Wear Analysis of Wind Turbine Bearings

Nacef Tazi*‡, Eric Châtelet*, Youcef Bouzidi**

*Charles Delaunay Institute, STMR, CNRS, University of Technology of Troyes, Troyes, France

**Charles Delaunay Institute, CREIDD, CNRS, University of Technology of Troyes, Troyes, France

(Nacef.tazi@utt.fr / naceftazi@gmail.com, eric.chatelet@utt.fr, youcef.bouzidi@utt.fr)

‡ Corresponding Author; Nacef Tazi, Nacef.tazi@utt.fr / naceftazi@gmail.com

Received: 09.05.2017 Accepted:01.06.2017

Abstract- Bearings are among the key mechanical components for conversion from wind to electrical energy in wind turbines, but their reliability are affected by external and internal environments. Wear is among the most frequent cause of failure of wind turbine tribological components such as bearings. In this paper, a fault tree analysis (FTA) is conducted for bearing failures due to wear. Influence of material bearing and its place of installation have been investigated. Occurrence of different wear types and failure detection in bearings are studied.

Keywords Wind turbine, bearing, wear, failure tree analysis (FTA), failure detection.

1. Introduction

Reliability and performance of wind turbines has been extensively studied [1-3], several reliability analysis methodologies were used to assess the wind turbine components performance, including failure modes and effects analysis (FMEA) and fault tree analysis (FTA) [3-5]. Tribological components such as bearings and gears are often the most critical components in wind turbine systems, and wear is the main cause of failure [3]. Wear is a complex process that can be triggered by different mechanisms, it has also different types. This study continues our investigations in wind turbine components reliability [3], we investigated in this paper types of wear that can be manifested in wind turbine bearings and lead to failure. Standard failure is defined as "termination of the ability of a component to perform a required function" [6]. Wind turbine bearing failures not only lead to shutdown of the system, but also to economical penalties and production losses. Literature shows few results and investigations about the effects of the different types of wear on wind turbine bearings. Improved reliability starts with accurate diagnosis of failures. The aim of this paper is to present a first step towards this improvement. For this purpose, a failure tree analysis (FTA) is developed along this study. The next figure shows the flowchart representing the process followed to develop the FTA in this study:

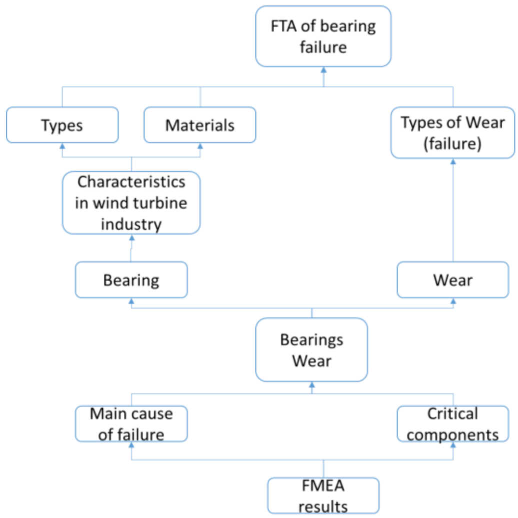


Fig. 1. Flowchart representing the process followed in this study (read from bottom to top).

As seen in figure 1, we firstly investigate from Failure modes and effects analysis (FMEA) of wind turbines [1,3-5] all critical components and main causes of failure. According to our last analysis [3], bearings are critical components in wind turbines, and we found that the main cause of failure was wearout. Figure 2 shows an overview of the most important failures in wind turbine system, where wear is the most frequent cause of failure. Next sections will develop main characteristics of bearings used in wind turbine systems, types and materials of bearings are presented. Types of wear are then investigated for bearings, and finally, Failure tree analysis using these data are constructed and presented in results section. Before conclusion, importance of place of bearing installation in system, its type and how the material can influence the failures are discussed, occurrence of wear types and failure detection in bearings are also discussed.

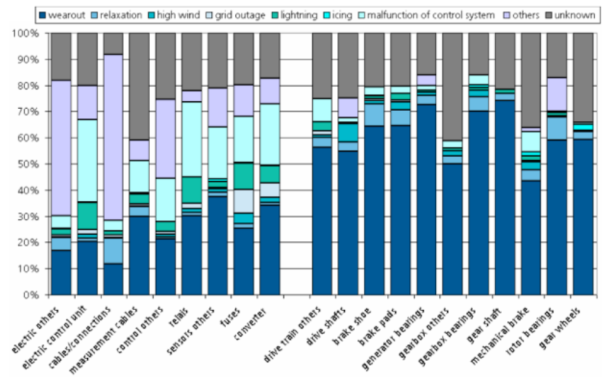


Fig. 2. Share of failures in the wind turbine system [3].

2. Data & Background

2.1. Bearings in wind turbine components: types & materials

Bearings are used in various places of the nacelle of a wind turbine, Figure 3 shows some main bearings positions in a standard wind turbine nacelle. The rotor shaft bearing (see figure) supports the blades and rotor, it transmits torque to the gearbox. Wind speed fluctuations lead to rotating speed and bearing loads variations [7]; Rotor shaft bearings are subject to an important stress (start, stop, acceleration…), they are exposed to fluctuation of load. This can lead to potential damages in this component due either to internal or external causes [7].

