CHEMICAL ENGINEERING TRANSACTIONS

VOL. 33, 2013

Guest Editors: Enrico Zio, Piero Baraldi

ISBN 978-88-95608-24-2; **ISSN** 1974-9791

A publication of

AIDIC

The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1333156

State of the Art of Maintenance Applied to Wind Turbines

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This paper is aimed to deal with maintenance aspects related to devices which are involved in the generation of electric power from clean sources as the wind energy. Particularly, the objective of this research is to analyze all those important studies that have provided a better view on the maintenance of wind turbines.
With that purpose, this document starts introducing the concept of O&M activities applied to wind turbines. A brief historical approach regarding the maintenance of these devices is described in order to continue with a review the condition based maintenance applied to these wind turbines. Due to the huge amount of data that are in used during the operation of these wind farms, the paper includes a section dealing with the data management and how they can help to take decisions considering that information which is more important and really profitable for the maintenance area.
Finally, this paper ends summarizing the main aspects of the research in the conclusions section, underlining those important issues related to the wind turbines and their state of the art.

Introduction

Wind energy is an important source of renewable energy, and reliability is a critical issue for operating wind energy systems. Wind energy conversion is the fastest-growing source of new electric generation in the world and it is expected to remain so for some time. During the last two decades wind turbines have been developed in size from 20 kW to 2 MW, while even larger wind turbines already are being designed.
A proper O&M management is the key to reduce downtime while increasing the availability of a wind farm. This fact will concern the reduction of unscheduled maintenance in high wind-speed months, maintenance services mainly placed in low wind-speed months and happening when they are needed in order to reduce replacement costs. Conover et al. state that the operating strategies are evolving as owners and operators are gaining more experience and realizing the benefits of focusing to the O&M activities. As an example, the following list represents the identified trends in the O&M strategies:

1. Start to schedule maintenance and repairs during the low wind periods (in order to reduce the impact on energy output).
2. Evaluate other strategies to optimize the project performance, as quantifying the tradeoff between paying overtime and losing potential energy during downtime periods.
3. Conducting research and/or initiating storm damage mitigation actions.
4. Prioritizing the responsibilities of the maintenance staff.
5. Defining the roles and responsibilities of the staff.

In this paper, the general target here is to analyze all those important studies that have provided a better view on the maintenance of wind turbines. With that intention this paper is structured in the following way: In Section II, a brief historical approach regarding the maintenance of these devices is described, Then, Section III provides a review of the condition based maintenance applied to these wind turbines. Section IV deals with the data management and how they can help to take proper decisions. This section considers that information which is more important and really profitable for the maintenance area, due to the huge

Please cite this article as: Barbera L., Guerrero Bolanos A., Crespo A., Gonzalez-Prida V., Guillen A., Gomez J., Sola A., 2013, State of art maintenance applied to wind turbines, Chemical Engineering Transactions, 33, 931-936 DOI: 10.3303/CET1333156

amount of data that are in used during the operation of the wind farms. The central findings are summarized together with the most remarkable issues identified from the state of the art in the conclusions in Section V.

Wind turbines maintenance: historical approach

One of the first steps into wind energy field is due Krokoszinski (2003) defined a systematic mathematical approach to the effect of O&M in order to support investment decisions. Due to the lack of proper terms, Krokoszinski used production technology terms and defined new terms such as Wind Farm Process and its Total Overall Equipment Effectiveness (TotalOEE), as well as redefining the terms theoretical production time, available production time and valuable production time in terms of unit full load hours. With these new concepts, Krokoszinski (2003) carried out a comprehensive description of the differences between produced electrical energy and delivered electrical energy, taking into account the external and technical losses, enabling the systematic description and quantifying the losses happening in a wind farm.

However, Nilsson and Bertling (2007) assured that current maintenance planning for wind turbines were still not optimized and that they could be much more efficient; probably because of the extra cost involved and the not proved payback period of such investment. Therefore, Nilsson and Bertling (2007) states that condition monitoring systems (CMS) could improve the maintenance management, especially for offshore wind farms. Hence, a CMS would continuously monitor the performance of the different wind turbine parts, helping to determine the optimal time for specific maintenance. Assuming an investment cost for one CMS is € 20,000, Nilsson and Bertling's results are presented in Table 1. What Table 1 represents is the how much should be the reduction of the different strategies to make profitable a CMS. Although replacing two at a time won't make CMS profitable, availability must simply increase by 0.43 %, what is totally achievable.

