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Condition Monitoring for Wind Turbines

"State of the Art" Report as

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PL: *Project leader* **WPL:** *Work package leader* **TL:** *Task leader*

1. Introduction

This report describes the state of the art in Condition Monitoring Systems (CMS) for wind turbines. This includes the description of the basic functionalities a CMS must provide to perform condition monitoring and fault prediction tasks. It should be understood as some kind of a “quick reference” to what requirements a CMS for modern type wind turbines must meet. The intention is to update the report at the end of the project, when some of the newly developed CMS technologies (inside and outside UpWind) become state of the art.

In section 2, an overview about the actual measurement and sensor technology for CMS purposes is given. It shows what to measure and how. The focus here is more on the principle physical effects of the measurement signal generation. Specific sensor types are not discussed. The section also gives information about the required sensor performance (accuracy, sensitivity, etc.) for the use in CMS.

Section 3 describes suitable algorithms for detecting and predicting faults on the main components of a modern type wind turbine. In section 4, the basic function requirements of an online CMS are summarised. This includes the analogue to digital conversion for data acquisition purposes, the data processing, the data storage and communication abilities of the CMS. Section 5 addresses the relevant standards and technical guidelines in the field of CMS for wind turbines. It gives also an overview about the actual certification procedures.

For the scope of this report, only online CMS are considered. This means that the systems measure continuously the data, do the pre-processing (classification and compression of data), save the relevant data and, in case of a detected fault, send out a warning or alarm to the wind turbine / wind farm operator. Offline CMS with only punctual data acquisition activities, often performed by human personnel, are not sufficient for offshore wind turbines and therefore are not considered in this report.

2. Measurements and sensor technologies for CMS

This section describes the different quantities, which have to be measured to perform condition monitoring and fault prediction tasks for large (offshore) wind turbines. The focus will be on the measuring methods and physical principles rather than on the specific sensor design or on a particular sensor model. However, some of the measuring methods depend on the physics of the respective sensor types.

For example, there are two types of acceleration sensors, the so called “piezo-resitive” and “piezo-electric” sensors. The first type is able to measure static acceleration. With the second type, due to its physical signal conversion principle, a measurement of static acceleration is not possible. Meanwhile, there are piezo-electric acceleration sensors available, which can reliably measure acceleration frequencies down to approx. 0.1 Hz. But taking into account that the next generation of large offshore wind turbine will have rotational and Eigen frequencies at around these 0.1 Hz, those sensors are not suitable for the measurement of very low acceleration frequencies. More information about acceleration measurement on wind turbines can be found in [2].

For condition monitoring purposes, most of the measured quantities are not evaluated according to their absolute values, but according to the deviation from a defined level (“base line”) as a trend analysis. This base line level can be derived, for example, from a measurement taken under a fault free condition of the component to be monitored. It can also be a component manufacturer’s recommendation. For the trend analysis, the absolute accuracy of the measured values is not that important. What is important for condition monitoring is the long term stability of the measured values to allow a reliable trend analysis.

The meaning of tags given in column “signal type” of the tables below are the following:

Digital:	Digital signal 0V/24V = Low/High (Typical 0-5V=Low, 10-24V=High)
Analogue:	Analogue signal, e. g. +/- 10 V or 4-20 mA (preferably)
Pulse:	Pulse signal, frequency contains information (Typical 0 to 24V rectangular)
Data:	Data from device, e. g. via RS232, a BUS system or a network (Ethernet)

2.1 Mechanical quantities

2.1.1 Strain, Torque, Bending, Shear

<u>Strain on structural components:</u>

To determine the dynamic load on structural components, the strain on the component’s surface is measured. This is done for example at the roots of a wind turbine’s rotor blades to measure the aerodynamic loads to the blades.

The standard strain measurement method is to use strain gauge resistor bridges as sensors in combination with signal amplifiers. For the use in wind turbines there are two major problems with this kind of sensors:

- Strain gauge sensors are sensitive to aging. They will change their electrical behaviour over time. Also corrosion can be a problem. This results in an unsatisfactory long term stability within the 20 years designed life times of wind turbines.

- Since there are long electrical cables and amplifiers with very high gain factors, strain gauge sensors are also very sensitive to EMC problems.

The above mentioned problems can be avoided by use of fibre optic strain gauges. The most popular type used for this is the Fibre Bragg Grating (FBG) sensor. The principle functionality of such sensors is described in the literature, e. g. in [3] or [4]. The following table 1 gives an overview about the measurement requirements.

Quantity	Base unit	Accuracy[1]	Bandwidth	Sensitivity	Range	Signal type
Strain	µm/m (µstrain)	5 %	0 – 100 Hz	1 µstrain	10000 µstrain	Analogue

Table 1: Measurement requirements for quantity strain

<u>Shaft torque:</u>

Shaft torque measurement is normally based on the use of strain sensors. These sensors will be applied to the rotating shaft in the direction of the main tension forces, which is at an angle of 45 degrees related to the shaft axis. From the measured tension/strain on the shaft surface the torque can be calculated. For strain measurement one of the above described methods can be used.