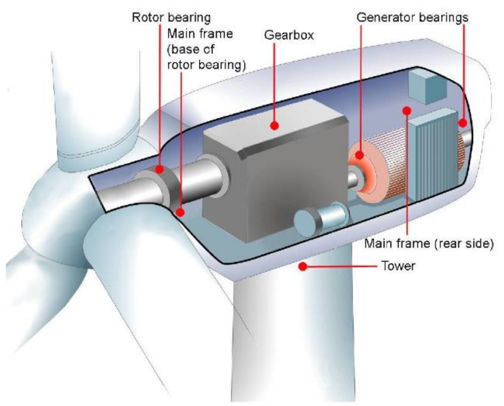


Fig. 3. Some bearing places in wind turbine nacelle.

Different types of bearings can be used to connect the rotor, gearbox and the generator, table 1 (appendix) resumes the structures of geared & gearless rotor shaft bearing assembly [7]. It shows different suitable bearings for every configuration, the two last configuration are synchronous generators that are not equipped with gearbox. Since the rotor shaft bearings are exposed to internal and external vibrations (wind, blades and gearbox vibrations), several damages may occur.

Other bearings are placed in wind turbine gearbox, such as planet (carrier) bearings, low, intermediate and high-speed shaft bearings. These bearings can also be CRB, SRB…. The next figure (Figure 4) shows bearing placements inside a wind turbine gearbox.

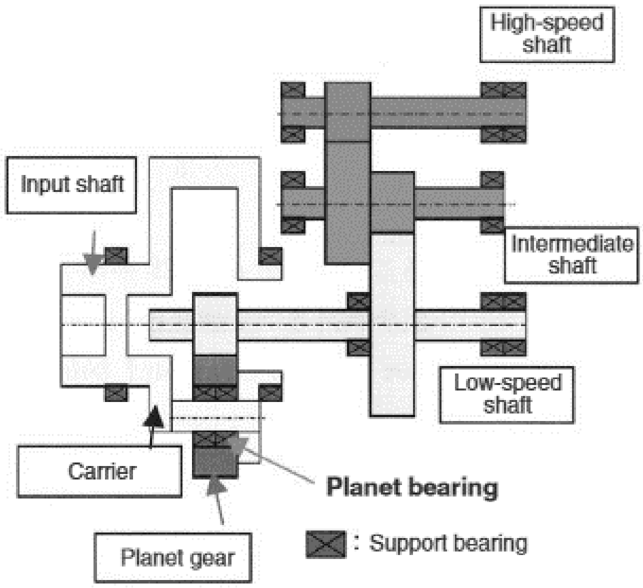


Fig. 4. Bearings placement in a wind turbine gearbox.

Same types of bearings are also used for wind turbine generator and yaw components [7].

According to the ISO standards ISO 7146 and ISO 4383 [8-9], the materials widely used for bearings are: Cast lead-bronze alloy, referred as "CuPb22Sn2" (76% Cu, 22% Pb, 2% Sn2; 55-80 HB), and aluminum alloy, referred as "AlSn20Cu1" (79% Al, 20% Sn, 1% Cu; 30-40 HB). Types of wear will be also investigated according to the bearing types and materials.

2.2. Types of wear in Bearings

Wind turbines work in a variable environment, placing considerable loads and challenges on the system's bearings and other critical components. Wind turbine bearings can be damaged due to external and internal causes, external causes can vary from the unsteady wind and gusts (that lead to high contact stresses and bearing skidding) to moisture or dust that creates corrosive/abrasive environments and lubricant degradations, and so on. These conditions also lead to scuffing, micro-pitting, wear, macro-pitting, false brinnelling and surface cracking [10-11].

Since wear is the main cause of failure revealed by our last study about wind turbine farms [3] , this paper will focus only on the different types of wear that appear in wind turbine bearings. Other studies from literature on bearings degradation will be used to complete our study: Eyre in [12] investigated different types of wear that occur in the industry, Paine in [13] presented examples of damages that occur in automobile engine bearings, Mehdizadeh & Khodabakhshi in [14] investigated different failure causes that lead to steam turbine bearing failures, wear was the predominant cause of failure, El-Thalji & Jantunen in [15] presented an interesting literature review of wear evolution in rolling bearings, Errichello et al. in [16] highlighted the tribological issues faced by the wind industry and Greco et al. [17] examined contact failures of bearings from wind turbine gearboxes.

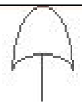
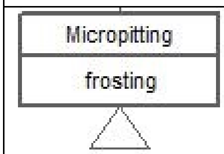
After investigating all the possible wear types for bearings and their types, next section will describe the FTA methodology used in this paper to get the fault tree of wind turbine bearing failures.

2.3. FTA methodology

ISO 31000 [18] describes the "risk" as: risk has consequences in terms of economic performance and professional reputation, but there is also environmental, safety and social considerations. Failure tree analysis (FTA) is a risk assessment tool that identifies the root causes of unwanted incidents, in other words, it traces the possible events leading to these unwanted events [19]. FTA was originated from the Bell Telephone laboratories in 1962, it was used for qualitative and quantitative analysis of systems [20] [21]. Later, many engineering disciplines adopted it, including automotive, nuclear and medicine. FTA was since used in wind industry to analyze the reliability of wind turbine components [22-23]. Compared to other risk assessment methods, FTA is a deductive top-down method. It can be qualitative, quantitative or hybridized.

