

R&D NEEDS FOR O&M OF WIND TURBINES

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ABSTRACT: Operation and Maintenance (O&M) of wind farms is usually an activity which is carried out by industrial parties only. This paper shows that in addition to the industrial developments, the results of R&D efforts lead to a more structured approach of the O&M issue and towards optimisation of the maintenance strategies of wind farms. In general, optimisation of the maintenance strategy should result into: reducing the direct costs for maintenance; reducing the downtimes; and quantifying, controlling, and reducing the risks of O&M costs over the lifetime. It is expected that offshore wind farms will benefit the most from the R&D results. The following R&D topics related to O&M of wind farms will be discussed in this paper:

- key figures for O&M of wind turbines (trends in costs, failures, etc.)
- development of cost models for quantifying O&M costs and uncertainties over the lifetime of (offshore) wind farms;
- feedback of O&M data for optimising O&M procedures and the necessity of data collection over large populations;
- the added value and limitations of condition monitoring.

1. INTRODUCTION

Wind energy has become a professional branch of industry. Since the mid-nineties, the annual turnover of many European manufacturers has increased with 30 to 40 % per year. Now that wind turbines have exceeded the experimental stage, designers, manufacturers, owners, project developers, and suppliers are putting more emphasis on lowering the operational costs over the total lifetime in order to improve the economics of wind energy projects. Especially the economics of offshore wind parks are strongly dependent on the failure behavior of the turbines. Small failures, although frequently appearing, will have minor impact on the availability of *onshore* wind turbines. However, in *offshore* wind farms, these small failures will lead to high unavailability and high operational costs due to the difficult accessibility and expensive repair costs

This paper discusses the needs for R&D to optimize the O&M strategies of wind farms. Relevant R&D topics are:

- key figures for O&M of wind turbines (trends in costs, failures, etc.)
- development of cost models for quantifying O&M costs and uncertainties over the lifetime of (offshore) wind farms;
- feedback of O&M data for optimising O&M procedures and the necessity of data collection over large populations;
- the added value and limitations of condition monitoring.

2. COSTS AND KEY FIGURES

For onshore wind turbines, a lot of operating experience has been collected and analysed. Since onshore wind energy is a mature branch of industry, reliable data is available. In Table 1 some key figures are presented, mainly derived from [1], [2], [4], and [17].

O&M costs become lower per installed kW with increasing turbine size. An example of this trend is annually presented by ISET [1], see Fig. 1. Fig. 2, shows the relationship between the prices of service contracts and the turbine size. As can be seen, the costs per kW decrease with increasing turbine size. The data have been derived from commercial brochures, e.g. [5], and actual prices paid by owners [1]. The prices for service contracts have been compared with prices specified in four offers. In the latter case, the service contracts include warranties, consumables, spar parts, 24 hours monitoring, etc. The “all-in” contracts are about 2 times more expensive than preventive maintenance only.

Table 1: Key figures for maintenance onshore
 (Investment costs » € 850/kw)

Failure rate	1,5 to 4 failures per year
Availability	> 98 %
Service contract	0.5 to 0.8 % of invest. costs per year = 4 to 7 €/kW
Service contract incl. warranty	1.0 to 1.6 % of invest. costs per year = 6 to 15 €/kW
Costs for corrective maint. year 5	0.5 to 0.8 % of invest. costs per year = 4 to 7 €/kW
Costs for corrective maint. year 15	0.5 to 2.5 % of invest. costs per year = 4 to 18 €/kW
Average O&M costs over lifetime	2 to 6 % of invest. costs per year = 17 to 51 €/kW
Insurance costs	5 to 8 €/kW (machine damage, third parties, revenue losses)
LPC (O&M costs)	5 to 20 % of kWh price (of which half due to maint.) 0.5 (year 1) to 2.2 (year 15) ¢cent/kWh