Table 1 Nilsson and Bertling results for CMS installation (Nilsson, Bertling 2007)

Strategy	Onshore, 1 turbine	Offshore, 1 turbine
1) Change in Preventive Maintenance	23 %	4.5 %
2) Change in Preventive&Corrective Maintenance	3.5 %	2.55 %
3) Increase of Preventive if Corrective Maintenance is 0	6.3 times	1.85 times
	1. At a wind farm, 30 turbines	
4) % of Corrective needs to be Preventive	2. 47 %	
5) Savings by replacement of 2 at a time	3. €230,000	
6) % availability must increase	0.43 %	

Regarding the 4th strategy, a change from scheduled to unscheduled maintenance of 47 % would make a CMS profitable. On the other hand, regarding the 5th strategy, replacing two components at a time instead of one would not make a CMS profitable (installation cost is € 20,000).

In light of these results, Nilsson and Bertling stated that CMS are totally profitable; highlighting the need of further studies about combining CMS and RCM systems in wind power, proposing CMS a good tool for collecting data for RCM systems.

Risk-based maintenance approach

Maintenance in wind farms is a complex activity. Research has shown that the present maintenance of both on- and offshore installations is not optimized. It has revealed large potential savings by optimizing maintenance decisions over the lifetime to reduce the total cost 1) for maintenance activities and component failure, and 2) costs due to production losses, especially for large offshore wind parks (Fischer, 2012). There are some techniques that allows to have a well-organized maintenance planning before starting to implement it. Most of them are based on the concept of risk-based maintenance. The advantage of risk-based maintenance strategies is that gives a global point of view of the maintenance process. That means that techniques like failure mode effects and criticality analysis (FMECA) or reliability-centered maintenance (RCM) is a structured approach that focuses on reliability when planning maintenance, i.e., finds a balance between preventive and corrective maintenance (Nilsson 2007). Also, RCM helps to extract the whole potential of maintenance in high monitored scenarios like wind farms.

There are some interesting results in this area. A quantitative analysis based in failure mode analysis (FMEA) methodology (Arabian-Hoseynabadi, 2010) gives both information about the most important systems for maintenance planning and also an adaptation of a quantitative methodology of FMEA based in the concept of risk priority number (RPN). This FMEA is an adaptation of one used in the aeronautical industry and has 3 main criteria:

- Severity: Which measures the impact of the failure in the main function of the asset
- Occurrence: Which is a qualitative mode to measure the failure rate
- Detection: Which talks about the ability to detect the failure before it appears on the asset

Table 2 RPN by wind turbine system (Arabian-Hoseynabadi, 2010)

Order	System	RPN
1	Rotor and blades assembly	1609
2	Generator	1204
3	Electric Controls	925
4	Hydraulics	921
5	Gearbox	909

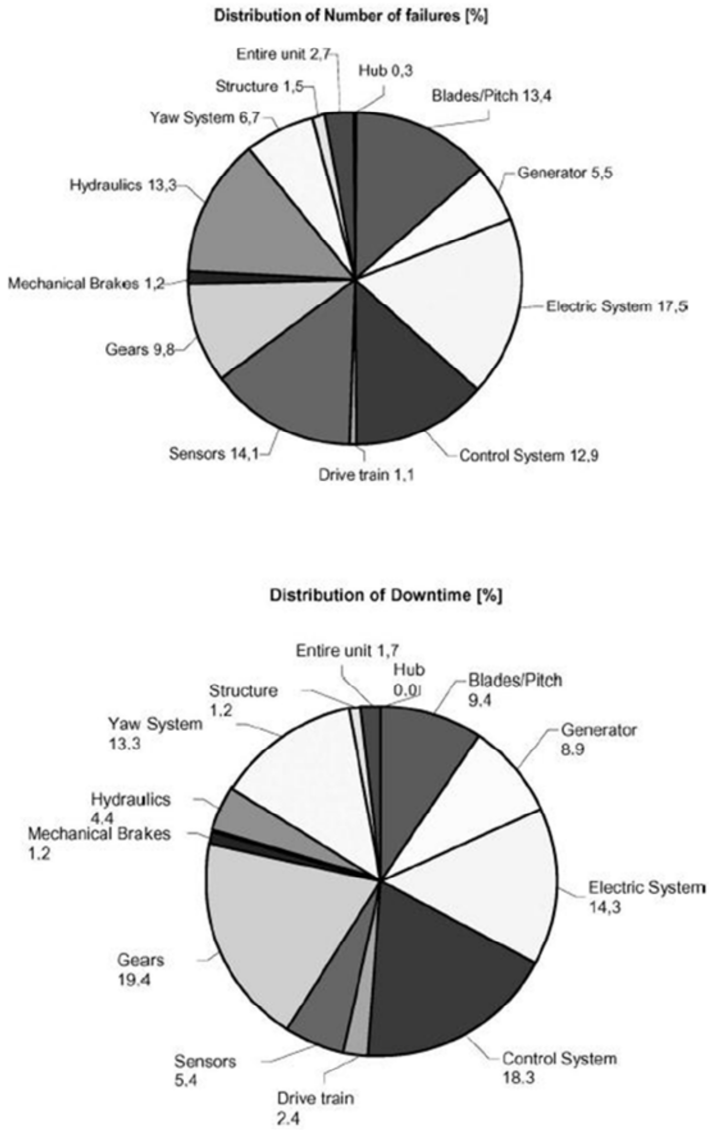

Figure 1 Comparison between downtime and number of failures (Ribrant, 2007)