All the possible types of wear investigated for bearings are used for the FTA. All the possible events lead to a top event entitled "bearing failure". Gates that are used in this FTA are presented in the next table:

Table 2. Gates used in the FTA analysis

FTA gate	Description
	Gate "Or"
	Basic gate
	Transferred gate, used to simplify graphs

The transferred gate presented in Table 2 and used in the FTA analysis is generally used to simplify the FTA representation, it can represent either basic events or FTA gates such as 'Or' & 'And' gates. Basic gate represents the primary event that leads to wear in bearings.

3. Results

According to this study, wear damage can be originated from eight different kinds of wear: Abrasive, adhesive, corrosive, erosive, fretting, false brinneling, micropitting and surface fatigue wear. Figure 5 presents the fault tree of events leading to bearing wear. Intermediate events are the different types of wear.

Intermediate events are assessed according to bearing standards [8-9,24], reliability analysis of bearing in the wind industry [1,3-5], and general industry [12,16]. The wear types are described and analyzed as following:

- Abrasive wear: this type of wear generally appears in middle (axial direction) of the bearing lining. Scratches confirm the damages. Bearings made of CuPb22Sn2 are less protected from scratches than bearings made of AlSn20Cu1 [25]. According to the ISO standard [24], abrasive wear is listed as contamination with particles, the lubricant is then mixed with foreign particles or with wear products. Types of bearing does not influence the wear occurrence [24-25].

- Adhesive wear: this type of wear appears in the main loaded area of bearings, it is accompanied by heat and wiping or seizure. This last aspect is mainly present in softer material such as AlSn20Cu1. According to [24], adhesive wear can be either a wear by friction or a wear due to insufficient lubrication. Failure occurs also when oil film thickness is not enough to avoid direct contact between shaft and bearing. Overloads, vibrations and improper design are the main basics events that lead to this wear. No evidence of adhesive wear appearance according to type of bearing has been found.

- Corrosive wear: this type of wear is mainly common in CuPb22Sn2 alloy bearings. According to [24], corrosive wear is listed as contamination with chemical particles. Overheat is the main cause of this degradation, but it can also be triggered by water, anti-freeze or other chemicals.

- Erosive wear: this type of wear is present in both investigated alloys (CuPb2Sn2; AlSn20Ci1) and is manifested around oil holes. It is generally caused by the mechanism fatigue. Foreign particles in the lubricating oil can also lead to erosion [24]. According to [24], erosive wear is also classified as contamination with particles. This degradation is caused by either poor design or filtration of oil trapes.

- False brinelling and fretting corrosion: is an accelerated form of wear noticed in blade pitch and yaw bearings [17], it is caused by structural vibration and leads mainly to lubricant leakage out of the contact area and removes protective oxide layers. All types of bearing are contaminated by this wear.

- Micropitting (frosting): this type of wear affect both bearings and gears, it is typically caused by skidding during unsteady operation [11,24]. According to [24], lubricant with low viscosity or leakage can also lead to this degradation.