The main problem with shaft torque measurement is to transfer the energy supply to the rotating components (e. g. for strain gauge amplifiers or FBG interrogation units) and to send back the measurement signals. In most cases, this is done by use of high frequency induction fields. The carrier field provides the energy for the shaft sensors and the measured values are modulated onto the carrier.

The measurement equipment cause both high costs and high installation effort. Therefore, in wind turbines it is usually only used in prototype machines to verify the load estimations made for the drive train components during the design phase. Furthermore, the data transfer is sensitive to EMC and other environmental influences (vibration temperature, etc.). This requires a high effort for calibration, operation and maintenance of the measurement equipment and makes it to unreliable for long term condition monitoring and fault prediction purposes. Table 2 show the measurement requirements.

Quantity	Base unit	Accuracy	Bandwidth	Sensitivity	Range	Signal type
Torque	Nm	5 %	0 – 100 Hz	Depends on turbine size	0 – 10 MNm	Analogue

Table 2: Measurement requirements for quantity torque

<u>Component bending and shear:</u>

The measurement of bending and shear on wind turbine components, e. g. on the rotor blades, are based on strain measurements. Therefore, the measurement requirements are the same as given in

[1] Related to the actual measurement value

table 1. The bending and shear values can be calculated with the respective material constants and the measured strain values.

2.1.2 Shaft orbit, distance

For condition monitoring of bearings on very slow rotating shafts, the orbit has to be measured. This is done by use of distance sensors, which measure the displacement of the shaft related to the main bearing housing in two axes rectangular to each other and also rectangular to the shaft axis itself. By vectorial addition of the distance values, the shaft orbit can be calculated. The measurement requirements are given in table 3.

Quantity	Base unit	Accuracy	Bandwidth	Sensitivity	Range	Signal type
Displacement (x-axis, y-axis)	mm	1 %	0 – 10 Hz	1 V/mm	0 – 5 mm	Analogue

Table 3: Measurement requirements for quantity distance / shaft orbit

2.1.3 Acceleration,

Acceleration in relation to measurements for condition monitoring and fault prediction is meant as very low frequency acceleration induced by oscillations of a wind turbine's supporting structure, tower and nacelle. The acceleration values can be used for example to monitor Eigen frequencies of components and their shift according to (potential) fault conditions. It can also be used for monitoring of wind turbine rotor faults. A detailed description about the correlation between rotor faults and the different oscillations of the wind turbine's nacelle is given in [5]. Table 4 gives the requirements for the acceleration measurement under the scope of condition monitoring and fault prediction.

Quantity	Base unit	Accuracy	Bandwidth	Sensitivity	Range	Signal type
Acceleration	m/s^2	5 %	0 – 20 Hz	2 V/g[2]	+/- 2 g	Analogue

Table 4: Measurement requirements for quantity acceleration

2.1.4 Oscillation velocity and displacement

Most of the sensors used for measurement of oscillation velocity and displacement are based on acceleration sensors. The velocity signal is generated by band pass filtering and subsequent integration of the acceleration signal. For a displacement signal, this procedure is done twice. Therefore, the items described in the section before are also covering the measurement of these quantities. Furthermore, all required information for condition monitoring and fault prediction in wind turbines can be derived from acceleration signals.

Oscillation velocity can also be measured by use of electrodynamic sensors. These sensors work with a permanent magnet moving in a coil probe. This measurement principle is not as robust as the piezo-

[2] Gravitational constant $g=9.81\ m/s^2$

effect based systems. Main problems are the sensitivity according to EMC, thermal fluctuations and mechanical shock. Therefore, these types of sensors are not very useful for condition monitoring and fault prediction purposes.

2.1.5 Vibration

Vibration measurement is used to evaluate the condition of bearings and gear wheels rotating at higher frequencies. For this purpose, the above described piezo-electric vibration (which can be understood as high frequency acceleration) sensors are ideal. These sensors can measure all mechanical vibrations in a frequency range of 3 Hz up to 20 kHz with a single sensor. Detailed information about condition monitoring of bearings and gear wheels are given in various publications, for example in [6]. Table 5 show the measurement requirements.

Quantity	Base unit	Accuracy	Bandwidth	Sensitivity	Range	Signal type
Vibration	m/s²	5 %	3 Hz – 20 kHz	100 mV/g	+/- 20 g	Analogue

Table 5: Measurement requirements for quantity vibration

2.1.6 Shaft RPM

Some of the characteristic values used for condition monitoring and fault prediction on bearings and gear wheels are correlated to the RMP. For RPM measurement, an easy and very reliable way is to use inductive approximation sensors, which face to the bolts of a shaft coupling or to the mounting bolts of the rotor hub. This will generate a pulse signal, where the pulse frequency (as the product of the rotational shaft frequency and the number of bolts) gives the RMP value. To achieve a reasonable signal resolution, the minimum pulse frequency should not be less than 5 Hz. Table 6 show the measurement requirements. The given bandwidth means that there should be at least 3 readings of the RPM value per second possible (“refreshing rate”). This corresponds with the minimum required pulse frequency of 5 Hz mentioned above.

