REMOTE DATA ACQUISITION FOR CONDITION MONITORING OF WIND TURBINES

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Abstract: While the number of offshore wind turbines is growing and turbines getting bigger and more expensive, the need for good condition monitoring systems is rising. From the research it is clear that failures of the gearbox, and in particular the gearwheels and bearings of the gearbox, have been responsible for the most downtime of a wind turbine. Gearwheels and bearings are being simulated in a multi-sensor environment to observe the wear on the surface.

Keywords: Wind turbines; critical components; condition monitoring

1 INTRODUCTION

The number of offshore wind turbines (WTs) is growing, in Europe there was a growth of 34% in 2013 in comparison with the previous year and with several plans for new WT farms the amount will keep growing [1]. The remote locations of offshore plants are hard to access, thus it may take a substantial amount of time to manually check the condition of the WT, or to replace the failed component. Therefor there is a need for remote data acquisition, so the deterioration process of WT components can be monitored remotely. The objective of this paper is to first identify the most critical components and the techniques in practice for condition monitoring of wind turbines and later on build a test-setup to validate the techniques. The deterioration process could be plotted over time according to information from multiple sensors, Figure 1 shows a possible plot.

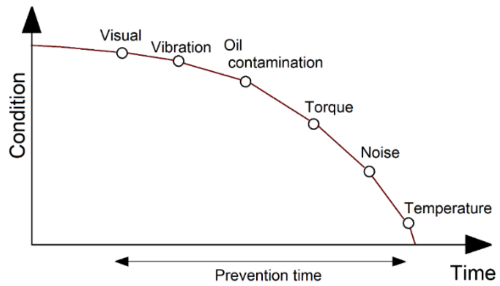

Figure 1 condition versus time

2 CRITICAL COMPONENTS AND CATASTROPHIC FAILURES

2.1 Critical components and failures in wind turbines

Information about the most critical components in WTs can be found in several sources. Most available information is acquired from long duration data acquisition, hence these data about failures in wind energy conversion systems (WECS) are highly reliable.An overview of existing and future databases can be found in [2]. One of the most prominent statistics has been collected by WMEP (Wissenschaftliches Mess- und Evaluierungsprogramm) commissioned by IWES (Institute for wind energy and energy system technology) [3] . Other European databases are Elforsk (Sweden) and VTT (Finland), LWK, WindStats Newsletter and ReliaWind to name a few. [4] has made a survey focused on the data from Elforsk, but has also concluded a comparison with the WMEP and VTT. Although these databases are made independent from each other, they can be compared and to a certain degree there are similarities [3]. In general, failures can be divided into two categories [5], (1) the frequent failures that cause a short downtime (mainly electrical components and (2) rare severe failures, due to wear of mechanical parts. Figure 2 shows the main source for the failure of mechanical components is by wear. The cause of electrical failures is less distinct because they are more influenced by external conditions, such as high winds, grid outage, lighting and icing on the blades [5].

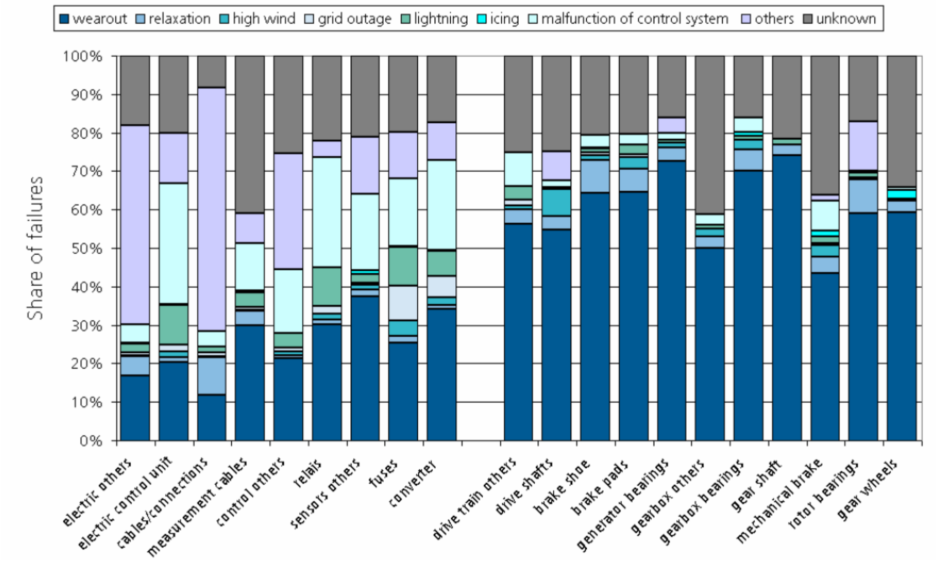

Figure 2 Failure causes for different WT components - WMEP [5]

