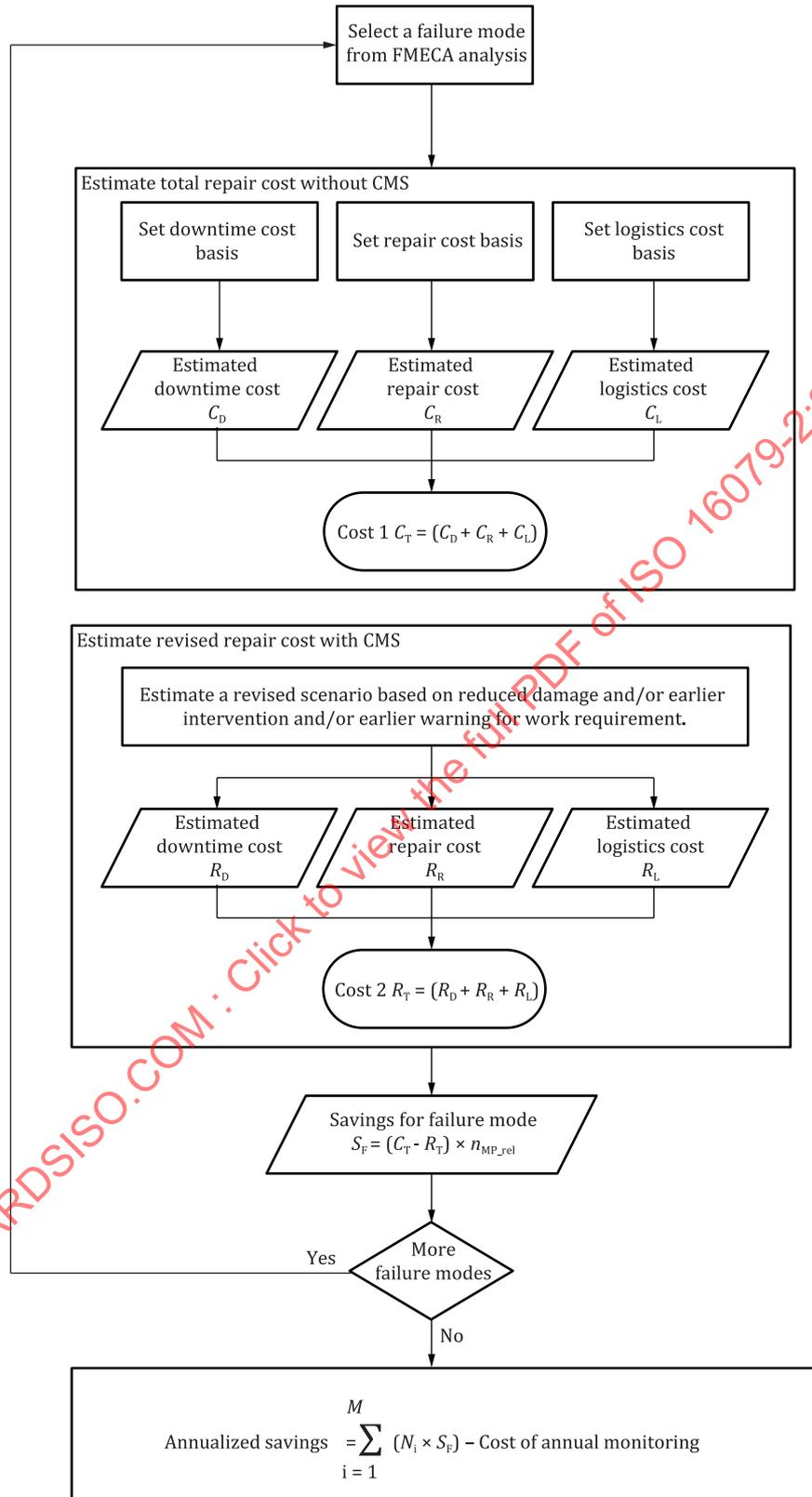
In order to quantify the potential cost benefit for the condition monitoring activity, this model includes the monitoring priority number, lost revenue, repair costs and cost of logistics.