Quantity	Base unit	Accuracy	Bandwidth	Sensitivity	Range	Signal type
RPM	RPM or Hz	1 %	3 Hz RR[3]	-	0 – 3000 RPM	Pulse

Table 6: Measurement requirements for quantity RPM

2.1.7 Shaft position

To perform some specialised algorithms of spectral analysis (FFT ➔ Order Spectrum), the absolute position of the shaft has to be measured. In most of the cases, a single pulse per shaft revolution is sufficient. Such a pulse signal can be derived from the above described measurement with an inductive approximation sensor. It only must be modified in a way that only one pulse per shaft revolution is generated by passing only one bolt or a small metal plate on the rotating shaft or hub.

[3] RR: refresh rate of the signal, i. e. number of measured values per second

If a higher resolution with interim values over one shaft revolution is required, an electronic position encoder can be used. From these sensors, the actual position value can be read out via a communication line (e. g. RS485 with the SSI protocol). Some of them have an additional analogue output, which gives a ramp shaped output signal (e. g. 0 to 360 degree is corresponds to 4 to 20 mA).

The bandwidth given in table 7 is related to such a type of sensors and means that the signal should have a refreshing rate of 3 values per second as described in 2.1.6 Shaft RPM.

Quantity	Base unit	Accuracy	Bandwidth	Sensitivity	Range	Signal type
Shaft position	degree	5 %	3 Hz RR[2]	-	0 – 360 degree	Analogue, pulse, data

Table 7: Measurement requirements for quantity shaft position

2.2 Electrical quantities

2.2.1 Power output

The power output in relation to condition monitoring and fault prediction is used to evaluate the overall performance (“power characteristic”) of the wind turbine. Most faults cause a decrease in the power output in correlation to the actual wind speed. Some more information about the monitoring of the wind turbine’s power characteristic is given in [5].

Another item for the use of the power output signal is the classifying of other quantities, which are correlated to the actual load condition of a wind turbine. This is the case for some of the above mentioned bearing and gear wheel vibration measurements. For power output measurement, there is a variety of transducers available. The measurement requirements for the power output are not very high according to the accuracy and bandwidth (see table 8). Therefore, cost effective “of the shelf” components can be used.

Quantity	Base unit	Accuracy	Bandwidth	Sensitivity	Range	Signal type
Power output	kW	5 %	0 – 5 Hz	Depends on turbine size	- 100 kW to + 20 MW	Analogue or Data

Table 8: Measurement requirements for quantity power output

2.2.2 Generator phase currents

The detection of electrical faults in the generator, e. g. problems with the stator windings, can be detected by high frequency signal analysis of the generator phase currents (refer to [7]). This requires a broad band measurement of the phase currents, as described in table 9. The given lower cut off frequency of 10 Hz is meant to allow the measurement also of the grid frequency (50 Hz / 60 Hz) and its first harmonics. For such measurements, state of the art “Hall effect compensation” current transducers can be used. Those sensors provide a potential free current signal with a reasonably high insulation voltage of several kV, which is beneficial with respect to the high generator voltages in large wind turbines.

Quantity	Base unit	Accuracy	Bandwidth	Sensitivity	Range	Signal type
Generator phase currents	A	5 %	10 Hz – 80 kHz	Depends on generator size	+/- 2000 A	Analogue

Table 9: Measurement requirements for quantity generator phase currents

2.3 Other quantities

2.3.1 Meteorology

<u>Wind speed:</u>

Like the power output, the wind speed in relation to condition monitoring and fault prediction is used to evaluate the power characteristic of the wind turbine. In this case it is not necessary to measure the “true” power curve as described e. g. in the IEC61400-12 standard. For condition monitoring purposes it is sufficient only to measure deviations from a “reference power characteristic”. Such a reference can be measured in a fault free condition of the wind turbine in scope and then be stored for later evaluation of the power output. For the measurements, the anemometer on the top of the nacelle can be used. Details about this can be found in [5].

The most common sensor type for wind speed measurement is the cup anemometer, which fulfil completely the requirements for condition monitoring related wind speed measurements. The output of this anemometer is a pulse signal. The wind speed value is related to the pulse frequency. The required measurement performance for the wind speed is given in Table 10.