The frequent failures have a small share of the annual downtime. As much as 75% of all failures only cause 5% of the WT's downtime, from condition monitoring point of view it is less interesting. This also means that about 95% of the annual downtime is caused by 25% of the failures, which will be the severe failures [5]. This is because some failures, such as bearing failure, mandates a replacement of the entire gearbox [4]. A major part of the downtime is due to a failure of the gear system (Figure 3), so it is important to investigate more into this subassembly.

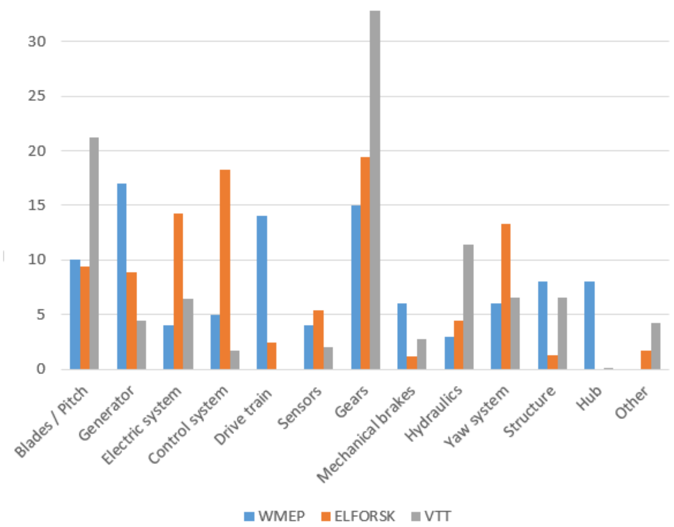

Figure 3 Downtime [%] per component (information from [4])

The different databases have major differences in gearbox failure (Figure 4). The Elforsk database concludes that the most failures are due to bearing failure, which is contradicting to the VTT database where there is no indication of bearing failures. A bearing failure usually mandates a replacement of the entire gearbox [4], so it could be that the bearing failures are listed as general failures for the VTT database. The Elforsk database also listed the number of failures due to wear. From this data, it is seen that especially gearwheels and bearings suffer a lot from wear [4].

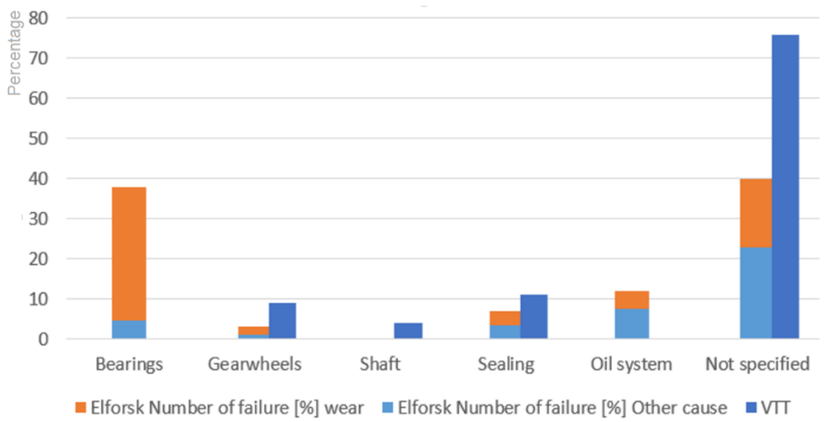

Figure 4 Causes of failures of gear system [%] [4]

More recent research was done (2007-2011) by WMEP at the Dutch offshore wind farm Egmond aan Zee. [6]. Figure 5 shows the distribution of downtime. Although the figure only includes data from one wind farm and the period it too short to make a final statement, it reported that the first three years the primary causes of downtime are the gearbox, the generator and fault of the control system. In year four the failures of the gearbox are drastically lowered. Other recent research, such as the WindStats newsletters, show that the gear system is still causing the most downtime [7-10]. So it can be concluded that most databases indicate that the gearbox causes the most downtime. According to Gcube (insurance services), based on 2012 US reports, blade damage (41.4%) and gearbox failure (35.1%), account for the most claims [11]. Major reasons for those defects are poor maintenance (24.5%) and lightning strikes (23.4%) [11].