The monitoring priority number, n_{MP_rel} , which is the outcome of the FMECA analysis as prescribed in ISO 16079-1, is combined with the net reduction in cost that will be achieved by taking the mitigating actions.

The n_{MP_rel} includes assessment of the component criticality, failure rate, ease of monitoring and detection, and the P-F interval (lead time) in one single number. A high monitoring priority number for a failure mode has a positive effect on the cost benefit of detecting a particular failure, whereas a low monitoring priority number indicates that detection of a failure mode is uncertain, thus having less effect on the annual savings.

The costs associated with each failure mode include:

- a) downtime, which is the loss of revenue due to lost power generation;
- b) repair, which is costs from parts, and labour;
- c) logistics, cost for crane hire, mobilization of staff etc. (especially significant for off-shore windfarms).



Key

N_i failure mode counter from 1 to M

M number of failure modes

Figure 14 — Process map for the cost-benefit analysis

The process map shown in [Figure 14](#) can be implemented in a spread sheet to provide a convenient tool for the analysis and will ease any later adjustments if required.

NOTE 1 One of the difficulties facing wind farm operators is that downtime during a high wind period not only prolongs the repair period, but also increases the amount of lost revenue. Account for such a complex representation of downtime cost is not included in this methodology, meaning that this provides conservative estimates. A typical offshore wind park in the North Sea assumes that any job scheduled to last three days will lose a day to the weather.

NOTE 2 This analysis holds provided that repairs of sufficient quality are carried out. Poor quality repairs lead to repeated failures, and possible consequential damage. Condition monitoring helps to optimize this process since repeated failures come to light relatively quickly and allow improvements to the processes to be identified.

As most of the figures used in a cost benefit analysis are based on assumptions and best estimates, a Monte Carlo Analysis can be utilized to give an output where the estimated savings are presented as a range rather than a fixed number and can be assigned a certain probability. The input for the analysis shall also be provided as a range rather than fixed values, which is often simpler.

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Annex A (informative)

Details on vibration-based descriptor types

A.1 Time-domain-based descriptors

These are implemented using digital filters which basically have similar properties to the analog filters used in earlier days before the digital revolution.

Common types: Low pass filters, high pass filters, bandpass filters, broadband envelope filters. The filters can be implemented as tracking filters with upper and lower limits dependent on orders of revolution as well as filters with fixed upper and lower frequency limits, in Hz. The output from the filters can be quantified using detector types such as true RMS, true peak and peak to peak values as well as Crest factor and Kurtosis.

Application: These descriptors are used to look at signal properties by excluding certain features. In terms of a wind turbine, a high pass filter may be used to exclude the effect of tower sway from a vibration measurement; or a low pass filter may be used to assist in the evaluation of tower natural frequency. This type of descriptor is good for overall assessment. This is the only descriptor type which can provide measurement results for turbine evaluation which shall be in accordance with ISO10816-21.

Advantages: Time domain filter descriptors measure the true value of the energy content in the selected frequency range for the filter. They work on all types of signals, periodic, spiky, non-periodic and stochastic signals. The energy content can be measured in real time. It is good for evaluating the severity of the vibration level. The signal to noise ratio is very good.

Disadvantages: As the filters require quite a lot of computational power, a compromise between the roll off of the filter and the frequency range must be considered. High roll off, that is, a very steep filter requires computational power and may compromise filter stability. This means that this type of filter is not good at picking out descriptors which are indicated in a very narrow frequency range.

Peak, peak-to-peak, crest factor and kurtosis detectors: Descriptors measured by these detectors shall be used with care. They are all based on detecting peaks in the vibration signal, they may produce erratic results and false alarms due to random peaks which are not related to any mechanical defect. This is especially the case on the low speed stages of the turbine. It is important that a bandpass filter is applied to the vibration signal when using these descriptor types in order to filter out irrelevant peaks before evaluation by these descriptor types. Even after filtering, a detailed analysis of the vibration signal is required to find out whether an increase in the level of these descriptors originates from a mechanical fault.

A.2 Frequency domain-based narrowband descriptors

A.2.1 General

These descriptors are implemented using a Discrete Fourier Transform (DFT). Several different algorithms can be used to implement this type of filter. It is functionally equivalent to calculating one line of an FFT spectrum. The result of the DFT is both a magnitude and phase value. The narrowband filters can be implemented as tracking filters with centre frequency dependent on orders of revolution as well as filters with fixed centre frequency.