Quantity	Base unit	Accuracy	Bandwidth	Sensitivity	Range	Signal type
Wind speed	m/s	5 %	3 Hz RR[2]	-	0 – 50 m/s	Pulse

Table 10: Measurement requirements for quantity wind speed

<u>Wind direction:</u>

The wind direction in relation to condition monitoring is used for data classifying. In wind farms, depending on the wind direction, wind turbines are exposed to different turbulence intensities in the wind flow. For example, if the wind comes from the north, the wind turbines on the southern end of the wind farm see higher turbulence intensity. Since some of the measurements, e. g. the bending or oscillations of the rotor blades, are sensitive to the turbulence intensity, the wind direction must be used to classify the data.

There are many different ways to measure the wind direction. For condition monitoring purposes, sensors which are using a wind vane are sufficient. Table 11 show the required measurement features. The position of the vane is measured with potentiometer (➔ analogue output) or with an opto-electronic grey code encoder (➔ data output, e. g. with 8 bit hard wired).

Quantity	Base unit	Accuracy	Bandwidth	Sensitivity	Range	Signal type
Wind direction	Degree	+/- 10 deg	3 Hz RR[2]	-	0 – 360 degree	Analogue or Data

Table 11: Measurement requirements for quantity wind direction

Temperatures:

The temperature of components can be used for classification of other measurements. It also gives hints to a developing fault, e. g. when the temperature of a bearing increases over the “normal” value for the related load condition of the wind turbine. To get suitable condition monitoring information, the individual component temperatures must be correlated with the ambient temperature.

The common way to measure temperatures in the range, which can be expected in wind turbines (-50° to +300° Celsius), is done with resistor sensors. These sensors use the temperature gradient of a metal resistor probe (e. g. a Pt100 sensor, which is made of Platinum and has a resistance of 100 Ohms at 293 K). The resistance is measured by feeding a defined DC current into the sensor and measure the voltage on its terminals. This measurement method is sufficient for condition monitoring purposes. Table 12 describes the measurement requirements.

Quantity	Base unit	Accuracy	Bandwidth	Sensitivity	Range	Signal type
Temperatur e	K (or °C)	5 %	0.5 Hz RR[2]	50 mV/K	-50 - +150 °C	Analogue or Data

Table 12: Measurement requirements for quantity temperature

2.3.2 Oil quality

Particle number:

Wear of bearings and gear wheels cause particles in the oil of wind turbine gearboxes. If the number and/or size of particles in the oil increase, a developing fault can be assumed. Therefore, the oil particle number measurement (requirements see table 13) can be used for condition monitoring purposes. The output value of an oil particle sensor can be a pulse or a counter data value increase related to a time base (e. g. per minute) for each particle above a minimum size.

Quantity	Base unit	Accuracy	Bandwidth	Sensitivity	Range	Signal type
Oil particle number	Number	10 %	1 Hz RR[2]	-	-	Pulse or Data

Table 13: Measurement requirements for quantity oil particle number

Oil conductivity and pH value:

The chemical characteristics of the lubricant oil can be monitored to evaluate the oil quality. Both, the conductivity and the pH value gives information about the contamination of the oil with water and the state of chemical decomposition of the oil itself and its additives. Table 14give the requirements for the measurements.

Quantity	Base unit	Accuracy	Bandwidth	Sensitivity	Range	Signal type
Oil conductivity and pH value	S and pH	10 %	1 Hz RR[2]	1 V/Sm 500 mV/pH	0 – 10 Sm 0 – 14 pH	Analogue or Data

Table 14: Measurement requirements for quantities oil conductivity and pH value

3. Data evaluation and fault prediction algorithms

This section introduces the common data evaluation and fault prediction algorithms for the main components of wind turbines.

3.1 Monitoring of the rotor

The rotor of a wind turbine can have the following faults:

3.1.1 Blade surface roughness

Reasons for increased blade surface roughness can be pollution (dirt, insects …), damages of the blade's surface painting (cracks, blowholes etc.) and icing. Increase of blade surface roughness causes a decrease of wind energy converter's power output due to the reduced aerodynamic performance of the blade profile. These effects can be identified by online measurements of the wind energy converter's power characteristic, i. e. the functional relation between mean wind speed and mean power output.

3.1.2 Rotor mass imbalance

The behaviour of the blades due to mass imbalance is given by the blade mass and the distance of the blade's centre of gravity to the rotor axis. If one of these parameters changes, the rotor is in a state of imbalance. Mass can change if material (for example water) penetrates a blade or if icing (asymmetric due to mass) covers the blades. Gravity centre radius can change if loose material inside the rotor starts to move, e.g. towards the blade tip during rotor revolution.

A rotor mass imbalance leads to a periodic transverse (relative to the rotor axis) oscillation of the wind energy converter's nacelle at rotor rotational frequency. The amplitude of the oscillation is a measure for the magnitude of the mass imbalance (when the damping conditions of the system have been considered). The virtual position of the resulting mass can be obtained by analysing the phase information of the oscillation. Therefore, the affected blade can be identified.

