COMPARISON OF THREE PREDICTIVE ANALYSIS METHODS FOR WIND TURBINE GEAR BOXES – A CASE STUDY OF SATELLITE BEARING WEAR AND GEAR TEETH SURFACE DAMAGES

Ramon Miralbes[1]; David Ranz[2]

[1]University of Zaragoza, department of Design and Manufacturing, Professor, DIDYF. EINA. C/ María de Luna s/n. 50018. Zaragoza (Spain). 876765069, miralbes@unizar.es
[2]University of Zaragoza, department of Design and Manufacturing, Professor, DIDYF. EINA. C/ María de Luna s/n. 50018. Zaragoza (Spain). dranz@unizar.es
DOI: http://dx.doi.org/10.6036/9685

1. - INTRODUCTION

Bearings are components of machines that have a limited service life that depends on many factors. However, gear boxes for wind turbines must be designed, as established in accordance with some regulations [1,2], to have a lifespan of 20 years, the works of some authors [3] indicate that this does not happen due to a premature damage in these gear boxes (GB) due to white etching crack damage in the bearings. Other reports [4] indicate that main failures were generated in the bearings with under 10% beginning in gear teeth and therefore, predictive analyses must be mainly focused on monitoring bearings. One of the main reasons why it is essential for these elements to have such long-term reliability is the complexity and cost of the substitution procedure in a wind turbine.

This paper is the result of field studies on a 2005 wind farm with 46 800 kW wind turbines, where a number of types of serious damage have occurred in the gear teeth and bearings, requiring the substitution or reparation of some parts. Due to their inadequate design, 12 gear boxes do not reach their expected lifespan because of the premature appearance of serious damage and another 12 bear serious damage that will require parts substitutions.

The most common damage detected in the gear boxes is due to indentations, micro pitting and grey staining in the teeth of the gears; as well as flaking, indentations, and wear in the bearings. These issues, especially flaking, can cause catastrophic failure of the gear box, including scuffing and broken sumps, resulting in high risk of fire.

In this instance, wind farm operators have conducted some inspections and predictive analyses to monitor the internal condition of the gear boxes by means of diverse methods: oil analysis, vibration analysis and boroscopies.
It must be pointed out that these gear boxes were installed 10 years ago, the monitoring systems found in new gear boxes were absent or not the same: in particular, those vibration monitoring systems that allow a continuous monitoring of the state of each part in the gear box and specifically, the bearings.

There is a large body of literature on the use of different types of analysis such as the analysis of vibrations, acoustic emissions, oil, thermography, electrical effects, shock pulses, performance monitoring, among others as determine failure in gear boxes [5]; it also indicates that the second main cause of shutdown in a wind turbine, after the generator, is the gear box. One of the conclusions of this study was that, in many instances, while the fault was developing, vibrations were too little for damage to be predicted or it did not appear, whereas oil provided early warnings. The main problem with oil analysis is that it is usually carried out off-line by taking samples [6]. The studies indicate that while electrical effects analysis is only experimental it may have huge potential; the use of the shock pulse method is not quite so common and is used to support vibration measurements. Thermography is another technique that is usually used off-line; it involves visual interpretation of hot spots but cannot easily detect incipient or moderate damage in the gear box. Another predictive analysis is based on acoustic emissions that can predict damage much earlier than vibration but the coupling must be studied in-depth so as to obtain good results.

Another predictive analysis is based on the processing of the available speed measurements in the wind turbine such as the Instantaneous Angular, but this technique still has some insufficiencies like the quantification of noise, the structural noise, etc. [8] and can only detect now with accuracy and efficiency a few fault features. So some non-conventional instantaneous angular speed methods are being developing like the use of instantaneous angular phase demodulation with empirical mode decomposition and envelope analysis [9].

This type of analysis shows a high potential and promising method to detect failures in gearboxes using cheap sensors and some installed sensors in the gearbox to detect failures; however nowadays there are no evidences of their use in planetary gearboxes and their application is quite limited to gear boxes for wind turbines.