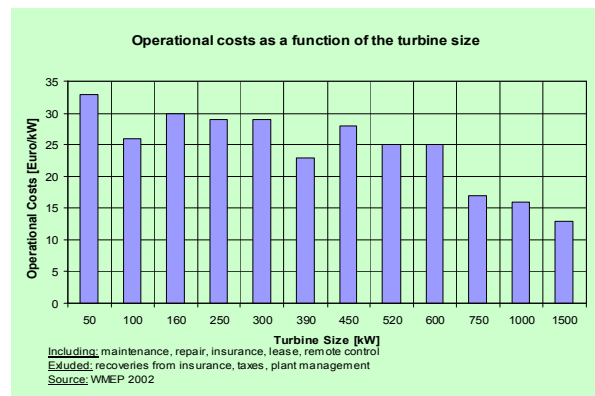


Fig. 1: Operational costs as a function of turbine size

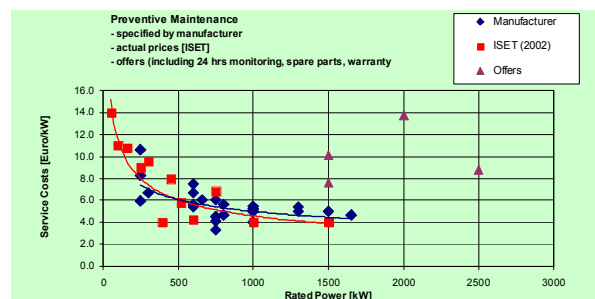


Fig. 2: Prices of service contracts as a function of turbine size

Danish and German studies have shown that turbines require more O&M if they get older [1], [9]. A German study performed by DEWI [8] indicates that after twenty years lifetime, approximately 64 % of the investment costs should be made for spare parts. Fig. 3 shows the costs for corrective maintenance over the lifetime. As can be seen, the costs are negligible for the first two years of operation. Usually, customers buy turbines with a two-year service contract, which includes preventive maintenance, corrective maintenance, and warranties. These contracts can sometimes be extended to five years. From year 5 on, the costs for corrective maintenance become somewhat unpredictable since only few manufacturers are willing to provide all-in contracts for more than 5 years. From year 5 on, the turbine owner has to pay directly for the repairs, or decide for new “all-in” contracts.

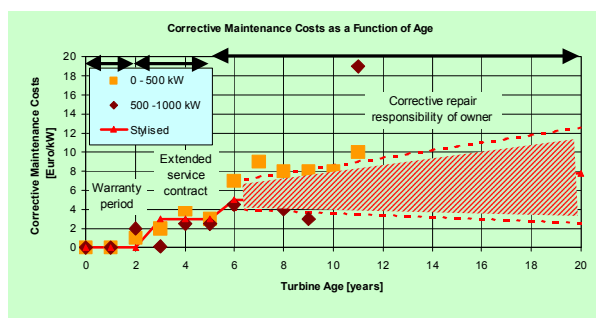


Fig. 3: Development of the costs for corrective maintenance in the different stages of the lifetime

The dashed area indicates the expected development of the costs, based on key figures found in [1], [3], and [5] and the discussion above. The dots in the graph [1] show that the specific costs are lower for larger turbines. Secondly, it can be seen that there is large uncertainty around the expected development after year 5.

From recent studies for developing operation and maintenance (O&M) plans for offshore wind farms, ECN has concluded that the costs for maintenance are much higher than for onshore. Typical figures are (including costs for maintaining the park infrastructure, civil structures, etc.):

- preventive maintenance 0,003 to 0,009 (€/kWh)
- corrective maintenance 0,005 to 0,010 (€/kWh)

The costs for *corrective* maintenance are a factor of 2 higher than for *preventive* maintenance, whereas for onshore turbines the costs for preventive and corrective maintenance are in balance. The large range in the O&M costs is caused among others by the following aspects;

1. size and reliability of the turbines (small onshore turbines vs. large turbines optimised for offshore applications)
2. maintenance concept chosen (access systems, hoisting facilities, etc)
3. distance to the shore
4. water depth
5. wind and wave climate
6. size of the wind farm

The contribution to the kWh price is approximately 25 to 30% whereas onshore [10], the contribution is in between 10 to 15 %. (The other costs are costs for investment and decommissioning.) On the other hand, offshore wind farms will run with a much higher capacity factor, say

45%. Onshore capacity factors vary between 22 and 30%. The annual energy output is thus expected to be 50 to 100 % higher for turbines with the same rated power.