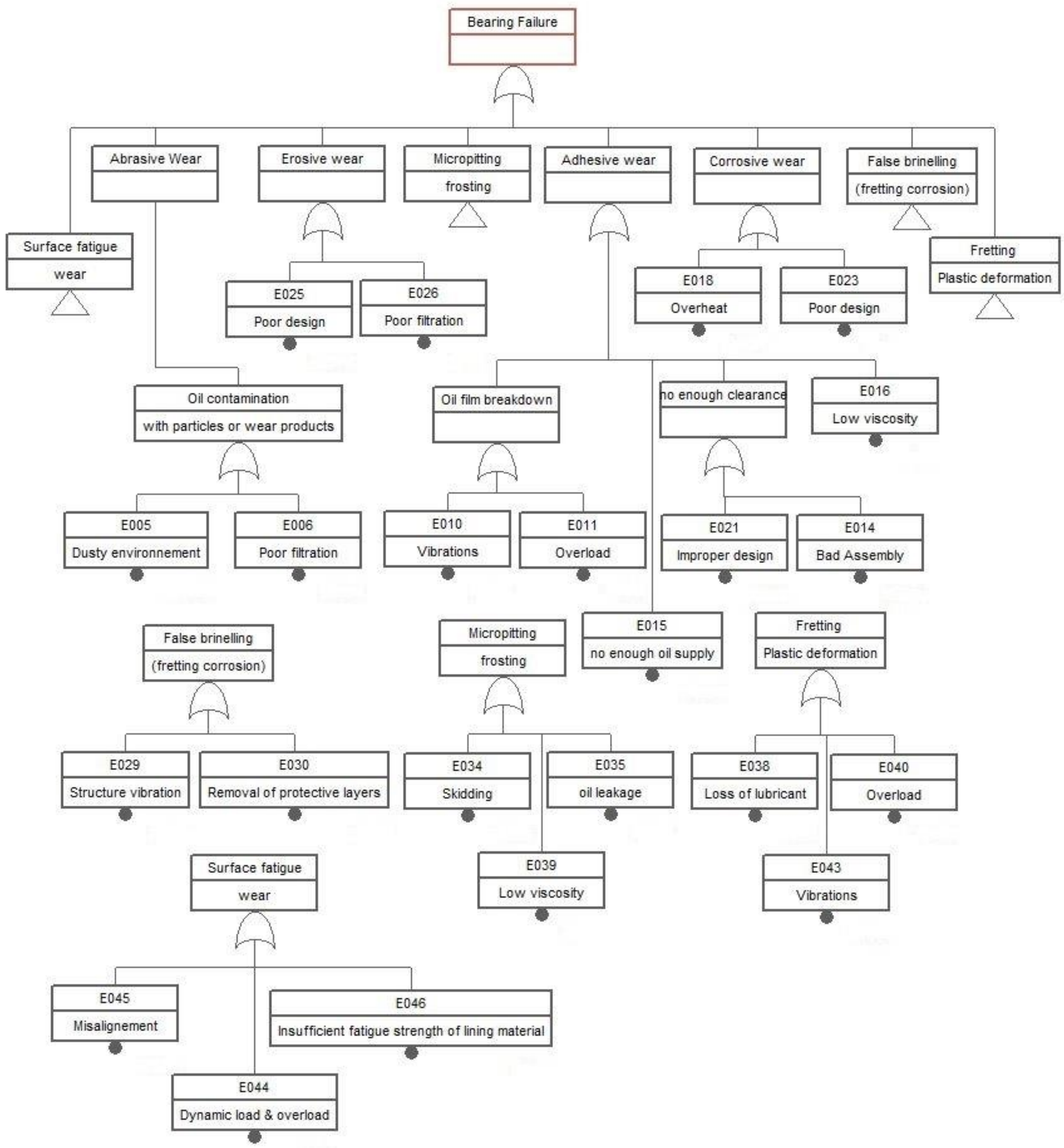


Fig. 5. Fault tree of bearing failure.

- Plastic deformation (fretting): this type of wear is generally due to loss of lubricant and is manifested all across the bearing by a change of color due to heating. It can also lead to alloy melting. This degradation can also be caused by structure vibration or overload [24]. It has also been suggested that this deformation occurs when wind turbine components are under extreme loading, an emergency stop or power line losses to the generator can drastically reduce bearings life, a typical turbine experiences in average 15000 overload cycles per year, this is mainly due to drive shaft torque oscillations [26]. All types of bearing are contaminated by this wear.

- Surface fatigue wear: this type of wear is manifested with fatigue cracks in both bearing alloys. Dynamic load and overload are the main causes of degradation [24]. All types of bearing and both bearing's materials alloys are contaminated by this wear.

Besides, according to figure 5, we can extract the most redundant failure modes leading to bearings wear. Figure 6 presents the most frequent failure modes leading to different bearings wear in wind turbine.

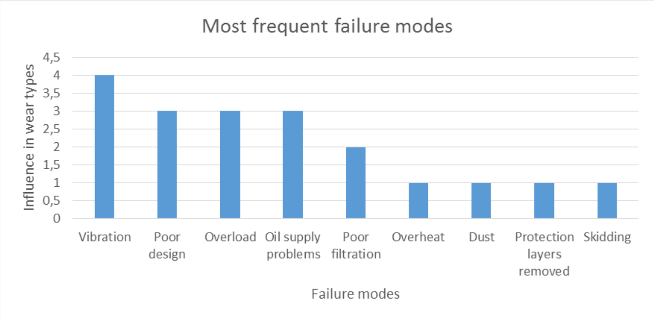


Fig. 6. Most frequent failure modes in bearings.

As seen in this figure, Vibration leads to most types of wear. Vibration can be internal from other wind turbine sub-systems in interaction [3], or external due to wind speed conditions. The second main factors influencing the appearance of wear types are: poor design, overload and oil supply problems. These factors can also be dependent and one of them can lead to the other (e.g.: improper design can lead to an overload that can lead to oil leakage). Poor design and overload factors can also lead; combined with vibration; to crack propagation. Thus, more than one mechanism can be responsible for the wear formation on wind turbine bearings.

Vibrations are hard to manage and efforts are made to minimize bearings defects due to this factor.

Measurement data proved that wind turbine bearings are designed to achieve high life time with high reliability, it can reach in average 31 years. However, the performance of the bearings in service in not the same as expected: Sandström et al. in [27] stated that this lifetime can drastically variate with wind speed and environment conditions. Thus, structural vibrations should be analyzed to control its influence on bearings lifetime and wear propagation. Some industrial solutions are proposed to handle this problem (see failure detection in bearings section).

4. Discussion & Analysis

4.1. Reliability data for bearings

There was no enough data to quantify the FTA proposed in this study. However, literature and industrial data are available for different types of bearings and their degradation. Lieblein and Zelen in [28] summarized the investigation results of the American standards association and presented a statistical analysis of ball bearings life. Weibull parameters (shape and scale parameters) were also statistically extracted from industrial tests on bearings. In addition, Barringer in [29] presented a summary of component reliability Weibull function parameters. One can note in the summarized table 3 of bearings 2-parameter Weibull extracted from gas turbine and chemical industry that bearings' beta is above "1.3". This parameter can be up to "2.0" for a properly installed and well-maintained bearings [29]. Le & Anrdrews in [30] fixed this parameter for wind turbine bearings between "1.2" and "1.5".

Table 3. Weibull parameters of some types of bearings.

Component	Beta values (Weibull shape parameter)			Eta values (Weibull characteristic life-hours)		
	Low	Typical	High	Low	Typical	High
Ball bearings	0.7	1.3	3.5	1400	40000	250000
Roller bearings	0.7	1.3	3.5	9000	50000	125000
Sleeve bearings	0.7	1	3	10000	50000	143000

To the best of our knowledge, there is no standard value of wind turbine bearings Weibull parameters. Indeed, bearings are influenced by different failure modes and are influenced by load and environment. Next section will investigate the place of installation and material on bearings degradation and propagation of wear.