2. - MATERIAL & METHODS

2.1. - THE CONSTRUCTION AND FAILURE MODES OF WIND TURBINE GEARBOX

The gear box is the element of a wind turbine which increases the rotation revolutions of the rotor blades and thereby divides the torque on this shaft to the same extent.

Gear boxes for wind turbine must have three or four stages; usually the first stages are of planetary type. The analysed gear boxes have three stages (Fig. 1) and the components are designed with a B for the bearing and with an S for other elements (Table 1). The first stage is planetary that allows a high multiplication of the speed for small velocities and high torques in a reduced space, and has a low speed shaft coupled to the blade axis by means of ribbing couplings, including the planetary ring. It is supported by the low bearings. The planetary ring is connected to three satellites using three planetary pins installed in the interior raceway of six bearings, two in each pin, allowing the relative rotation of the satellites. The planetary ring gear joined to the casing engages with the satellites, which, in turn, engage with the sun axis. This is also the exit shaft of the first stage (low speed shaft) and the entry shaft of the next stage. The sun axis, with exterior ribbing, leads to the interior shaft bearing. It is coupled with the interior ribbing of the interior splined shaft, which is joined with the 2nd stage crown gear and leaded in the sun shaft bearing. The 2nd stage crown gear engages with the 2nd stage pinion, mechanized in the medium-velocity axis (Intermediate Speed Shaft) and coupled to the medium-velocity shaft bearing. This pinion is splined in the zone where it couples with the 2nd stage crown gear, which engages with the 3rd stage (high speed shaft) pinion-shaft coupled to the high-velocity shaft bearing.

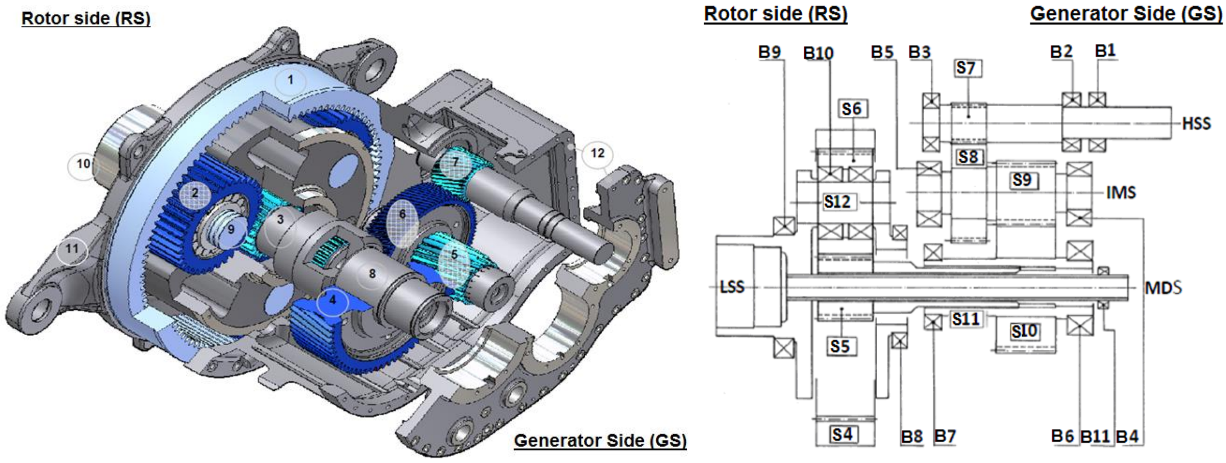

Fig. 1. Schematic drafts of the gear box

These components, along their life, due to diverse causes listed above, suffer diverse types of damages (Fig. 2) that are listed above:

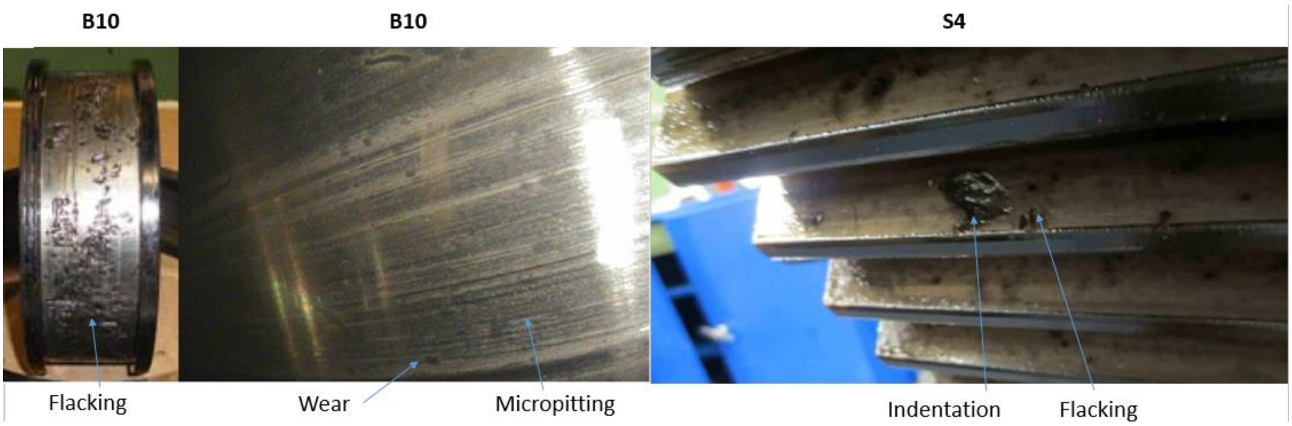

Fig. 2. From left to right: internal ring of B10, internal ring of B10 and planetary ring gear (S4)

1. Wear: caused by abrasive particles, inadequate lubrication, or vibration.
2. Indentations: caused by faulty mounting, overloading or foreign particles.
3. Smearing: of roller ends and guide flanges, of rollers and raceways, of raceways at intervals corresponding to the roller spacing, of external surfaces, or in thrust ball bearings.
4. Surface distress
5. Corrosion: deep-seated rust or fretting corrosion.
6. Passage of electric current
7. Flaking: caused by preloading, oval compression, axial compression, misalignment, indentations, smearing, deep-seated rust, fretting corrosion, or fluting or craters.
8. Cracks: caused by rough treatment, excessive drive-up, smearing, or fretting corrosion.
9. Cage damage: caused by vibration, excessive speed, wear, lockage, or other factors.

These types of damage are due mainly to incorrect mounting process, inadequate lubrication, large stops with inadequate lubrication, design failures, foreign particles of other elements, inadequate sealing, or use and age.

The analysed gear boxes have wear damage caused by abrasive particles, indentations caused by overloading, indentations caused by foreign particles, and flaking caused by indentations. They are due to a design inadequacy that results in the satellite bearing being overloaded, so indentations appear and lead to flaking. The released metallic particles can be caught inside the bearing or between the teeth of the gears; usually they are carried by the oil and generate wear in other bearings caused by abrasive particles, indentations caused by foreign particles that will, in turn, produce more flaking. If the metallic particles are caught inside the teeth of the gears, they cause indentations there, trapping material and potentially leading to flaking or broken teeth. If damage due to flaking is serious it can cause an abrupt seizure of the bearings and catastrophic failure of the gear box.

2.2. - PREDICTIVE MAINTENANCE PROCEDURES

For the predictive analysis of the internal condition of bearings, especially in gear boxes, there are diverse methods and procedures [8]. Out of these methods, oil analysis, boroscopies, and vibration analysis are the methods used and they are compared in table 3.

2.2.1. – Boroscopy

Boroscopy, is a diagnostic tool for the inspection of motors and other industrial machines but usually there are sometimes accessibility limitations owing to the geometry of the machines and zones of organs that are immersed in oil (table 1) [10].

It must be highlighted that boroscopy is a complex technique that must be performed by experienced field technicians and the inspection of one gear box requires 3–4 hours; it is a slow and laborious technique, but it can detect any type of damage in bearings and gears. The analysis of the images and the characterization of the damages of the rolling elements have been carried out using the ISO 15241 [11] for the teeth the ISO 10825 [12].