John McLane, President GCube Insurance Services inc [11]:.

"Monitoring is especially critical for turbine gearboxes as that component experiences the greatest engineering stress and up tower repair considerations."

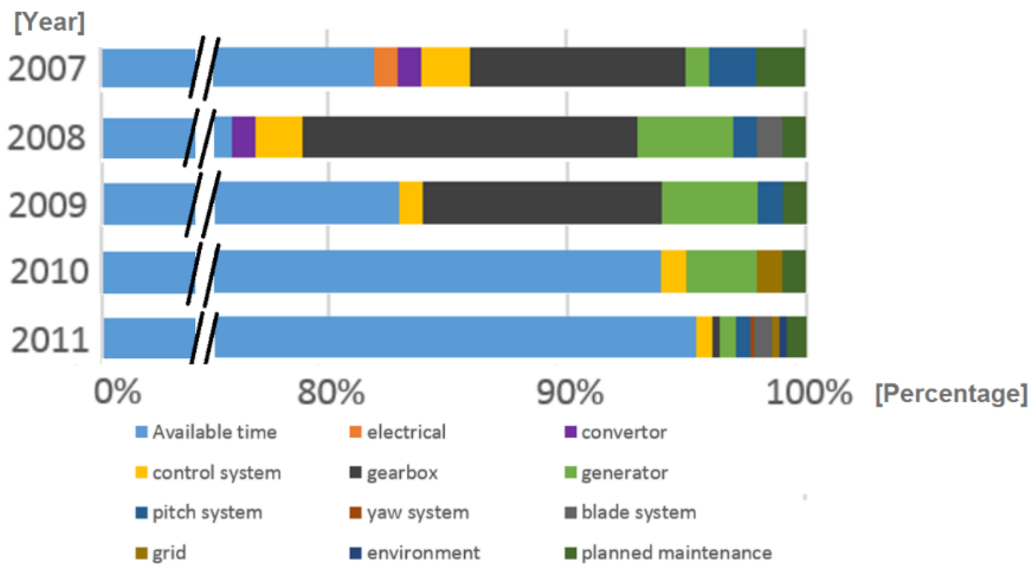

Figure 5 Downtime Egmond aan zee 2007-2011[6]

2.2 Catastrophic failures

With highly flammable materials, multiple potential ignition sources and oxygen, all elements for a catastrophic fire are available [12]. [13] combined statistics from the Caithness Windfarm Information Forum (CWIF) [14], press reports and other publicity. The most common cause of (fatal) accident is blade failure (19%), followed by fire (15%), which means an average of 11.7 fires a year [13]. More than 90% of those fires reported lead to completely losing the WT, or at least grave damage to major components [13]. This is because firefighting is not possible for fire brigades and WTs are often at remote locations [12]. [13] estimates that around 10 times more fire accidents happen, so a lot of the fires are not being reported [14]The most frequently described ignition sources are (in order of importance) [12]

(1) Lightning: due to higher altitude an exposed locations

(2) Electrical installations: Overheating of electrical components, bad wiring, short circuits,…

(3) Hot surfaces: overheated bearings, gearboxes, mechanical brakes .

In situations where the WT itself is not capable to slow down, mechanical brakes are applied to limit the rotation speed of the blades. Especially if they are worn or badly lubricated, they can reach very high temperatures [13]. This may result in sparks igniting the nacelle, or very rapid spinning of the blades which can lead to blade or structural failure.

(4) Maintenance; cutting, welding, soldering,…

It is clear that the critical components should be monitored in order to prevent long downtime or catastrophic failure.