4.2. Influence of the place of installation and type of bearing material

Section 2 illustrated different types of bearings placed in different locations of the wind turbine. Although all bearings face wear and degradation, it would be interesting to discuss either types of bearing or its positions can protect or minimize the wear process in the system. The most recent study about influence of place of installation and type of bearing and its material covered more than 616 bearings, located in different places in a system. The study [25] identifies 866 types of bearing failures and covered both mainly bearing material alloys (CuPb22Sn2 & AlSn20Cu1). In [25], results has shown that type of bearing or its place of installation has no influence on the occurrence of the wear, whereas wear was more pronounced on bearings made from 'AlSn20Cu1' alloy than 'CuPb22Sn2' alloy, this can be generally explained by the lower resistance of the aluminum alloy to metal particles that can lead to wear, the adhesion between aluminum and ferrous materials is higher than cupper and ferrous materials [31]. For corrosive wear only, 'CuPb22Sn2' alloy is less resistant than 'AlSn20Cu1' alloy, this can be explained by the resistance to corrosion of aluminum alloy [25].

Types of wear studied in diesel engines [25] were all covered in our FTA analysis.

4.3. Occurrence of different wear types in bearings

Vencl & Rac in [25] conducted a study over 616 bearings in diesel engines, the next figure (figure 7) summarizes their results, where abrasive wear has been presented as the most frequent wear type (59.4%), adhesive (18.9%) and surface fatigue wear (11.1%) are also frequent. Eyre in [12] also confirmed in his study that abrasive wear occurs frequently in the industry.

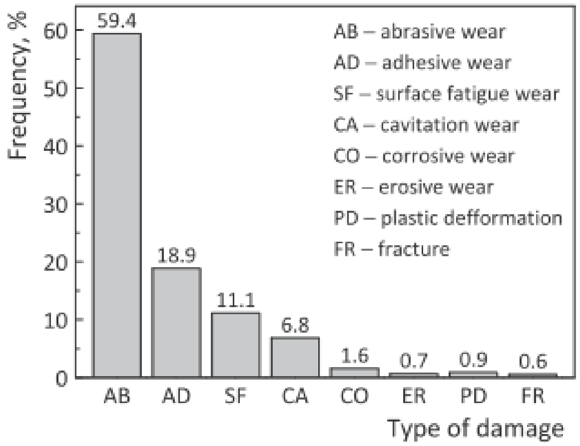


Fig. 7. Percentage occurrence of different types of bearing damages [25].

At this step, there was no enough data from public available failure reports of wind turbine to quantify occurrence of types of bearings damages in wind turbines. Since the reports generally refer bearing failure causes as a wear failure (without describing the damage source), we cannot deduce the type of wear in bearings directly.

4.4. Failure detection in bearings

According to the maintenance policy used in wind turbine systems, there are several techniques to detect the beginning of a failure in bearings and in other tribological components. These techniques can vary from simple visual inspection to complex sensors system installation. These last techniques are more used in wind turbines under the name of condition monitoring system (CMS) technique, its aim is to detect changes in component state conditions that will represent deviations from the normal operational behavior and leading to possible failures [32]. Sensors are used to monitor heat, noise or vibrations of bearings, the most frequent CMS techniques used for wind turbine bearings are:

- Vibration sensors: are mainly used for gearbox and rotor bearing [33]. The next figure (Figure 8) shows the main positioning vibration sensors in the SKF WindCon system [34]. As seen in the figure, the main bearing has a minimum of a radial and an axial sensors (position 1; 2), the generator bearing also need two radial sensors (position 8). Other gearbox and generator components are also monitored such as shafts.

- Trend analysis: it compares the current state of bearings with the healthy operating states, it can also be based on statistical and parameter-based methods [35]. This technique also helps to describe the fault evolution and it severity in components. Figure 9 illustrates the use of this technique for wind turbine generator bearing. The figure shows the increase of vibration trends in a characteristic frequency range with the development of a bearing failure. After the replacement of the bearing (replacement made in Jan 10 - see figure 9), the vibration levels drop, showing that the faulty bearing has been the cause of the changes in the vibration trend [32].

- Envelope curve analysis: (vibration analysis) is among the most effective techniques for bearing condition monitoring [37]. This technique is a process of demodulation of component vibrations with small amplitude in a narrow frequency band [32], it allows faults detection with a high certainty, and it is used mainly for gearbox and bearings [38].

- Water-content sensors: is an oil based condition monitoring solution, the sensors are used to measure the humidity or to detect moisture in the oil. Presence of water in oil can drastically reduce bearing life [39], it can also lead to different kind of wear.

- Wear-debris sensors: measure wear debris and indicate the development of faults like pitting [40]. Figure 10 illustrates this technique when used on gearbox. In period (A), the figure shows an increase at a moderate rate of debris in gearbox for more than a year, when the rate of debris accumulation reached a limit point (B), it triggers inspection. The reliability of the component and its availability was not affected during operation until damage reached the threshold to activate the maintenance.