Simp. Desig.	Axis	Side (Generator /rotor)	Observations/ limitations
B1	High (HSS)	LG	High visibility
B2		LG	High visibility
B3		LR	High visibility
B4	Medium (IMS)	LG	Non accessible
B5		LR	Non accessible
B6	Sun shaft (MDS)	LG	Partial visibility
B7		LR	Partial visibility
B8	Low (LSS)	LG	Non accessible
B9		LR	Partial visibility
B10	Satellite bearing		Partial visibility
B11	Interior shaft bearing		Non accessible
S1	Casing		Zone immersed in oil; non visible
S2	Reaction Arm		Exterior; simple view accessible
S3	Planetary box		Only visible exterior zone
S4	Planetary ring gear		Zone inside oil; non visible
S5	Sun shaft		Partial visibility
S6	Planetary satellites		Partial visibility
S7	Pinion-shaft 3rd stage (High velocity—HSS)		High visibility
S8	Crown gear 3rd stage (medium velocity gear—MDS)		High visibility
S9	Pinion-axis 2nd stage (medium velocity—MDS)		High visibility
S10	Crown gear 2nd stage (low velocity gear—LSS)		Partial visibility
S11	Interior splined shaft		Non accessible
S12	Planetary Pins		Non accessible

Table 1. Observations and limitations of the boroscopy analysis

Usually some bearings are easily accessible; however, to see them fully requires moving the gear box and the carrying out of several boroscopies. Thus, bearings are often only partially analysed. The field of vision is therefore limited and usually only the top zone of the bearings is analysed, but not the contact zone of the raceways of the rolling elements. It is also difficult to access the interior raceway of the bearings due to the rolling elements and the cage. To access all the various satellites and their bearings, the gear box must be unlocked, moved and locked two or three times to access.

For the boroscopies, flaking can be considered moderate, serious or grave damage, depending on the scope, while indentation and wear are considered low damage as they do not pose a potential mid-term risk.

On the contrary, one of the main advantage of boroscopy is that it allows analysts to quantify damage and categorize damage severity in different grades.

2.2.2. - Vibration analysis

For vibration analysis, the portable equipment Vibrotest 60 was used (Fig. 3) and a bearing condition unit according with the ISO 15242 [13] was the procedure used to determining the damage undergone. This technique is cheaper because it is possible to acquire data of the sensor on-line.

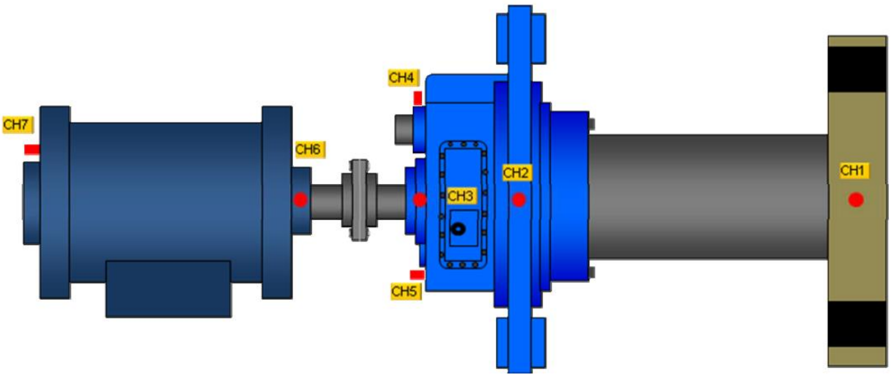

Fig. 3. Scheme of the measure points in the vibration analysis

Usually, damage to bearings, especially flaking, wear, fissures, breaks and material entrapment, generates a zone in the raceway or in the rolling elements with an increase or decrease of material and with a discontinuous surface. Then, when a rolling element moves over this zone, a pulse or vibration moving towards the exterior raceway and the casing called “crash pulse” is generated

Meanwhile, since the global vibrations of bearings reflect the condition of the machine and its organs, the crash pulses provide information about the condition of each bearing and its components. The evaluation of the condition of a bearing by using only one measurement is impossible given that the amplitude and regularity of the crash pulses depend on factors such as installation, velocity, loads, mount tolerances and lubrications as well as the position of the point of measurement; in addition, sound and vibration propagation conditions plus the method used to fix the sensors also play a role. With this particular method it has been demonstrated that only moderate and sever damages can be detected, especially in the low velocity bearing but using more advanced vibration analysis it could be possible to detect low damages [14, 15].