In [4] the results are presented of a Danish offshore wind farm in the North Sea and in the Baltic Sea. These figures of approximately 0.9 €cent average over the lifetime are comparable with the ECN figures of 0.8 €cent to 1.9 €cent. In both cases it should be emphasised that there is very little operational experience available on which the figures can be based. The figures have been based on cost modelling which use “onshore failure statistics” and “repair strategies commonly used in offshore industry” as input. In sensitivity studies later on, it has been assumed that the onshore failure rate will decrease and that the offshore repair strategies will become cheaper for wind energy applications.

From the above-presented public data, the following can be concluded:

- For onshore wind farms, a lot of operational experience is available, showing that the O&M costs and the turbine downtime have come to an acceptably low level for commercial exploitation.
- For onshore wind farms, the O&M costs can be very well predicted and controlled during the first 2 to 5 years of operation. After 5 years of operation, the costs for corrective maintenance (or for extended “all-in” contracts) become higher but the exact level is difficult to establish on beforehand and thus covered with uncertainties.
- For offshore applications, operational data is at present not available. The figures for O&M costs are mainly based on extrapolating onshore data. Due to this, the figures are covered with great uncertainty which makes it difficult to get finances and insurance for future offshore projects.

Based on its experiences and the conclusions above, ECN has decided to work on the following R&D topics.

- Developing models to model O&M costs, quantify the uncertainties, and downtimes, taking into account the actual failure rates and the actual consequences;
- Collecting and feeding back O&M data, and exchanging operational experiences over a large population;
- Investigate the applicability of condition monitoring to reduce the number of unexpected failures and limit the consequence damage to better plan maintenance actions, and to reduce the downtime.

3. COST MODELLING

Cost modelling is especially of interest for offshore turbines. Fig. 4 shows the approach for determining the costs and downtime of offshore wind farms as it has been developed by ECN. The main input parameters are:

1. the failure frequency of the turbines and their components and the associated repair action (*reliability and maintainability*);
2. the costs, weather windows, and mobilisation time of access systems (*accessibility*);
3. the wind and wave climate at the site for determining the duration of stand still and energy production.

The model results among others in costs, downtimes, critical items, waiting time for certain repair actions, etc. With these results it is possible to optimise the

maintenance strategy, e.g. by changing the design (lower failure rates) or choosing different access or hoisting systems. The model does not only result in average values, but also gives the uncertainties as so called Cumulative Distribution Functions (CDF). This is especially relevant to determine the influence of the stochastic behaviour of the wind and wave conditions on the downtime.

(Note that for onshore cost modelling, the influence of the weather conditions on the waiting time is negligibly small. The different possibilities for accessing a turbine are not relevant.)

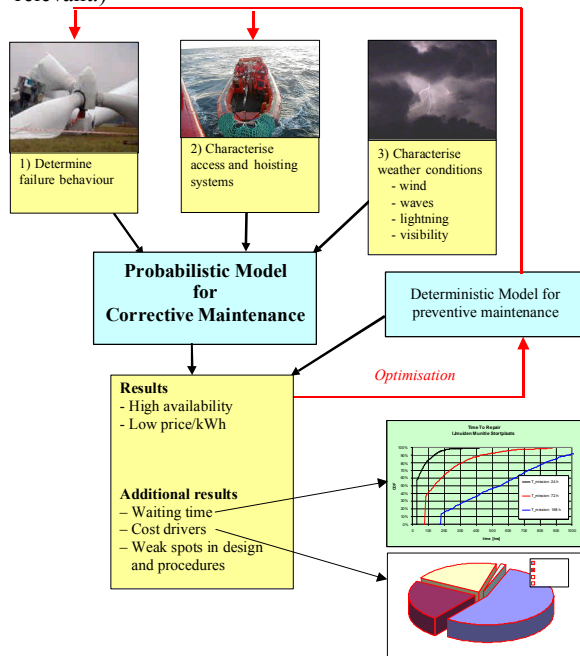


Fig. 4: Schematic presentation of the process to determine the annual O&M costs, downtimes, and uncertainties for optimising the O&M strategy

3.1 Failure Behaviour

It is worthwhile mentioning here that usually, the failure behaviour of a turbine is derived from the SCADA system. The SCADA system gives information on the number of failures of certain components and the resulting downtime. What is often missing is the consequence of a failure in terms of labour costs, costs for spare parts and consumables, and costs for hiring equipment. In order to use the failure data for cost modelling, such details are necessary. To limit the number of incidents to be modelled, the incidents are often classified into so called Fault Type Classes (FTC). An example is given below [11], [12].