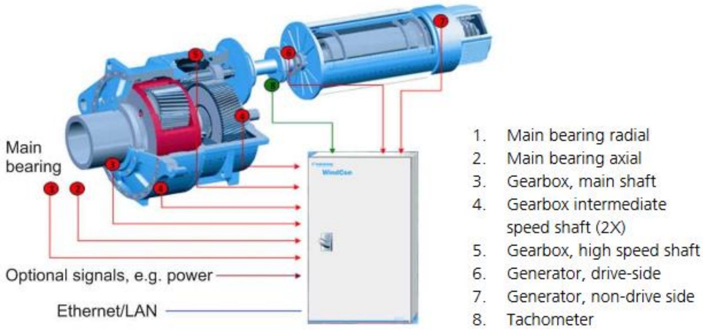


Fig. 8. Example of sensor configuration for vibration based condition monitoring applied in the SKF WindCon system.

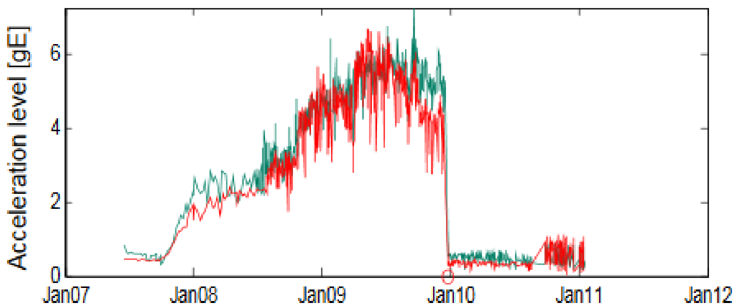


Fig. 9. Trend analysis used for fault detection in wind turbine generator bearing [36].

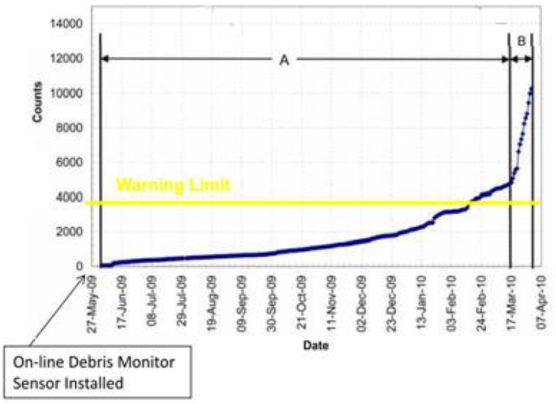


Fig. 10. Wear debris sensors used for fault detection in gearbox [41].

- Acoustic emissions: are used to detect lubrication film thickness abnormalities [42]. This technique is not widely used in the wind turbine components, practical problems related to noise spreading from other components complicates its implementation as well as the quality of the output signal [43].

Other bearings such as blade or yaw bearings can also be monitored with the same sensors. However, it is not common in the wind industry to install sensors for these components, since other failure modes are more frequent than wear in these components [44]. Nowadays, research is even focused on developing new technologies of bearing that requires less maintenance or are based on eco-friendly materials [45-47].

To conclude, fault detection in bearing avoids damage of the main components (gearbox, generator…), avoids economic losses due to shut down and component replacement and finally increases the performance of wind turbines.

5. Conclusion

In this study, a preliminary reliability overview through FTA analysis was developed with all the possible wear types manifested in wind turbine bearings. The methodology proved that:

- Abrasive, adhesive, corrosive, erosive, fretting, false brinelling, micropitting and surface fatigue wears are the most predominant wear types present in the wind turbine bearings;
- Structure vibration highly influence the bearing life time and the propagation of wear;
- The type of bearing has no influence on the occurrence of the wear;
- The place of installation has no influence on the occurrence of the wear;
- The type of bearing material can trigger some wear types under the same or similar conditions. Adhesive, micropitting, false brinelling and surface fatigue wears occur frequently when bearings are made from aluminum alloy, whereas corrosive wear is present in 'CuPb22Sn2' alloy.
- Abrasive wear seems to be the most frequent wear type noticed in bearings in the industry.
- Fault detection techniques improves components reliability, condition monitoring system (CMS) has proven its effectiveness for wind turbine systems, it is generally applied to main bearing, gearbox, generator bearing and tower oscillations.

The reliability analysis presented in this paper is qualitative and has been concentrated on the design phases, no maintenance policy was introduced here. Thus, this study does not assess the wind turbine bearings reliability through time. Lack of data from wind turbine bearing operations did not allow us to perform a probability distribution of the wear types in order to know the most prominent type of wear in the wind turbine bearings, future works will focus on developing this part.

Acknowledgements

This work is supported by the Grand-Est region of France and the FEDER.

References

[1] S. Sheng, "Report on wind turbine subsystem reliability, a survey of various databases," National renewable energy laboratory - NREL/PR - 5000 - 59111, 2013.

[2] F. Spinato, P. Tavner, G. Van Bussel and E. Koutoulakos, "Reliability of wind turbine subassemblies," *IET Renewable Power Generation*, vol. 3, no. pp. 387-401, 2009, http://dx.doi.org/10.1049/iet-rpg.2008.0060 .

[3] N. Tazi, E. Châtelet and Y. Bouzidi, "Using a Hybrid Cost-FMEA Analysis for Wind Turbine Reliability Analysis," *Energies*, vol. 10, 2017, doi: http://dx.doi.org/10.3390/en10030276 .

[4] H. Arabian-Hoseynabadi, H. Oraee and P. Tavner, "Failure modes and effects analysis (FMEA) for wind turbines," *International Journal of Electrical Power and Energy systems*, vol. 32, pp. 817-824, 2010, http://dx.doi.org/10.1016/j.ijepes.2010.01.019.