Later, a frequency analysis and an evolving analysis by means of demodulation methods such as detective enveloping selection or bearing condition selection could be conducted to determine the type of damage incurred and the damaged zone of the bearing [16]
It must be pointed out that the gear box model analysed is not initially equipped with sensors to perform continuous on-line vibration analysis. In the same way, due to the geometry of the GB, it was not equipped with sensors in the sun shaft so it is impossible to monitor the vibrations of B6 and B7.

On analysing the state of the art related to detection of faults through the use of vibration analysis in the planetary, there are some studies by different authors using a variety of methods (local mean decomposition, Hilbert-Huang transform, etc.) [17, 18] which can only diagnose severe faults in the planetary such as teeth breaks and severe flaking.

2.2.3. - Oil analysis

There are diverse techniques to analyse lubricants so as to predict the internal conditions of the machines and detect possible damage at an earlier stage such as the emission and absorption spectrometries, magnetic particle detection and ferrography, particle counting, and microscopy. These methods can be used to determine the amount of particles in the oil foreign to it coming from mechanical organs and, by analysing their composition, it is possible to determine the type of organ they originate from (Table 2).

In this paper, emission spectrometry (inductively coupled plasma microscopy according with ASTM D7691 [19]), particle counting and magnetic particle detection (PQ index according with ASTM D8184 [20]) were used. Emission spectrometry is based on the observations that when atoms are excited, they radiate specific wavelengths depending on their electronic configurations. These can be detected and translated into a measurement of the concentration of each periodic element. The results obtained with this technique are similar to those obtained with other types of spectrometries and ferrografies, and have both higher accuracy and precision than microscopy and particle counting.

Material	Cause/damaged element	Material	Cause/damaged element
Aluminium	Pumps, trust washer, piston	Barium	Refrigerant leaks
Calcium	Antifoam additive	Copper	Bronze bearings, trust washer, hubs
Tin	Bronze bearings, welding	Nickel	Pumps, valves, gears
Iron	Bearings, gears, casings, piston rings, cylinder walls	Silicon	Air / Antifoam addictive
Sodium	Detergent additive, refrigerant additive	Zinc	Brass bearings, antioxidant additive
Vanadium	Turbine blades	Lead	Bearings, wear-resistant gears
Chromium	Rolling elements of bearings, pistons rings, cylinder walls	Titanium	Parts with exotic alloys
Silver	Some bearings	Magnesium	Detergent additive. Refrigerant additive
Boron	In refrigerants, anticorrosion additive	Phosphorus	Wear-resistant additive. EP additive
Potassium	Refrigerant additive	Molybdenum	EP additive

Table 2. Elements detected by means of oil analysis

The particle counting oil analysis is a procedure where, metallic particles are attracted and separated from oil and are quantified by using the particle quantification index (PQ).

Finally, another analysis performed was metallic particle detection by means of a metal detector indicating whether the detection threshold of metallic particles had been reached.

It must also be acknowledged that oil analyses can quantify the damage of the organs and the type of affected organs but it cannot detect the exact damaged elements between other of the same type.

	Boroscopy	Particle counting	Microscopy	Bearing vibration analysis
Variable	Pictures and videos	Particle Quant. index	Quantity of each material in ppm	Bearing condition unit index
Limit criterion	Visual state	>50	>55	10 times the initial
Capacity to distinguish the damaged element	Yes	No	No	Yes
Capacity to distinguish the type of damage	Yes	No	No	No
Capacity to distinguish the seriousness of damage	Yes	No	No	Yes
Wear	Yes	No	No	No
Indentation	Yes	Yes	Yes	Yes
Smearing	Yes	Yes	Yes	Yes
Surface distress	Yes	No	No	Yes
Corrosion	Yes	No	No	No
Flaking	Yes	Yes	Yes	Yes
Cracks	Yes	No	No	Yes
Cage damage	Yes	No	No	Yes
Inaccessible bearings	B4, B5, B8 and B11			B6 and B7

Table 3. Comparison between the methods of analysis used

3. - RESULTS

Another inspection made was the visual inspection of repaired and substituted twelve gear boxes in the repair shop where they were completely disassembled and all their internal organs analysed in depth. Additionally, a total of 46 wind turbines were studied through periodic boroscopies, vibration analysis and oil analysis. Comparing the analysis in the repair shop, it can be pointed that, in some cases, appears the "False Positives" that are cases in which the method used detect a failure but, after the in detail inspection using boroscopy or after dissembling the gear box, this failure does not exist.