- *FTC-1: Repair cleaning and reset.* The repair can be done during a visit to the turbine, no additional equipment is needed.
- *FTC-2: Replacement.* For this class, not only personnel needs to be transported but also small and medium sized spare parts. In general it can be said that they can be hoisted through the tower with an internal crane.
- *FTC-3: Failure of large components.* This class includes the failure of large components that need to be hoisted outside the tower.

3.2 Access and Hoisting Systems in Relationship with the Weather Conditions

The costs for equipment and access systems can be derived from the current market prices. The prices are covered with large uncertainties if the boats or cranes need to be hired occasionally. For preventive maintenance, long-term contracts will be signed with little uncertainty, or the supply boats can even be bought. The down time needed to repair failures and the resulting revenue losses can be a major cost driver. The downtime depends largely on the selected repair strategy and on the selected equipment and access systems. Each type of equipment has its own limits with respect to wave height and wind speed. A method has been developed in [11] and [12] to determine the repair time as function of:

- the maximum wave height at which equipment can be used;
- the maximum wind speed at which equipment can be used;
- the duration of the repair.

The time to repair is a stochastic variable, which means that not only the average value can be calculated but also the probability that the repair action will take longer or shorter.

The probabilistic cost model has been applied successfully to determine the damage of offshore wind farms due to lightning [11], [12], [14] to develop a maintenance strategy for the DOWEC wind farm [14] and for advising consortia that are planning offshore wind farms.

The presently available cost model is useful to determine long term average values. Future developments are focussed on developing cost models that assist operators and maintenance departments in taking sound decisions in their day-to-day operation.

4. COLLECTION AND FEEDBACK OF O&M DATA

As has been stated already in the previous section, the collection and feedback of O&M data is necessary to develop an adequate O&M strategy and to estimate the O&M costs over the lifetime. A structured approach for collecting and analysing O&M data of wind turbines has been developed by ECN in the last decade. Some major conclusions and recommendations from these R&D activities are:

1. Clearly determine the objective of data collection
2. Automate the data collection process to the extend possible
3. Reduce the possibility to fill in forms in a free format. A format as used for an FMEA (Failure Mode and Effects Analysis) forces technicians to fill in logbooks less ambiguously and makes the analysis much easier.
4. The larger the population from which data can be collected, the more statistically robust conclusions can be drawn from the collected O&M data.

ECN has used the R&D results a.o. to analyse the reliability of turbines in a structured way, to advice manufacturers in maintenance management [3], and to perform risk analyses of wind turbines for obtaining permits [16].

4.1 Objectives for Data Collection

The objectives of collecting failure and maintenance data can be numerous and depend on the personal interest. However, the most important objectives for turbine owners, operators, and manufacturers to collect data are:

- Comparing the performances of different types and makes of turbines. Key figures are among others: energy production, availability, failure rates, and annual maintenance costs.
- More in-depth studies will reveal the influence of: location, terrain, wind climate, farm lay-out, spacing and wake effects, and maintenance strategies;
- Generating reliability figures for systems and components in order to: compare the actual figures with the target values provided by the manufacturer; reveal weak spots in design to be discussed with the manufacturer or component supplier; reveal weak spots maintenance procedures to be discussed with service contractor.
- Determination of cost drivers.
- Obtaining a better understanding of failure mechanisms and causes.

In other branches of industry, e.g. offshore, it is common practice that larger operators collect and exchange O&M data. They want to benefit from each other's experiences and from the larger population. This can be done by setting up user groups (e.g. for gas turbines), or by setting up a database e.g. [15]. The objective of the latter activity can also be very important for wind energy: *“Enhance the reputation of the industry by demonstrating a high degree of understanding of system performance and characteristics. This is especially relevant in the communication with bankers and insurance companies, but also between the partners involved.”* At present, the possibility for setting up a similar database with a limited number of operators that own a substantial number of megawatts is being investigated in the Netherlands.

4.2 Influence of the Size of the Population

As compared to the turbine owners or to independent service companies, the manufacturer has access to much more O&M data from a larger population of identical turbines. To illustrate the influence of the size of the population and the collected data on the uncertainties of the O&M costs, the following example is given, considering two types of failures only:

1. failure of the main bearing of the gearbox, and
2. failure of carbon brushes.