3.1.3 Aerodynamic asymmetries

Aerodynamic rotor asymmetries are caused, if the blades have different aerodynamic behaviours, for example if the angle of attack is different due to assembling faults of the blade pitch drive. Another reason could be a difference in the blade profiles caused by production tolerances or permanent deformation during operation. Since the aerodynamic forces are very sensitive to the angle of attack (related to pitch angle faults) or to the blade profile (related to profile deformations), aerodynamic asymmetries of the rotor lead to significant differences in the thrust for the individual blades.

Aerodynamic asymmetries of the rotor generate two different types of nacelle oscillations at the rotor rotational frequency. One type is the axial oscillation; the other type is a torsion oscillation around the vertical tower axis. Cause for both oscillation types are the different bending moments imposed to the nacelle, which are generated by the individual blade thrust. Monitoring the amplitude of these oscillations provides a measure for the magnitude of aerodynamic rotor asymmetries. The phase angle of the oscillation related to the absolute rotor position points to the blade, which causes the asymmetry.

3.1.4 Detection of rotor faults

An approach to detect and monitor the above mentioned rotor faults by analysing the wind turbine's power characteristic and the rotor induced nacelle oscillations is described in detail in [5]. Other methods used are the direct measurement and analysis of the blade oscillations itself as described for example in [8]. With the introduction of the new strain sensor equipment based on Fibre Bragg Gratings (FBG) as described in section 2.1, it seems to be possible to have a reliable and long term stable measurement procedure for rotor condition monitoring.

3.2 Drive train monitoring

3.2.1 Faults in roller bearings

In the scope of the condition monitoring, there will be bearings on shafts, in the gearbox and in the generator. Most of the bearings used in wind turbines are roller bearings.

For monitoring and fault prediction of roller bearings, the following algorithms can be used:

- **Statistical algorithms:** Statistical algorithms are used to analyse the time signals of vibration sensors. Vibration signals taken from intact bearings show a normally distributed amplitude density. If damage on the bearing starts to develop, the shape of the vibration distribution deviates from the Gauss shaped curve. Statistical algorithms give an absolute measure for the condition of the respective bearing and therefore can easily be applied to all types of bearings. On the other hand, the algorithms show a relatively poor selectivity, which means that a change in the value does not point to a certain faulty component of a bearing.
- **Time series based algorithms:** An approach using only the pure time signal, e.g. from a vibration sensor, is the calculation of several characteristic values. These values are the RMS of the vibration signal, the Crest Factor (i. e. the quotient of the Peak value and the RMS within a defined time window).
- **Frequency analysis based algorithms:** All bearing elements generate vibration at defined frequencies, the so called fault frequencies. They depend on the geometry of the bearing and the roller elements as well as on the rotational frequency of the respective shaft. For the analysis of periodic signals, the following FFT based data evaluation algorithms can be used:
    1. Standard FFT for periodic vibration effects with fixed frequencies
    2. Order analysis for vibration effects on variable speed components
    3. Bearing Condition and Envelope Curve spectral analysis (BCS/ECS analysis)

3.2.2 Gear wheel faults

Most of the statistical algorithms, the time series based algorithms and the frequency analysis based algorithms for bearings as described above can also be applied to gear wheels. In addition, for gear wheels, the side band analysis is a powerful measure to detect faults. In case of a developing fault on a gear tooth, once per revolution of the related gear wheel, a stronger pulse is generated during force-fit contact.

Therefore, the resulting time signal has a pulse sequence at tooth mesh frequency where the amplitudes of the pulses are varying with the shaft/gear wheel rotational frequency. From a signal analysis point of view, this is an amplitude modulated signal with a carrier at tooth mesh frequency and a modulation at wheel rotational frequency. Applying the FFT to such a signal generates a spectrum with a peak at carrier frequency and side band peaks including their harmonics at multiples of the rotational frequency. The magnitude of the side band amplitudes is a measure for the extend of the fault.

3.3 Monitoring of the electrical components

3.3.1 Generator

- **Windings and rotor cages:** In general, generator faults cause electrical asymmetries. These asymmetries can be detected with specialised measurement systems and algorithms. Some of those systems are described in [7].
- **Slip rings and brushes:** Typical faults of slip rings and brushes are increased surface roughness of the rings or the brush contact face, break out of carbon material from the brushes and decreasing contact pressing forces. All these faults lead to increased brush sparking. One method to detect this is to measure the temperature of the brushes or the brush-holder, e. g. with thermo imaging as described in the sections below.

3.3.2 Transformer

For detection of wiring and contacting faults on transformers thermo graphical investigation methods can be used. Thermography also can be useful to detect winding problems, which will lead to inhomogeneous temperature deviations in the phase windings of the transformer.