Another approach, based in statistical data is used by Ribrant (2007). In this paper we can analyze the results of 8 years of failure information. They focus the paper in number of failures and downtime per system. One of the most interesting results is that the systems with low reliability (more failures) do not cause the major downtime. In this figure we can see a comparison of systems of a wind turbine according to number of failures and downtime. According to the downtime and assuming than the capacity loss cost is bigger than other, this study based in statistical data confirms the main results of the RPN calculations and confirms the Gearbox and the control system as the most critical in the wind turbine.

Condition Monitoring Systems and failure detection

Condition Monitoring Systems (CMS) were not used since wind energy became a commercial technology. This is because wind turbines have an inherent high technical availability, what it is mainly due to fast and frequent service maintenance, instead of a good reliability or maintenance management (Verbruggen et al. 2002). As an example, wind turbines were simply run to failure and the service maintenance was based on pure periodic manual inspections (Nilson, 2006). First condition monitoring technologies were offline, performed when the machine is shut down and/or require the attention of an operator (Sutherland et al. 1994).

CMSs must produce actionable information to be useful, what means that it must be specific and credible enough thus actions can be taken basing on the data collected. However, the detection of a potential failure is not a simple matter. When a failure starts to occurs there is a delay until it can be actually detected. Therefore, a monitoring system can just produce a signal only after the point P (see Figure 2).

However, the early detection of failures is not a simply issue (Nilson, 2006; Gray and Watson, 2010). As Figure 2 shows, there is a delay between the starting of the failure and when this can be actually detected. Therefore, the aim of CMS is to act in the Potential Failure interval, thus avoiding a failure of the system optimizing production and its maintenance.

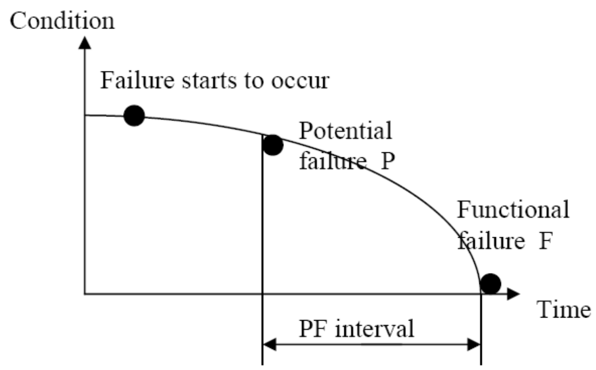

Figure 2 Potential Failure Interval (Nilson, 2006)

According to Kusiak and Li (2011), to predict turbine faults using data from SCADA systems (based on real data), the faults can be usually predicted 60 minutes before they occur and six minutes interval for collecting data is too long.

What is monitored and how

Once showed the importance of wind energy for the energy market, the emphasis of the owners and operators shifted from installation and commissioning to a focus on optimizing the operation and maintenance activities (Conover, VandenBosche & Rhoads 2000). Some important references that deal with the specifications for each component and wind energy conversion systems regarding their condition monitoring and state of the art are: (Hyers et al., 2006) and (Amirat et al., 2007). In the same context, an interesting case study on this field can be found in reference: (Beltrán, 2000). Other references about condition monitoring that are useful on the area of Wind energy are for instance:

- (Lu et al. 2009) Review of most recent advances of condition monitoring and fault diagnostic techniques (Gearbox and Bearing, Generators, Power Electronics and Electric Controls; Rotors, Blades and Hydraulic Controls; and System-Level Fault Detection and Isolation)

- (Yang et al., 2009) Wind turbine synchronous generator drive train. Application of wavelet transforms in the light of the disadvantages of spectral analysis in processing signals. Detection of mechanical and electrical faults by electrical signals.
- (Yang et al., 2009) describes a technique that, using the generator output power and rotational speed, derives a fault detection signal. Low calculation times, applicable to different wind turbine models and successfully applied, detecting both mechanical and electrical fault-like perturbations.