Assume that a manufacturer has sold 100 identical turbines of 1.5 MW to various owners. The average lifetime is 5 years per turbine, so the number of operational years is 500. The gearbox bearing has failed 20 times, the carbon brushes have failed 60 times.

The costs for repairing the main bearing of the gearbox are 16500 € and the breakdown is as follows:

- **Downtime** (including logistics time for organising repair crew spare parts, travel time, etc. and the actual repair time) = 5 days which results in revenue losses of 5 days * 24 hrs/day * 1500 kW * 0.3_{capacity factor} * 0.07 €/kWh = 3780 €.
- **Labour costs** = 3 persons * 3 days * 8 hrs/day * 60 €/hr = 4320 €.
- **Crane** = 100 €/hr * 3 days * 8 hrs/day = 2400 €.
- **Materials and consumables** = 6000 €

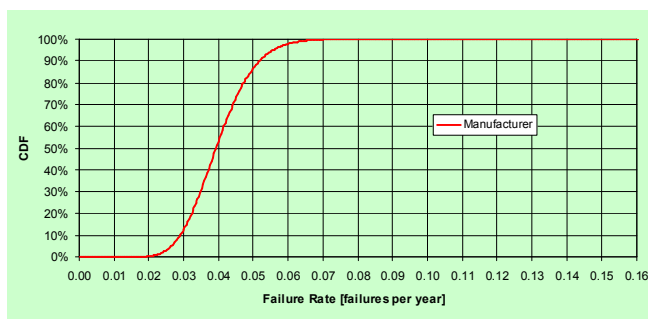
The costs for repairing the carbon brushes are 1115 € and the breakdown is as follows:

- **Downtime** (only actual repair time since the monitoring system sends a warning) = 3 hours * 1500 kW * 0.3_{capacity factor} * 0.07 €/kWh = 95 €.
- **Labour costs** = 2 persons * 6 hrs/day * 60 €/hr = 720 €.
- **Materials and consumables** = 300 €.

The expected failure rate of the main bearing is 20/500 = 0.040 failures per year. The annual costs for repairing the bearing failures are 0.040 failures/year * 16500 €/failure = 660 €/year.

The failure rate of 0.04 in fact represents the expected value. However, this value is covered with uncertainty. The amount of uncertainty depends on the number of operational hours, and on the number of observed failures. The uncertainty can be presented as a cumulative distribution function (CDF)¹ as given in Fig. 5. This figure should be read as follows. The probability that the failure rate is less than 0.03 is approximately 10 %. The probability that the failure rate is less than 0.040 is 52% and the probability that the failure rate is less than 0.05 is 86%.

Fig. 5: Cumulative Distribution Function (CDF) of the



annual failure rate of the gearbox bearing

To be on the safe side, a failure rate should be chosen which belongs to a higher failure probability, say 65% or 75%. In the latter case, the annual failure rate $\bullet_{75\%} = 0.047$. The expected annual repair costs are $0.047 * 16500 = 776$ €.

The same holds for the failures of the carbon brushes. The average annual failure rate is 0.120 per year. The annual costs will be $0.120 * 1115$ € = 134 € per year. To be on the safe side, the costs corresponding to the 75% value will become $0.130 * 1115$ € = 145 € per year. The manufacturer can offer the repairs of these failures of 776 € + 145 € = 921 € per year.

If we now assume that one of the customers has 10 turbines in operation for five years, the number of bearing failures has been 2, and the number of carbon brush

¹ The occurrence of certain failures can be described by means of the Poisson process [7]. This process assumes that during a certain period, the probability that a failure will occur remains constant. For n observed failures in T turbine years, the probability density function of the failure frequency per year, $f(\bullet)$, can be described as a Gamma function:

$$f(l ; a, b) = \frac{b^{-a} | a^{-1} \exp\left(\frac{-l}{b}\right)}{\Gamma(a)}$$

with: $\bullet = n$ and $\bullet = 1/T$

failures has been 6. The annual failure rates are identical to those of the manufacturer, namely 0.040 and 0.120. However, the population and the number of failures are much smaller. This results in larger uncertainty bounds for the failure rates. The 75 % values now become 0.054 and 0.148 respectively. The CDF of the failure rate of the gearbox bearing is given in Fig. 6, together with the CDF of the manufacturer. It can be seen that due to fewer events and fewer operational years, the uncertainty bounds have increased substantially. The turbine owner should make reservations of $0.054 \cdot 16500 + 0.148 \cdot 1115 = 1056$ € per year.