3 MAINTENANCE AND CONDITION MONITORING

3.1 Types of maintenance

The goal of maintenance is to reach the highest availability of the WT for the lowest cost possible [5]. Maintenance can be divided into two categories, on the one hand there is preventive maintenance, and on the other hand there is corrective maintenance [4, 5, 15, 16]. The last one means the WT is in full operational mode until the equipment breaks down [4]. Thus, the maintenance procedures are done only during shutdown of the WT. The historical approach is to run a WT to failure, but with the increase in number of WTs this approach has become too expensive and less practical [15]. A small failure may not immediately result in catastrophic failure of the WT however, this one small failure could lead to the breakdown of other major components. Often special equipment is required for repairs on offshore WTs which may not be available or employable which in turn prolongs the downtime[4, 15, 17]. Additionally, maintenance planning cannot be done precisely. Due to these disadvantages of corrective maintenance, we are more inclined towards a preventive approach. This type of approach can be divided into (1) scheduled maintenance, (2) condition based maintenance and (3) reliability based maintenance. Scheduled maintenance or also called cyclic maintenance means the WT will be inspected on predetermined periods [4, 5, 15, 16]. This type of maintenance also has a drawback, regular access to the WT is a challenge for offshore operations and it is rather expensive. Because the previous types of maintenance don't meet the requirements of a low-cost reliable system there is a need for condition based maintenance. This system monitors the current state of the components and determines the remaining lifetime [5, 15]. This way maintenance can be planned ahead and downtime will be reduced to a bare minimum. The last type of maintenance relies on a database of information about past experiences of the monitored component and makes a comparison between the WT in specific and the entire wind farm [5]. This strategy may result in identifying the mean time to failure which is based on the remaining lifetime [5].

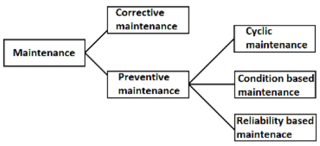

Figure 6 Types of maintenance

3.2 Process flow in condition monitoring

CM is implemented in different steps [18], initially data is collected using multiple sensors to understand the current state of the WT. Next the signals are processed for compression, amplification and filtering.

Information is extracted from the signals by using different techniques such as fast Fourier transform (FFT), Short-time Fourier transform (STFT), Wigner-Ville distribution (WVD) and wavelet analysis (WA) [19]. By comparing the present state of the component with the baseline information the reliability of the component can be estimated. The use of several sensors is to reduce false alarms and to have a better estimation on the condition of the equipment. If the comparison detects a fault two potential outputs can be expected [18].

1. Palliative maintenance, this means adaptations are made so the WT will last till a certain date, so the maintenance can be planned.
2. Curative maintenance, this means a permanent solutions for the problem is found.

On the occasion with no faults detected a preventive maintenance will be performed from the forecasted results. A complete overview of the process can be found in Figure 7. The main objectives of maintenance are to make the system the most reliable, to recover from breakdowns or avoid them, and reduce the costs to a minimum [18].

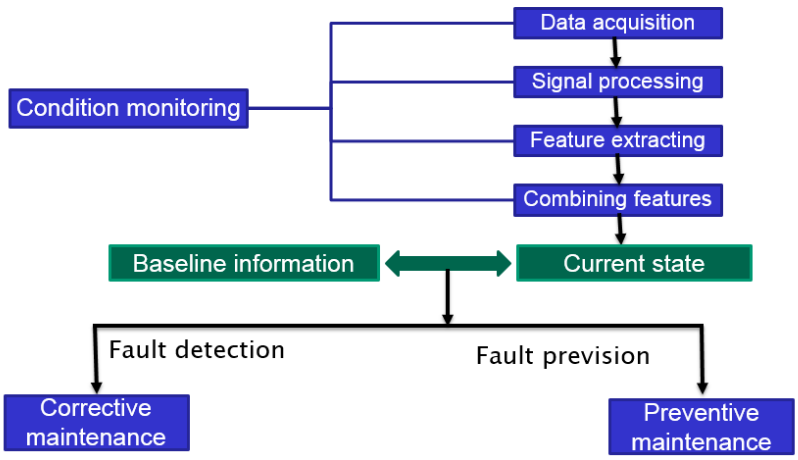

Figure 7 Global overview of the process of condition monitoring [18]