The main causes of poor lubrication are lubricant leaking and high content of particulates. The causes of vibration and shock include poor design, misalignment, fitting error and foreign object getting into gearboxes etc. These failure modes can be detected by installing vibration inspecting system. Gears and bearings work in a high speed rotating condition and they get aged easily. Periodical maintenance is a useful way to solve this problem. So it is required to calculate the optimal maintenance interval.

Methods base on physics of failure

Generally, failures occur due to the accumulation of irreversible changes that take place in the microstructure of a component subjected to certain loading or environmental conditions (Gray and Watson 2010). However, and as it was commented before, this accumulated damage might not be measurable (thus findable) at a desirable time or simply being detected at the very time when the failure happens. What Physics of Failure stands is that if the physics that defines a damage evolution is fully understood, accurate models and prediction can be done regarding the expected component life.

Basing his work on an investigation of using SCADA information for identifying turbine faults by anomalous performance measurements (Zaher et al. 2009), Gray and Watson proposed a method for using this SCADA information with an applied knowledge of failure physics in order to calculate theoretical damage accumulation, and hence, the risk of failure.

In Andrawus et al. (2007) discussed the concept, relevance and applicability of the MSF and DTMM techniques to the wind energy industry. DTMM (Delay-Time Maintenance Model) is a well-known system for its simplistic mathematical modeling.

Modeling System Failure (MSF) is a technique that investigates the operations and failure patterns of equipment by taking into account failure distribution, repair delays, spare-holding and resource availability to determine maintenance requirements. Therefore, the first step consists on identifying a statistical distribution that best fit the assessed failure characteristics. Secondly, a parameter estimation method is selected and the calculated parameters are used to build a Reliability Block Diagram (RBD) which permits the use of Monte Carlo simulations to determine the optimal levels of key maintenance variables (costs, spare holdings, level of reliability and availability required between others). (Andrawus et al., 2007)

On the other hand, the DTMM model examines equipment failure patterns by taking into account failure consequences, inspection costs and intervals to determine an optimal inspection interval. Therefore, the DTMM model allows the determination of the optimal inspection interval in terms of how much a failure will affect the whole system. In comparison with a CBM approach, based on measurable parameters, if the interval P-F is too short, CBM becomes useless (Andrawus et al., 2007).

Managing data

While the benefits of CM provide a strong case for their use in power plants, operators are weary of blindly adopting the technology without a reasonable economic justification. (Zaher et al. 2009). Due to the huge amount of data, trying to take every data into account for the decision becomes an impossible task. Therefore, a tool that would screen these data and present the more important one might be beneficial.

In despite of some alarms registered by wind farm’s SCADA system, the use of real data is not valid due to its low quality (Sainz, Llombart & Guerrero 2009). In this way, Sainz et al. carried out the characterization of turbines using the robust statistical technique of the Least Median of Squares combined with a random search to deal with this problem. For example, the most required figure on wind turbine characterization is the power curve relating wind speed and power production (an example is shown in (Figure 3).

While Zone 1 represents the shade effect due to the presence of obstacles, zone 2 data represent a not performance of the turbine. However, the fluctuations around the mean data in zones 3 and 4 might represent the starting of a bad performance, but this fact cannot be assured without considering more information. In other words, these data position might be due to the quality of the data: sensor accuracy, electro-magnetic interferences, etc.

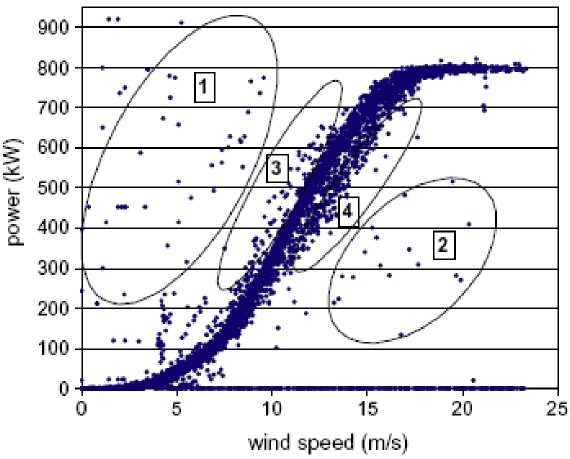

Figure 3 Example of a real data set to be considered (Sainz et al., 2009)

Conclusions

This paper presents an overview of the current state of the art regarding maintenance and its application on wind turbines. We have firstly offered a view of O&M activities in the context of wind farms, which is aligned with the usual procedures for operation and maintenance in industrial and complex assets. Then, the main studies on this sort of maintenance and, particularly, on condition monitoring has been presented. The methods and the way of monitoring have been summarized. At last, a review on data management is provided in order to simplify and make more profitable the huge amount of information that takes part during the operation life of this sort of devices.

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