[5] J. Ribrant, "Reliability performance and maintenance, a survey of failures in wind power systems. Master thesis at KTH School of electrical engineering," KTH school of electrical engineering, Stockholm, 2006.

[6] International Standard Organization - ISO, "13372:2012 - Condition monitoring and diagnostics of machines -- Vocabulary," International standard organization, Geneva, 2012.

[7] S. Yagi, "Bearings for wind turbine - NTN technical

review no.71," NTN global technical review. Available (http://www.ntnglobal.com/en/products/review/pdf/NTN_TR71_en_P040.pdf), 2004.

[8] International Standard Organization - ISO, "ISO 7146: 2008; plain bearings - appearance and characterization of damage to metallic hydrodynamic bearings -- Part 2: Cavitation erosion and its countermeasures; last reviewed and confirmed in 2012," International standard organization, Geneva, 2008.

[9] International Standard Organization - ISO, "4383; Plain bearings -- Multilayer materials for thin-walled plain bearings," International standard organization, Geneva, 2012.

[10] M. Kotzalas and G. Doll, "Tribological advancements for reliable wind turbine performance," *Philosophical transactions of the royal society,* vol. 368, pp. 4829-4850, 2010, https://*doi*.org/*10.1098*/*rsta.2010.0194*.

[11] P. Blau, L. Walker, H. Xu, R. Parten, J. Qu and T. Geer, "Wear analysis of wind turbine gearbox bearings," U.S. Department of Energy -DOE - ORNL/TM-2010/59, Tennessee, 2010.

[12] T. Eyre, "Wear characteristics of metals," *Tribology international,* vol. 9, pp. 203-212, 1976, http://dx.doi.org/10.1016/0301-679X(76)90077-3.

[13] Paine and Cambell, "Examples of damage which can occur in automobile engine bearings," TA 100/2. London: Glacier Metal Co, London, 1969.

[14] M. Mehdizadeh and F. Khodabakhshi, "An investigation into failure analysis of interfering part of a steam turbine journal bearing," *Case studies in engineering failure analysis*, vol. 2, pp. 61-68, 2014, http://dx.doi.org/10.1016/j.csefa.2014.04.001.

[15] I. El-Thalji and E. Jantunen, "A descriptive model of wear evolution in rolling bearings," *Engineering failure analysis,* vol. 45, pp. 204-224, 2014, http://dx.doi.org/10.1016/j.engfailanal.2014.06.004.

[16] R. Errichello, S. sheng, J. Keller and A. Greco, "Wind turbine tribology - a recap," EERE wind and water power program. US department of Energy, DOI: 10.2172/1036041, 2011.

[17] A. Greco, S. Sheng, J. Keller and A. Erdemir, "Material wear fatigue in wind turbine systems," *Wear,* vol. 302, pp. 1583-1591, 2013, http://dx.doi.org/10.1016/j.wear.2013.01.060.

[18] International Standard Organization - ISO, "31000 - Risk management, principles and guidelines," International standards organization, Geneva, 2009.

[19] G. Goodman, "An assessment of coal mine escape way reliability using fault tree analysis," *Mining Science and Technology,* vol. 7, pp. 205-215, 1988, http://dx.doi.org/10.1016/S0167-9031(88)90610-X.

[20] M. Rausand and A. Hoyland, System reliability theory: models, statistical methods, and applications, London: Wiley - ISBN: 978-0-471-47133-2, 2004, pp. 58-63.

[21] W. Jianing and Y. Shaoze, "Reliability analysis of the solar array based on fault tree analysis," in *9th international conference on damage assessment of structures - IOP publishing - Journal of physics: conference series 305 (2011) 012006*, http://dx.*doi*.org/*10.1088/1742-6596/305/1/012006*.

[22] P. P. D. Botsaris, "Systemic assessment and analysis of factors affect the reliability of a wind turbine," *IIPP,* vol. 10, pp. 85-92, 2012, doi:10.5937/jaes10-2130.

[23] A. Seebregts, L. Rademakers and V. Horn, "Reliability analysis in wind turbine engineering," *Microelectronics Reliability,* vol. 35, pp. 1285-1307, 1995, http://dx.doi.org/10.1016/0026-2714(95)99378-V.

[24] International Standard Organization - ISO, "ISO 7146-1; Plain bearings - appearance and characterization of damage to metallic hydrodynamic bearings - part 1: general," International standard organization, Geneva, 2008.

[25] A. Vencl and A. Rac, "Diesel engine crankshaft journal bearings failures: case study," *Engineering failure analysis,* vol. 44, pp. 217-228, 2014, http://dx.doi.org/10.1016/j.engfailanal.2014.05.014.

[26] J. Rosinski and D. smurthwaite, "Troubleshooting wind gearbox problems," *Gear solutions; http://www.gearsolutions.com/article/detail/5966/troubleshooting-wind-gearbox-problems-*, pp. 22-33, 02 2010.

[27] M. Sandström, H. Haraldsdóttir, O. Carlson, J. Corné and F. Larsson, "Lifetime analysis of a wind turbine component: An investigation of how to use physics-based models and general OEM documentation to estimate the remaining lifetime of a wind turbine component (Master thesis report)," Breeze and Chalmers University, Goteborg, 2016.