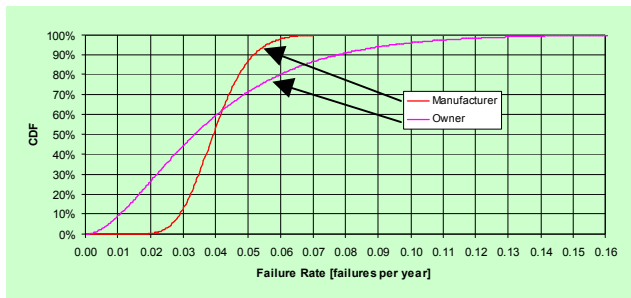


Fig. 6: CDF's of failure rates of gearbox bearing determined by manufacturer and owner. As can be seen, the uncertainty bounds are much bigger for the CDF determined by the owner since it is based on fewer incidents and fewer operational years

The conclusion is that the uncertainties in the estimation of the O&M costs that can be expected in the next coming years, can be reduced if more data is available. The statistical results become more robust. It is therefore recommended that operators and owners collect their own data and share it with others who own or operate the same turbines.

To further improve the methods of data collection and to better use the collected O&M data it is recommended that industrial parties (operators, owners, manufacturers) collaborate.

5. CONDITION MONITORING

The application of condition monitoring has grown considerably in the last decade in several branches of industry. The interest from the wind turbine industry and operators is increasing very recently. Because of small financial margins in the wind turbine branch, the relatively small production losses, the minor effects the electricity network (a wind turbine is operating stand-alone), and the easy access, the application remained limited to some experimental projects. Additionally, most components have been designed for the lifetime of the turbine, which implies that degradation leading to replacement is expected not to occur. Practice however has proven that major components often fail earlier.

At present, with the increasing installed power of the wind turbines, the application of offshore wind turbines and major problems with gearboxes, the necessity of condition monitoring cannot be neglected any longer. Some components, although designed for the turbine lifetime, fail earlier than expected. This is emphasised by the approach of insurance companies in Germany, which simply require application of monitoring provisions. Otherwise, expensive preventive replacements or inspections should be carried out periodically. Also the

development of special purpose instrumentation for wind turbines result in more or less off the shelf systems for a reasonable price.

More and more, manufacturers recognise the added value of condition monitoring given that the condition monitoring system works provides the required information:

- Condition monitoring does not prevent failures from happening but if failures can be recognised at an early stage, appropriate measures can be taken to limit the consequence damage.
- Maintenance actions can be better planned which leads to less unexpected failures, thus less downtime.
- Any measured data is useful for verification of the design assumptions.
- Insurance companies may ask for regular inspections or condition monitoring.

The largest benefits from condition monitoring can be expected for offshore wind energy to change from corrective maintenance to condition based maintenance.

It should be noted here that most experiences with condition monitoring have been gained in other branches of industries, e.g. chemical industry or the paper industry. These industries have in common that the machines run under more or less stationary conditions. Wind turbines however, suffer from stochastic loading, which makes interpretation of measured data rather complex. At present, research is going on with the emphasis on determining algorithms for early failure detection. This is still the major bottleneck before condition monitoring will be used on a large scale. Hardware like sensors, data-acquisition systems, and communication are less problematic.

Before applying condition monitoring, it should be clear what component may fail gradually and what technique is useful to determine the failure at an early stage. The most well known technique is vibration analysis of gearboxes and bearings. More components will be discussed in the next section.

A second step in the application of condition monitoring is to design a network for communication, data reduction and data acquisition. The main "components" of a condition monitoring system are:

- Sensors applied to vulnerable components and in each turbine an intelligent unit for local data processing (alarms)
- A communication network between the various turbines and operators
- A data collection system for collecting finger prints and recognition of long term trends

Usually, condition monitoring systems run more or less stand alone; they are not connected to the turbine controller. This is to make sure that if they fail, the turbine is not shut down. Below, additional information is given on monitoring of rotor blades and of the drive train.