3.3 Condition monitoring techniques (CMTs)

CMTs can be divided on several bases. A first distinction can be made whether the monitoring is done off-line, on-line or in-line. Off-line monitoring means the machine is subjected to periodic inspections, it implies the machine is shut down and samples are taken [15]. On-line condition monitoring implies that the actual status of the WT is being monitored ,where raw information is processed onboard of the WT or in a control center[15]. The last form of monitoring is in-line where all of a fluid is monitored, while on-line monitoring of a fluid only samples parts of the fluid [15]. For early detection, prognosis and the remote locations of the WTs an on-line monitoring system is advantageous. The CMSs are basically divided into two groups, (1) subsystem or intrusive CM and (2) global system or nonintrusive CM [18]. The CM of the subsystem overlooks the subcomponents with local parameters [20]. Condition monitoring can also be divided into direct and indirect monitoring systems [7]. Some of these techniques are listed in Table 1, other techniques are also possible. There are also several data analysis and processing systems, such as SCADA and fuzzy logic. [15] Another approach is to adapt techniques from other domains to WTs. CM has been established much more in aerospace and the helicopter community [21, 22]. Health and usage monitoring systems (HUMS) are developed for helicopters, but can also be adapted for use in a WECS. Two of the possible HUMS are Time synchronous averaging (TSA) (Not proven to be effective for bearings, because of the slippage, but works for gears) and amplitude demodulation [21].Currently vibration analysis (VA) and oil analysis (OA) are most used. This research however will combine multiple other techniques.

Table 1 Condition monitoring techniques

Technique	Researcher	Sensor	Used for	Signal analysis
Temperature measurement	Peng Guo , Nan Bai [23]	/	/	AAKR(Autoassociative Kernel Regression) &moving window (time based)
	Y. Wang, D.G. Infield [24]	/	Bearings & fluids	NSET(Nonlinear state estimate technique)
		Possible sensors: Thermocouple, optical pyrometer		
Vibration analysis	Crabtree, Feng, Tavner. [25]	Accelerometer	Axial bearing	Enveloping
	A. Cuc [26]	Accelerometer	Structural damage	STFT, WVD (fisher criterion)
	Drexel [27]	Accelerometer	Bearing and gears	FFT, H-FFT (Hanning), Band monitoring
Position measurement	Crescini, et al. [28]	LVDT	/	FFT
Torque analysis	Nishibe et al. [29]	Magnetoelastic torque sensor	ICE (automotive)	FFT
	H. J. Sutherland, D. P. Burwinkle [30]		Turbine Gear tooth	-Time-at-torque technique -rainflow counting technique -Time varying

4 TEST METHODOLOGY

A twin-disc model is chosen to experimentally simulate the gear contact. Because the gear contact undergoes a rolling-sliding contact one of the discs is driven by a motor while the other one is free rolling. Because of this there will be partial slip as the surface velocities of both discs will differ. A multisensory environment was created in order to identify a suitable sensing technology and detect earliest conditional changes. The selected sensors are:

- Friction sensor (Load cell)
- Temperature sensor (Pyrometer)
- Displacement sensor (LVDT)
- 2 Accelerometers
- 2 Hall effect sensors
- Remote vision system (RVS)

Also a lubrication system was made to simulate oil lubrication of gears. The signals of the sensors are connected to the computer with NI appliances (BNC-2110 shielded connector block and NI PCI-6036E) and are collected at a rate of 20kHz every 20 minutes.

5 RESULTS

5.1 Test characteristics

To detect surface defects and changing test conditions several tests were done using different characteristics. Between the tests a distinction was between in lubrication, rotation speed, load and curvature of the driven disk. During the first test no surface defects were seen. In order to get results faster the surface of the driven disc has been made convex for the following test, as this increases the contact pressure. The characteristics are listed in Table 2.

Table 2 Test characteristics

Test number	**1**	**2**	**3**	**4**
Lubrication	Oil	Oil	Dry	Oil
Rotation speed (rpm)	410	410	300-410	410
Load (N)	200	400	1000	1000
Radius curvature(mm)	0	25	12	12
Rotations(million)	1.08	2.77	2.11	3.27

5.2 Machine failure

During the fourth test it was seen during a visual inspection that the driven axis was not rotating smoothly and the vibration signal also indicated large peaks. After stopping the machine and examining the fault it was seen that one screw that holds the disk on its place had broken off. This caused the other screw to bend. This phenomenon is seen by the LVDT, the accelerometers, the friction sensor and the RVS. As of the broken screw the disk could move axial. This movement is seen on the RVS because the contact area shifted. Because the one screw bended the disc got an indentation on the surface. This indentation is seen with the displacement sensor as an additional sinusoidal wave with a higher frequency that the rotational speed (Figure 8). The frequency is 20Hz, which is consistent with the PSD from the friction force at that moment (Figure 9). On both the accelerometers the failure was seen as peaks up to 1.5g for every rotation.