Application: These descriptors are good for speed dependent measurements, good for detecting single frequencies using very narrow filter bands and good for vector measurements (magnitude and phase). These descriptors are configured based on the FMSA, which has provided a range of single frequencies

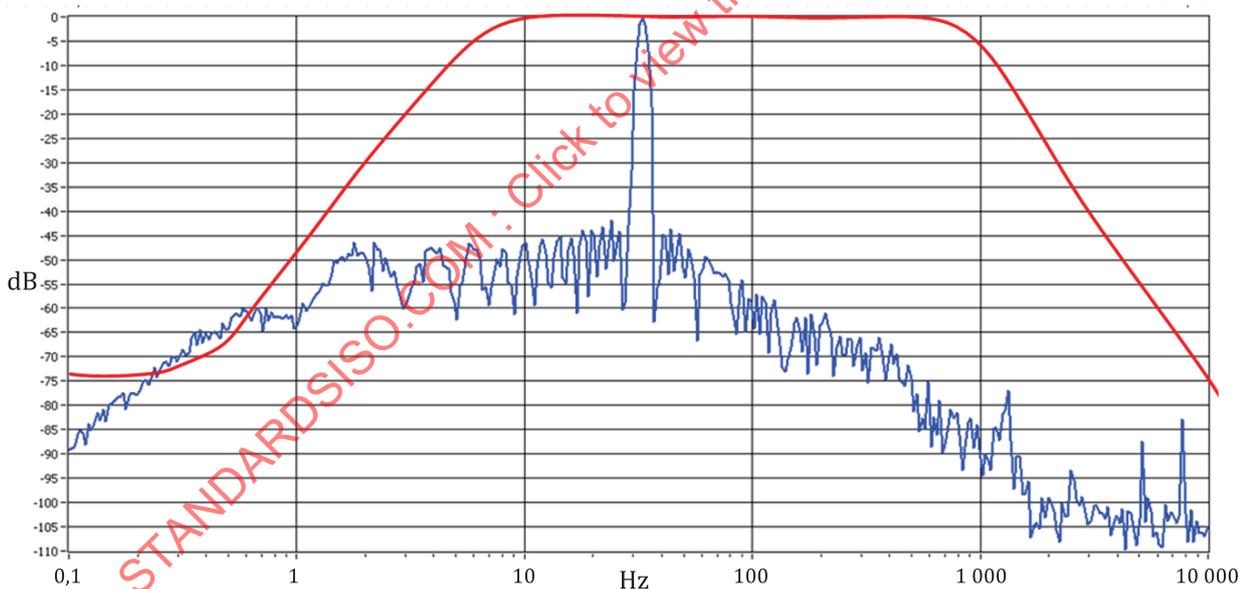
or combination of frequencies characteristic of specific faults. Since a single frequency component is essentially a vector component, magnitude and phase, a simplification shall be made to produce a scalar descriptor value. In most cases, only the magnitude of the signal will be considered. However, where phase is meaningful, it can be extracted as a separate descriptor. Where necessary, several frequencies can be grouped together in order to cover a set of frequencies typical of a fault signature. For example, a descriptor may be set up to detect all the frequencies relating to a single bearing, plus harmonics and sidebands, then the sum of all the amplitudes can be used as the descriptor. This reduces the final number of descriptors required.

Advantages: Very fast and computational efficient algorithm. Can be applied for real time measurements as well as postprocessing of recorded time waveforms. Very good for descriptors where the frequency varies with running speed.

Disadvantages: As the DFT is a transformation to the frequency domain, it requires that the analyzed signal be periodic in nature. It cannot be used to analyse signals which contain many peaks and transients. A correct expression of the energy content of the signal cannot be provided. However, for relative measurements, it is applicable.