3.3.3 Contacting and switching gear

- **Contacting faults:** Faults with contacts leads to increased resistance due to reduced conductivity. Cause for this can be loose terminal screws/clamps, corrosion etc. The increased resistance causes a higher power loss when the current goes over the contact. The resulting increase of the temperature can also be detected with thermography. By evaluating thermo images of the electrical contact or switch in scope at a certain current load, either compared to other components of the same type or compared to stored images of former thermo graphical investigations can be used to detect an increasing contact resistance.
- **Switching gear:** The contact plates of switches will be eroded by sparks during each switching action. This causes burning marks on switch contacts and leads to an increased resistance. As described above, this will cause a higher contact temperature at the same current and therefore can be detected with thermography.

3.4 Summary

The algorithms described above are partly very complex and require a quite deep understanding of the special effects occurring with digital spectral analysis. An overview about some of the algorithms is given in [6]. Another source for information is the description of the functionality of specific condition monitoring systems. Most of the CMS suppliers provide sufficient theory documentation for the internal signal analysis fault prediction algorithms used in their systems.

4. CMS base unit functionalities

The base unit of a CMS must provide several functions. Analogue or pulse signals from sensors must be filtered and converted to digital information. Characteristic values must be calculated and must be held in data bases for further evaluation. Communication with a remote central server and/or operator must be assured. In the following, the actual state of those functions integrated will be described.

4.1 Data acquisition

Data acquisition in modern type CMS is normally done by Analogue to Digital Converters (ADCs). The main specification parameters for ADCs are the sampling rate and the digital resolution. Typical values for CMS are rates up to 20 kHz and a 12 Bit resolution. This covers most of the CMS measurement requirements, as given for example in section 2. To avoid large amounts of data to be handled, the sampling rate should be adjustable to the maximum signal band width, i. e. if the significant signal frequency is at 10 Hz, the sampling rate should be at about 100 Hz.

To meet the requirements of digital signal processing, analogue filtering should be provided by the CMS. Especially for the spectral analysis of signals, the Shannon theorem must be considered. It says that the sampling rate has to be twice as high as the maximum possible frequency in the sampled signal. Taking into account that filters do not have ideal transfer functions, normally a sampling frequency of 5 to 10 times of the cut off frequency (-3 dB limit) of the filter is used.

To adjust the ADCs input voltage range (typical +/- 10 V) to the signal level, analogue amplifiers should be used. Filter and amplifier parameters should be software programmable to set up an optimised data acquisition of the CMS.

4.2 Data processing

Data processing in the CMS consists of the following steps:

4.2.1 Pre-processing

To provide the digitised sensor signal for the condition monitoring and fault prediction algorithms in a suitable format, some pre-processing could be useful. For example, to avoid high computation effort, the over sampled sensor signals, as described in the section before, can be reduced by applying digital filter algorithms. With the reduced data set, an FFT algorithm can be executed faster than with the full data set. It has to be stated that digital filtering cannot substitute the proper signal sampling as described in section 4.1. The FFT spectrum of signal, which is not sampled with a suitable frequency can contain peaks, which are not related to a component in the original time signal. This cannot be corrected with a subsequent digital filtering [9].

Another item for a signal pre-processing is the interpolation of signals. If two signals must be merged for analysis, e. g. if they are sampled with different frequencies, an interpolation algorithm must be applied. A main item for condition monitoring in wind turbines is the order analysis algorithm. This algorithm is based on the rotational angle of the WT rotor or a shaft in the drive train instead of time equidistant samples. The required data samples can be generated by applying an interpolation algorithm to the time series of the signal to be order analysed, using a second signal containing the angle information. This can be a signal from a position encoder or from an RPM sensor.

4.2.2 Data analysis

CMS data analysis for WT is mainly based on FFT and similar algorithms. These algorithms are useful to detect periodic excitations in all types of vibration and oscillation signals. Implementation and execution of FFT based signal processing differs quite a lot for the CMSs of the different manufacturers. Therefore, it is difficult to give general statements about the data analysis and the generation of characteristic values in CMSs. Normally, the CMS providers supply substantial information about the algorithms and characteristic values used in their systems. This information can be obtained from the CMS manufacturers, e. g. via the respective home pages.

4.3 Data bases

To perform trend analysis and detailed investigation according to fault developments and fault causes, CMSs normally provide a data base. The following sections describe the data base requirements.

4.3.1 Data compression

To reduce the amount of data to be handled, the CMS data base should be able to compress data. Certification regulations (see section 5.2 and [11]) recommend storage of basic signals from each sensor at least one times per day, with consideration of different load conditions of the wind turbine. This leads to high data volumes per day. Therefore, a suitable data compression should be carried out.

4.3.2 Data base location

There are different approaches according to the location of the data base. One philosophy is to hold all the data in the CMS at the respective wind turbine itself. Another approach is to transfer all the data to be stored to a centralised data base server, e. g. at the technical operator’s site. Of course, there are a lot of solutions in between these two extremes. An optimised solution must be found for each individual wind turbine and wind farm configuration.