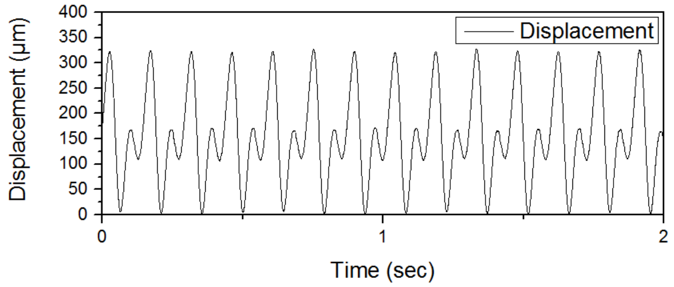

Figure 8 LVDT sensor during machine failure; notice the additional sine wave

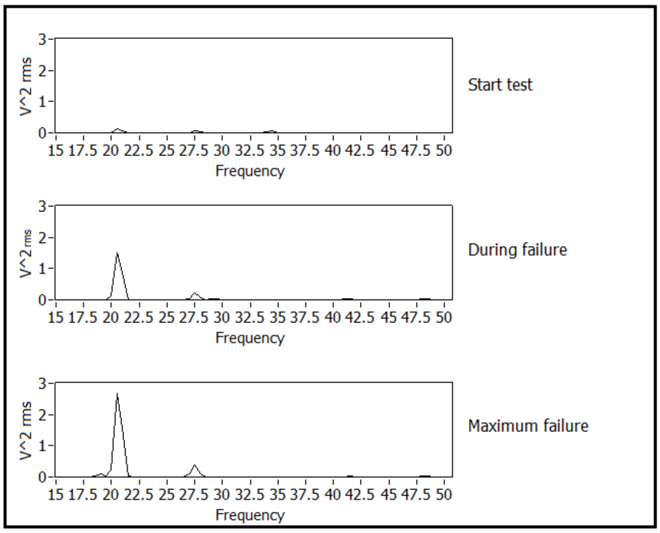

Figure 9 PSD of the friction force

5.3 Surface defect

In order to be able to detect failures of the disk a comparison was made between the machine running without any disks, with new disks and with worn disks (pitting). This wear can be detected by the accelerometers. In the time domain is seen that the RMS values and Peak to peak values of the signal increase. This is seen in Table 3. With spectral analysis there was an increase in amplitude. However it was not possible to link this to the wear because more research has to be done on the frequency of the failure.

The vibrational levels during test 1 and 2 do not show the same characteristic. But for test 3 and 4, with higher load and more rotations there was more wear and for these test the vibrational levels increase over time. Although this is less distinct for test 4 as the machine failure was also present there. Also the friction force shows the same increasing trend for the RMS values of the data.

Table 3 RMS and Pk-Pk values for No disc, New disc & Worn disc

Test disk	No disk	New disk	Worn disk
RMS vertical accelerometer	0.047g	0.058g	0.133g
Pk-Pk vertical accelerometer	0.361g	0.373g	1.425g
RMS horizontal accelerometer	0.026g	0.035g	0.191g
Pk-Pk horizontal accelerometer	0.249g	0.352g	1.720g

6 CONCLUSION

Most databases about WT failures conclude that the gearbox is the most troublesome component of the WT, but also catastrophic failures could be taken in account. Electrical components and wiring are not suited for monitoring, but overheating and wear of the gearbox or mechanical brakes could be monitored. As there is already a lot of research done on gearboxes, monitoring of the brake system should be considered a potential area for future investigation. This review proposes for a laboratory scale test setup that can be used to validate the online data where the acquired signals from multiple sensors will be processed to realize an early fault detection. During this research a test setup was built to simulate gears and detect failures in a multisensory environment. During the tests it was possible to detect a machine failure with multiple sensors and also a surface defect was detected by the accelerometers and by the friction force

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