True peak and true peak-to-peak values of the signal cannot be measured. Measurement of a true RMS value as prescribed in some standards is not possible using DFT. Equivalent peak or peak-to-peak value can be calculated by multiplying the calculated value by $\sqrt{2}$ or $2\sqrt{2}$, respectively. Using these factors assumes that the analyzed signal is a pure harmonic signal, which is very rarely the case. A general deviation factor of the equivalent calculations cannot be provided; it depends upon the signal.

As the DFT requires that the signal be of a periodic nature, a window function such as the Hamming window shall be applied. The weighting function influences the analysis result and has the effect that the signal to noise ratio is poorer than for the time domain filters. See Figure A.1.



NOTE Damping outside the passband is more than 3 000 times for the time domain filter versus approximately 100 times for the DFT using the Hamming weight. Other window functions such as Hanning, Flat Top can be used but with no significant difference in noise level compared to using the Hamming weight.

Figure A.1 — Comparison of the signal-to-noise ratio for a time domain bandpass filter (red) and a DFT using the Hamming weight (blue)

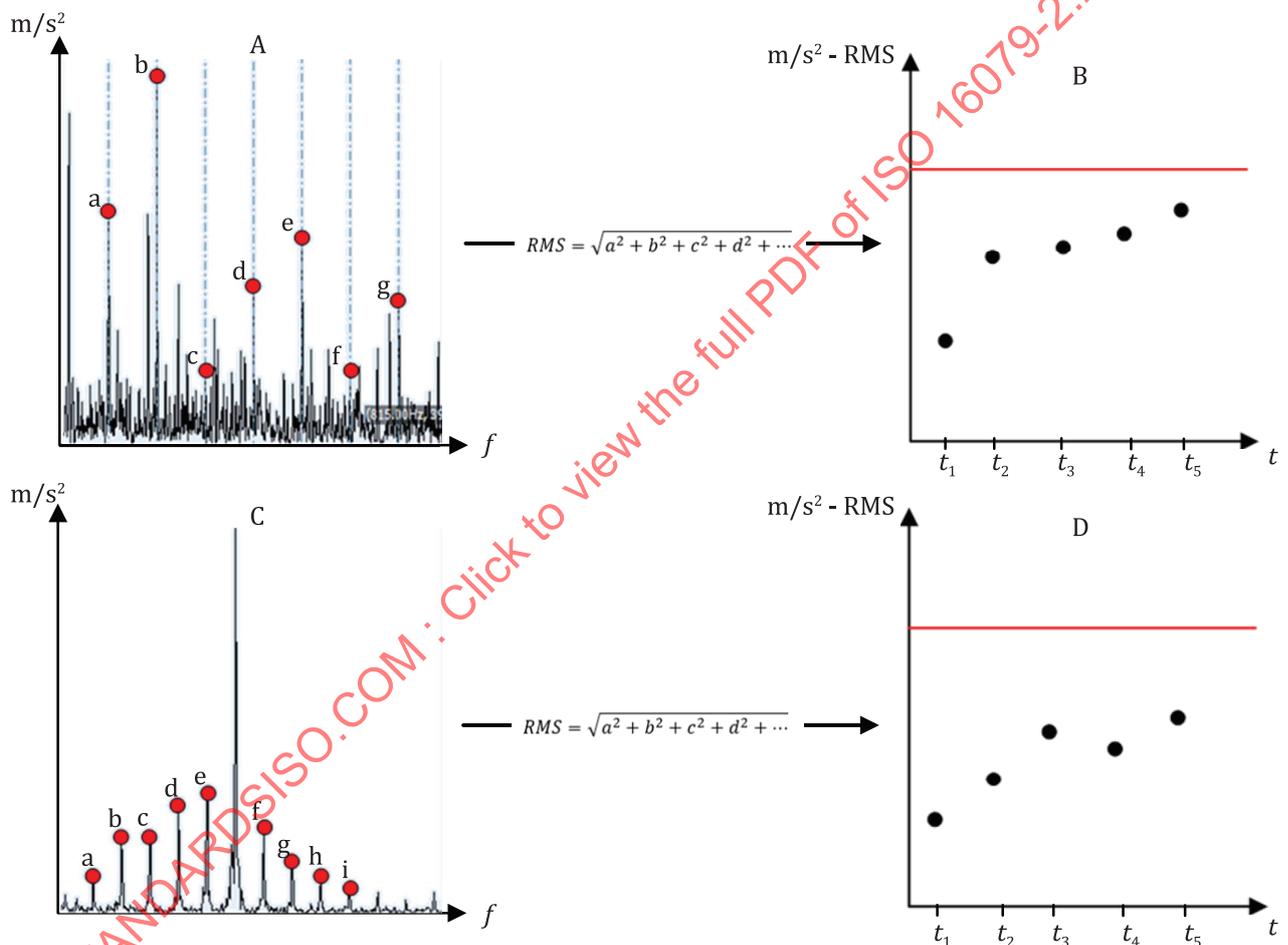
A.2.2 Frequency domain-based-descriptors generated by feature extraction