4.4 Communication

For the internal communication in a wind turbine and for communication of the wind turbine with the outside world, Ethernet networks with TCP/IP protocol have become a quasi standard. Other possible solutions could be WLAN from a wind turbine to a centralised SCADA system or Farm Server. The principle structure of the communication network is shown in figure 1. It provides all the required communication channels for one or more CMSs installed in a wind turbine.

The structure of the network is leaned on the example given in the IEC61400-25 standards. All components in the network are addressed by the internal IP numbers. For outside contacts, the SCADA-System / Farm Server will act as a proxy. Connection from a remote office at the operator’s / M&R service provider’s place is made by dial in (Analogue Modem, ISDN, …) or will remain permanently (VPN, GPRS, UMTS, …).

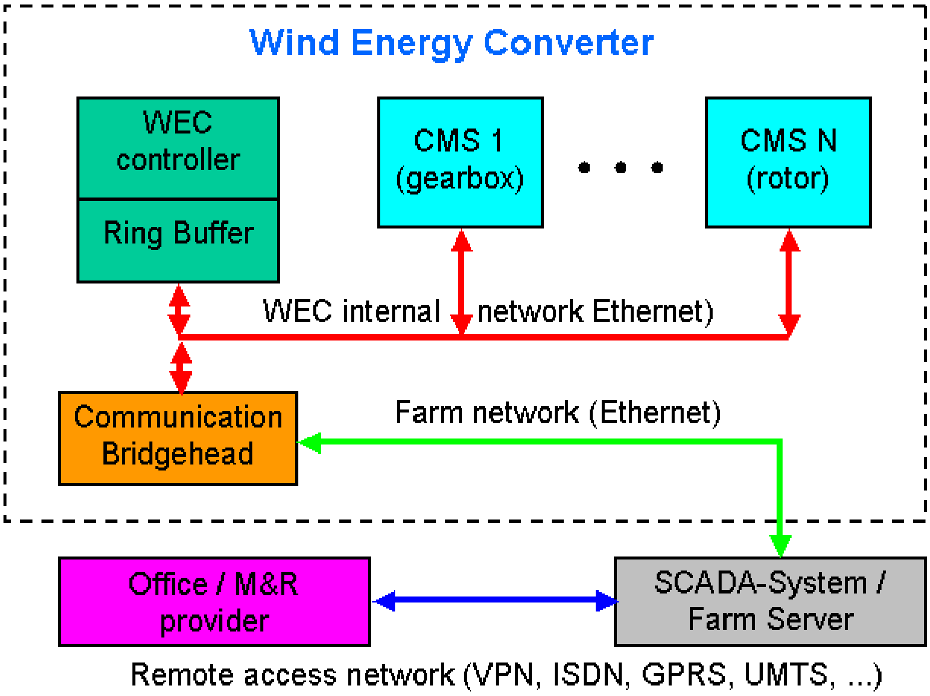

Figure 1: Wind turbine communication network structure

4.5 Hardware performance

The CMS hardware must provide CPU, RAM and storage device capacity for all the tasks mentioned above. It must work under extreme conditions, e. g. for use in an offshore environment. The life time of the components should be at least as high as of the wind turbine to be monitored itself, i. e. about 20 years. This widely excludes the use of PC based equipment, e. g. PC hard disk storage systems. Another point is the availability of spare parts for the CMS hardware, which will not be provided over such a long time when using PC hardware.

5. Standards, Technical Guidelines and Certification for CMS

5.1 Standards and Technical guidelines

The following section describes the main international standards and technical guidelines with relevance for the implementation of CMS in wind turbines (the standards are not mentioned in the reference list, access can easily be made by “googeling” the reference number):

5.1.1 Standard IEC 61400 “Wind turbines”

The IEC 61400 is a comprehensive standard, covering most of the relevant technical items of wind turbines. The relevant part for CMS applications is the Part 25 with its subparts (see structure given below). Once implemented, the given definitions of the internal communication between the different wind turbine components as described in section 4.4 will allow easy access to the internal data of the controller by a CMS. This can be used to get information about the actual load condition of the wind turbine, e. g. to classify fault descriptive measurements like vibration levels according to the power output. Furthermore, the different temperatures and environmental conditions measured by the controller can be made available for the CMS.

The subpart 6, which is under development at the moment, deals with the communication of CMS itselfs with the outside world. Amongst others, the format and contents of CMS data (time series, spectra, trends, warnings, alarms, etc.) to be transmitted to a data base server or an operator are defined here.