[28] J. Lieblein and M. Zelzn, "Statistical investigation of the fatigue life of deep groove ball bearings," *Journal of research of the national bureau of standards*, vol. 57, no. DOI: 10.6028/jres.057.033, 1956.

[29] P. Barringer, "Weibull reliability database," 22 02 2010. [Online]. Available: http://www.barringer1.com/wdbase.htm. [Accessed 15 12 2016].

[30] B. Le and J. Andrews, "Modelling wind turbine degradation and maintenance," *Wind Energy,* vol. 19, pp. 571-591, 2015, DOI: 10.1002/we.1851.

[31] B. Bhushan, Principles and applications of tribology, second edition, London: John Wiley & Sons - ISBN: 978-1-119-94454-6, 2013.

[32] K. Fischer and D. A. Coronado, "Condition monitoring of wind turbines: state of the art, user experience and recommendations," Fraunhofer - IWES, Bremerhaven, 2015.

[33] Renewables certification DNV-GL, "Guideline for the certification of condition monitoring systems for wind turbines," GL renewables certification, Hamburg, 2013.

[34] B. Heintz, "Optimierung und Standardisierung der Analyse und Diagnose von Schäden am Antriebsstrang von Windkraftanlagen (Optimization and standardization of the analysis and diagnosis of damage to the power train of wind power plants) - Master thesis," Kaiserslautern, 2010.

[35] C. Andersson, "Efficient fault detection & fault diagnosis on +4000 wind turbines using vibration monitoring," in *Conference of the Wind Power Engineering Community*, Berlin, 2013.

[36] K. Fischer, "Maintenance Management of Wind Power Systems by means of Reliability-Centered Maintenance and Condition-Monitoring Systems," Chalmers university of technology, Gothenburg - , 2012, DOI: 10.13140/RG.2.1.1874.3446.

[37] D. Siegel, W. Zhao, E. Lapira, M. AbuAli and J. Lee, "A comparative study on vibration-based condition monitoring algorithms for wind turbine drive trains," *Wind energy*, vol. 17, pp. 695-714, 2014, DOI: 10.1002/we.1585.

[38] Brüel and Kjær, "Brüel & Kjaer Vibro," 2016. [Online]. Available: http://www.bkvibro.com/en/monitoring-techniques/envelope-analysis.html. [Accessed 10 12 2016].

[39] B. O. Jacobson, Rheology and Elastohydrodynamic Lubrication, Nieuwegein: Elsevier Science, 1991.

[40] J. Ukonsaari and H. Moller, "Oil Cleanliness in Wind Power Gearboxes, Elforsk rapport 12:52," ELFORSK, Stockholm, 2012.

[41] A. Toms, "Oil debris monitoring: Part of an effective gearbox monitoring strategy," in *69th STLE annual meeting and exhibition*, Buena Vista, 2014.

[42] D. B. Board, "Stress wave analysis provides early detection of lubrication problems," *Machinery lubrication*, 2003.

[43] R. Ahmad and S. Kamaruddin, "An overview of time-based and condition-based maintenance in industrial application," *Computers & Industrial Engineering*, vol. 63, pp. 135-149, 2012, http://dx.doi.org/10.1016/j.cie.2012.02.002.

[44] R. Hill, V. Peters, J. Stinebaugh and P. Veers, "Wind Turbine Reliability Database Update," Sandia Report, California, 2009.

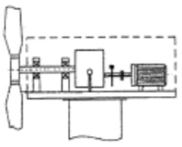
[45] NAKANISHI, Yoshitaka, SHIMAZU, Kenryo, MATSUMOTO, Yasuaki, *et al.* Eco-friendly bearing for tidal power generation. In : *Renewable Energy Research and Applications (ICRERA), 2012 International Conference on*. IEEE, 2012. p. 1-5.

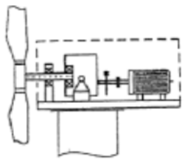
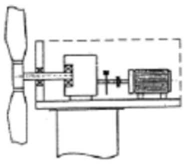
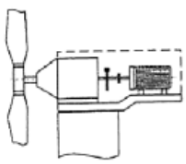
[46] ZHANG, Huiyi et JACKMAN, John. A feasibility study of wind turbine blade surface crack detection using an optical inspection method. In : *Renewable Energy Research and Applications (ICRERA), 2013 International Conference on*. IEEE, 2013. p. 847-852.

[47] NAKANISHI, Yoshitaka, SANDERSON, Jason, HONDA, Takuro, *et al.* Influence of axial direction on performance of biomimetic sealing system. In : *Renewable Energy Research and Applications (ICRERA), 2015 International Conference on*. IEEE, 2015. p. 263-266.

Appendix

Table 1. Geared & gearless wind turbine rotor shaft bearing assembly

Structure	Rotor bearings type	Generator bearing type	Features
	• SRB • SRB • SRB	• SRB • CRB • DTRB	• Two bearings are used • The gearbox is supported on the rotor shaft • This configuration contains gearbox

	• SRB	• CRB	• The generator side bearing is also used as the gearbox’s input bearing • This configuration contains gearbox
	• SRB	• CRB	• The generator side bearing is also used as the gearbox’s input bearing • The load on the blade side bearing is supported by the nacelle • This configuration contains gearbox
	• TRRB • DTRB	• Not used	• No rotor bearing is used and the rotor load is transmitted by the gearbox bearing • This configuration contains gearbox