These descriptors are implemented based upon Fast Fourier Transform (FFT) such as autospectra and envelope spectra. A descriptor value is calculated by extracting one single spectral component or a

group of spectral components from the spectrum measurements. The energy content of the extracted spectral components is calculated by the square root of the square sum of the spectral components. The calculation shall be compensated for the type of window function used for the FFT analysis.

Application: Good for getting an overview of relative increases in vibration level at different frequencies. Good for making assessment of the energy content of harmonic families, sideband families and other combinations of frequency components. Trending on the harmonic and sideband families is a good method for assessing changes in the severity of a fault.

Advantages: Fast and efficient computational algorithm. Extraction of spectral components is a straightforward process. Where necessary, several frequencies can be grouped together in order to cover a set of frequencies typical of a fault signature. For example, a descriptor may be set up to detect the vibration amplitudes relating to a bearing fault, including the harmonics, or be setup up to detect sideband frequencies generated by a gearbox fault.



Key

- A frequency spectrum showing a harmonic family
- B trend on the square root of the square sum of each member of the harmonic family calculated at time, t_1, t_2, t_3 etc.
- C frequency spectrum showing a sideband family
- D trend on the square root of the square sum of each member of the sideband family calculated at time, t_1, t_2, t_3 etc.

Figure A.2 — Example of feature extraction from an autospectrum

Disadvantages: The transformation to the frequency domain requires that the analysed signal be of a periodic nature. Analysis of non-periodic signals does not give the correct expression of the energy content of the signal. Measurement of a true RMS value of a specific frequency range as prescribed in a standard like ISO 10816-21 is not possible. However, for relative measurements, it is often applicable.

A.3 Pre-processing of time waveforms prior to frequency analysis

A.3.1 General

Pre-processing of the time waveform can be used to compensate for the varying speed of the turbine and can also be used to remove noise from the signal thus improving the signal to noise ratio of the signal before further analysis and feature extraction.

A.3.2 Angular resampling of the time waveform

The most common technique of digitizing a signal from a vibration transducer is to let an AD converter sample the signal with constant time spacing before further processing of the signal using FFT analysis. The constant time spacing represents a problem if the rotational speed of the machine is varying. In such a case, the frequencies related to the running speed appear in different lines of the frequency spectrum as the time waveform used for analysis is represented by a different number of samples for each rotation. This phenomenon is called smearing (see Figure A.3).