Subpart 4 describes the access to the data from controller or CMS. There is still a discussion going on of what will be the most effective way to do this. An advanced solution would be the use of web services. This will allow data access by use of standard internet based solutions, e. g. web browsers. The problem here is that this requires quite high CPU performance and most of the actual wind turbine controllers cannot support this. It is likely that the subpart 4 will support more than one solution for the data transfer protocol. This is an item under discussion at the moment. More information about the IEC 61400-25 can be found on the IEC web site: Link to IEC61400-25

Structure of IEC 61400 Part 25 “Communications for monitoring and control of wind power plants”

Subparts published 2006-12:

- IEC 61400-25-1 Overall description of principles and models
- IEC 61400-25-2 Information models
- IEC 61400-25-3 Information exchange models
- IEC 61400-25-5 Conformance testing

Subparts under editing:

- IEC 61400- 25-4 Mapping to communication profile
- IEC 61400-25-6 Logical node classes and data classes for condition monitoring

5.1.2 Guideline VDI 3834

VDI (“Verein Deutscher Ingenieure”) is the Association of German Engineers. Since February 2005, a work group is developing the VDI 3834 technical guideline “Measurement and evaluation of mechanical vibration in wind turbines and their components” as a German national project, but it will be also published in English and is open for international participation. Work has been started on the demand of several European wind turbine manufacturers, service providers, operators, etc. The main intention of the guideline is to provide widely accepted rules, criteria and recommendations for measurement and evaluation of vibrations in the components of wind turbines. At the moment, the definition of the suitable measurement specifications (frequency range, signal levels, etc.) is in progress. A first draft is expected for early 2008.

5.1.3 Guideline FGW "Maintenance of Wind Farms"

The guideleine, worked out by the German "Fördergesellschaft Windenergie" (Development fund for wind energy, FGW) describes the requirements for the maintenance of wind turbines in wind farms. Different maintenance and repair strategies are discussed. One of them is the condition orientated strategy, which uses input from CMS to allow scheduling of wind turbine downtimes to carry out maintenance & repair actions. Furthermore, the guideline addresses the information, regulations and responsibities which are required for performing an optimised maintenance & repair for wind farms. At the moment, the guideline is available only in German language. But it is likely that it will also published in English in the future. The German version can be purchased online from the FGW ordering site: (http://www.wind-fgw.de/tr_engl.htm#Ordering).

5.1.4 Guideline Gothaer Versicherung

The technical guideline "Fundamentals for the condition depending maintenance of wind turbines" describes the topic from the point of view of the German insurance company "Gothaer Versicherung". In the guideline, there are regulations given, how to schedule maintenance & repair actions according to wind turbines. It discusses also the requirements and qualifications of the operating personnel and the technical inspection crew. A detailed check list of how to inspect the main drive train components and the rotor are given. It also provides a template for an inspection report.

5.1.6 Other Standards and technical guidelines with respect to CMS

The following list shows a selection of further international standards which are also helpful for CMS applications in wind turbines:

- ISO 5348:1999-07 "Mechanical vibration and shock - Mechanical mounting of accelerometers"
- ISO 10816 "Mechanical vibration - Evaluation of machine vibration by measurements on non-rotating parts"
    - Part 1: General Guidelines
    - Part 3: Industrial machines with nominal power above 15 kW and nominal operating speeds between 120 r/min and 15000 r/min when measured in situ
    - Part 5: Machine sets in hydraulic power and pumping plants
- ISO 10817 "Rotating shaft vibration measuring systems"- Part 1: Relative and absolute sensing of radial vibration
- VDI 3839 – Part 1 "Instructions on measuring and interpreting the vibrations of machines"
- VDI 3841 "Vibration monitoring of machinery"

5.2 CMS Certification

The requirement for a certification process became necessary some years ago, when the German insurance company Allianz promoted the installation of CMS in wind turbines. Due to a growing number of faults on the gearboxes and bearings of wind turbines, Allianz insisted on installing a CMS for the respective components or, alternatively, replace these components regularly every 5 years. To assure a minimum functionality of the CMS, a certification procedure has to be worked out.

A first step towards this was made by the German Allianz Zentrum für Technik (AZT). AZT has worked out a paper with requirements for CMS in wind turbines. On the basis of this and some other papers, a technical guideline has been formulated by the Germanischer Lloyd (GL), wind energy department, Germany [[11]]. Meanwhile, this certification is accepted all over Europe as a standardised functional description of CMS for wind turbines. The GL certificate is mandatory, if the CMS should meet the requirements of the wind turbine insurance regulations.

Meanwhile, the main manufacturers/suppliers of CMS for wind turbines have achieved the certificate for their systems. A regularly updated table, which shows the certified systems, can be found on the GL web page: (http://www.gl-group.com/pdf/certlist_cms.pdf) .

6. References

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[10] IEC61400-25, Subparts 1-6 (partly published, partly as IEC internal drafts)

[11] Germanischer Lloyd WindEnergie GmbH, “Guideline for the Certification of Condition Monitoring Systems for Wind Turbines”, Edition 2003, Hamburg, Germany