5.1 Rotor Blades

Strain monitoring can be used for lifetime prediction. Methods are not yet "well developed" but there certainly is interest and potential for condition monitoring based on strain measurement. The measurement techniques and the necessary rotating interfaces, which push up the investments, are reasons that this type of monitoring is not often used. Techniques based on optical fibres are in

development and will be suitable for commercial application within some years. Vibration monitoring and acoustic emission are also interesting for condition monitoring of the blades. Acoustic emission can be used to detect failures in the blade.

5.2 Gearbox and Main Bearing

Gearboxes are widely applied components in many branches of industry. Condition monitoring is more or less common practice. Despite all design effort, wind turbines often had and still have problems with gearboxes and bearings. So condition monitoring is of growing interest, because the costs of replacement are very high.

Condition monitoring techniques for gearboxes are:

1. Vibration analysis based on different sensors
2. Acoustic emission
3. Oil analysis

For vibration analysis, different types of sensors can be used. Most commonly used are acceleration sensors. Also displacement sensors can be used, which might be of interest for bearing operating at a low speed (main bearing).

The fault detection is often based on frequency analysis and level detection for certain frequency bands, (see Fig. 7, source Prüftechnik). Based on the level of amplitudes, status signals can often be defined and generated. Diagnosis is often done by the supplier of the condition monitoring system or of the gearbox supplier. Specialised knowledge is required for signal interpretation. The effectiveness of these systems is becoming more evident for large-scale applications. Due to the non-stationary operation, it appears to be difficult to develop effective algorithms for early fault detection, especially for variable speed operation. Practical experience builds up very slowly, because component degeneration is fortunately a slow process and additional information about turbine loads and operational conditions are only fragmentarily available.

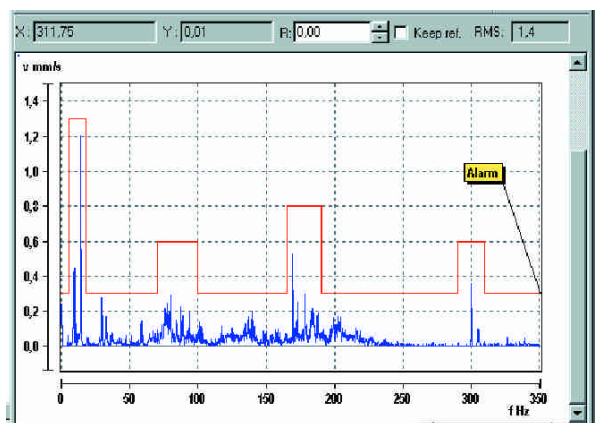


Fig. 7: Example of fault detection based on FFT (source Prüftechnik)

Acoustic emission is another technique, based on higher frequencies. For vibration analysis the frequencies related to the rotational speeds of the components are of interest. For acoustic emission higher frequencies are considered, which give an indication of starting defects. The effects normally attenuate after short period.

5.3 Economical Aspects

Because financial margins are very small for wind turbines, economic aspects play a very important role. The installed power per wind turbine is relatively small. Wind turbines are available in the order of 1 MW, while other power generation units are in the range of 10 up to several hundreds of MW's. So the production losses due to failures are very small for wind turbines, as compared with other branches of industry. Moreover, due to the low installed power per wind turbine, the investment level for condition monitoring system is relatively high. So from economical point of view, the margins for investments are very small for on shore application.

For offshore application, the situation is quite different. Due to the restricted accessibility of wind turbines for maintenance, the waiting and repair periods, following a failure will be considerably longer, which implies increasing production losses and repair costs. Together with decreasing prices of condition monitoring systems, the economical break even will decrease significantly.

A condition monitoring systems, based on vibration analysis is in the range of €10000 to €15000. Although the robustness with respect to failure detection/forecasting is certainly not yet demonstrated, the level of investment makes application feasible.

On line oil analysis is still very expensive. However these kind of sensors are relatively new, which implies that reduction of prices is likely over the coming years. Similar to vibration monitoring oil analysis is also focussed on one of the most critical wind turbine components, being the gearbox.