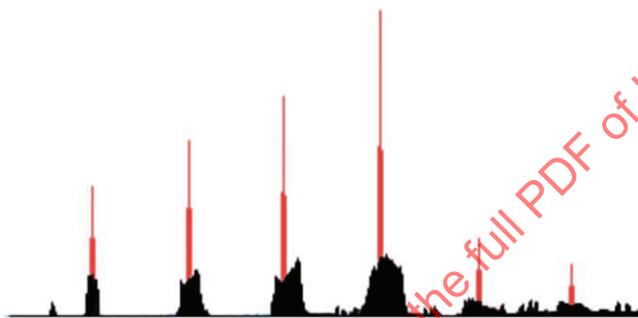
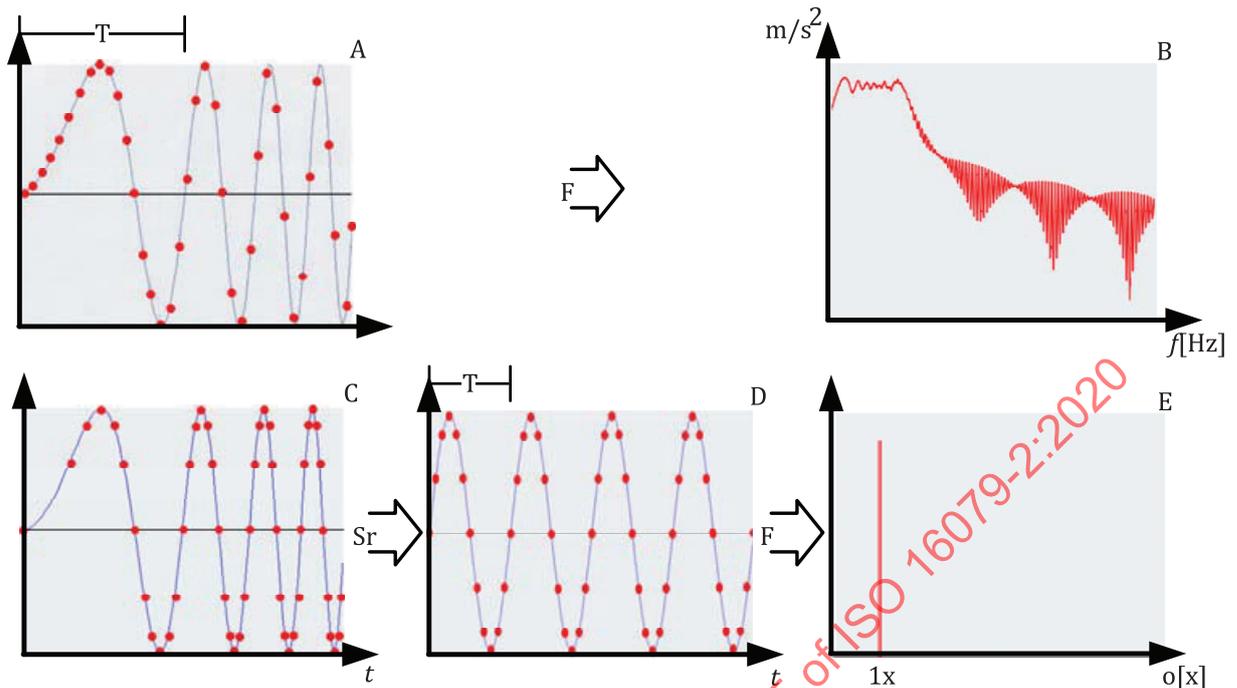


Figure A.3 — Illustration of smearing shown as the black spectrum components versus order-based components shown in red

By resampling the signal using constant angular sample spacing related to the shaft rotation, smearing can be avoided. The constant angular spacing of samples has the effect that one rotation of the shaft is always sampled by the same number of samples. As one revolution of the shaft always is sampled by the same number of samples, all frequency components related to the running speed remain in the same lines of the FFT spectrum irrespective of the running speed of the machine. The angular resampling method requires that a speed signal (tachometer) be available to provide a signal for each rotation to synchronize the resampling process (see Figure A.4).



Key

- T one revolution
- A time domain – constant sampling frequency; time waveform recorded while shaft speed is changing. e.g. a run-up
- B frequency domain – frequency spectrum showing smearing due to the changing shaft speed
- C time domain – resampling of time signal using same number of samples per shaft revolution
- D angular domain – due to the constant sampling rate, the frequency of the signal does not seem to change
- E order domain – the horizontal axis is scaled in multiples of one shaft revolution – orders, no smearing in spectrum

Figure A.4 — Illustration of the angular resampling principle

By knowing the exchange ratios for the various shafts in a wind turbine gearbox, order-based analysis can be used to enhance frequency components related to each shaft by resampling the signal related to the rotational frequency of the individual gearbox shafts. This makes feature extraction related to each part of the gearbox much easier and accurate.

A.3.3 Time domain averaging

Time domain averaging prior to further analysis is used to improve the signal to noise ratio by removing components that are not synchronous to the running speed from the time waveform. It is required that the averaging of the time waveforms be synchronized to the same angular position of the shaft. Angular resampling prior to the averaging is a must when the speed of the turbine is varying (see Figure A.5).