Apart from the condition monitoring systems, based on vibration analysis and existing applications, there are also techniques, which can especially be developed for wind turbines. One of the techniques, based on general (available) measurement signals, requires specific algorithm development and verification. However, it is expected that these kinds of algorithms can be implemented in the control system of the turbine, which implies that no extra hardware investment is involved.

Condition monitoring of the blades is rather new, and very expensive at this moment. The measurement techniques are based on optical fibers. The sensors are still expensive, however large series and automation of the production process can cause a dramatic decrease of production costs. Also at the side of the instrumentation, developments are necessary with respect to cost reduction and improvement of robustness. Developments are still necessary for algorithms as well as for the instrumentation and sensors.

6. CONCLUSIONS

It can be concluded that the O&M approaches can be improved with the results of R&D projects. The best examples are the use of O&M data for reliability analyses of wind turbines, and for cost modelling of offshore wind farms. The topic is strongly related to asset management, which is commonly used in many branches of industry that have reached a professional level. The wind turbine industry is about to reach the same professional level.

To better benefit from the R&D results, industrial parties should collaborate in collecting and exchanging O&M data. O&M data from larger populations will reduce the uncertainties in the estimation of O&M costs and thus

reduce the financial risks. Furthermore, it will enhance the reputation of the wind industry by demonstrating a high degree of understanding of system performance and characteristics. This is especially relevant in the communication with bankers and insurance companies, but also between the partners involved.

White spots in the O&M issues on which R&D is still necessary are demonstrating the added value of condition monitoring and developing algorithms for predicting the remaining lifetime of components. Finally, the further development and use of probabilistic cost modelling for the quantification of risks and uncertainties is an ongoing activity. The focus will be on a tool that assist operators in taking cost effective decisions in their day-to-day work, especially offshore.

REFERENCES

- [1] M. Durstewitz et al.: "*Wind Energy Report Germany 2001; Annual Evaluation of WMEP*"; ISET, Germany 2002
- [2] Energie- og Miljødata (EMD), database with energy production figures, incidents and accidents.
- [3] Braam, H. and Rademakers, L.W.M.M.: "*The MAINTENANCE MANAGER Collecting and Analysing Maintenance Data of Wind Turbines*", ECN-C--01-012, 2001
- [4] BTM Consult: *World Market Update 2001* (hfdst 6). Denemarken, maart 2002.
- [5] Bundesverband Windenergie: "*Market Survey 2001*"
- [6] Verhoef, J.P.; Verbruggen, T.W.: "*Conditiebewaking aan windturbines; Een verkennende studie*" in Dutch: "*Condition Monitoring of Wind Turbines, An Overview*"; ECN-C--058, juni 2001
- [7] D. Vose: "*Risk Analysis; A Quantitative Guide*"; second edition, 2000; John Wiley & Sons, Ltd; ISBN 0-471-99765-X
- [8] Refeld, K. et al.: "*Untersuchungen der Actuellen Kostensituationen der Windernienutzung in Deutschland*"; DEWEK 2000, Wilhelmshaven, Germany, 07-08 June 2000.
- [9] "*Wind Energy Basics Part Nine: Costs and Economics*"; Wind Directions September 2002.
- [10] Concerted Action on Offshore Wind Energy in Europe: "*Offshore Wind Energy; Ready to Power a Sustainable Europe*", December 2001
- [11] L. Rademakers, et al: "*Lightning Damages of OWECs - Part 1: Parameters Relevant for Costs Modelling*"; ECN-C--02-0053, May 2002
- [12] H. Braam, et al: "*Lightning Damages of OWECs - Part 3: Case Studies*"; ECN-C--02-054, May 2002
- [13] H. Braam, et al: "*Cost Modelling of Lightning Damage For Offshore Wind Farms*"; DEWEK 2002
- [14] L. Rademakers et al: "*Assessment and optimisation of operation and maintenance of offshore wind turbines*", to be presented at EWEC 2003, Madrid
- [15] Offshore Reliability Database OREDA, http://www.sintef.no/units/indman/sipaa/prosjekt/or_eda/
- [16] H. Braam, L.W.M.M. Rademakers "*Guidelines on the Environmental Risk of Wind Turbines in The Netherlands*"; Global Wind Energy Conference, Paris, 2002
- [17] J. Lemming, et al: "*O&M Costs and Economical Life-Time of Wind Turbines*"; EWEC 1999, Nice