Table 4 indicates that vibration analysis can always predict severe damage in the satellite bearings but only predicts moderate or low damage in a few cases (<20%) and does not generate many false positives (2.1 %). These types of damage do not pose immediate risk to the gear box, which may work for 6 months or 1 year; in the event that damage becomes serious or grave, vibration analysis will detect it and the gear box will be stopped and repaired before it poses a risk for the wind turbine. Thus, it is a reliable method to predict severe damage in satellite bearings.

In the case of vibration analysis to predict damage in high speed shaft bearings, no damage arises but some false positives have occurred (11/96). It cannot be estimated whether vibration analysis can predict damages in these bearings owing to the occurrence of a non-acceptable number of false positives.

In the case of the oil analysis, whilst the FE analysis in the oil prediction method is not reliable and in some cases false positives occur an in-depth oil analysis can predict, in a few cases, damage of any type and not many false positives occur (1/9).

As for gear boxes with serious and grave damage requiring replacements or repairs to the gear box, the magnetic particle analysis did not detect metallic particles in oil, as was the case in some gear boxes with moderate damage; in summary, then, it can be concluded that particle magnetic analysis does not detect damage in bearings. The main reason is that it is quite difficult for a small oil sample to pick up particles detached due to flaking; sometimes, they cling to the casing or are trapped by other organs. False positives might also occur given that metallic particles can be produced from other organs such as gears or the casing. Therefore, analysis of magnetic particles does not reliably indicate the internal conditions of gear boxes.

In the case of the complete oil analysis was conducted in only 13 gear boxes but only in one of them that was damaged, it did not detect damage.

For some gear boxes, diverse oil analyses did not detect abnormal values of diverse indexes or magnetic particles, but there were some data of low and moderate damage in some bearings.

In other cases, data are contradictory because sometimes abnormal values indicating damage appeared, but not continuously, and sometimes different indicators were present. For instance, an the case of gear box 13, in the last oil analysis, the particle quantification index indicated high amounts of iron and steel, and boroscopy confirmed low damage in some bearings.

To sum up, as demonstrated, boroscopy is the predictive technique that provides most information about the actual conditions of the gear box. Nevertheless, there is a serious disadvantage since it is time consuming and requires the presence of a fully trained analysis technician to carry it out. On the other hand, oil analysis does not require specially qualified field technicians as the analysis is usually conducted in an external laboratory, and taking an oil sample does not take technicians long. For vibration analysis, the time required is lower than for a boroscopy but the in-field technician must be specifically trained for the task.

	Detected	Total Possible	Percentage (%)
Vibration analysis. Damages in B10			
Low damage in B10	2	8	25.0
Moderate damage in B10	2	24	8.3
Serious damage in B10	8	8	100
False Positives in B10	2	96	2.1
False positives in B1. B2 y B3	11	96	11.5
Iron (Fe) Analysis			
Low damage	3	13	23.1
Moderate damage	0	17	0.0
Serious damage	0	16	0.0
False Positives	2	15	13.3
Particle quantification analysis. Oil analysis in depth			
Low damage	3	24	12.5
Moderate damage	1	7	14.3
Serious damage	0	1	0.0
False Positives	0	9	0.0
Iron (Fe) Analysis. Oil analysis in depth			
Low damage	4	24	16.7
Moderate damage	1	7	14.3
Serious damage	0	1	0.0
False Positives	1	9	11.1
Magnetic analysis. Oil analysis in depth			
Low damage	3	24	12.5
Moderate damage	2	7	28.6
Serious damage	0	1	0.0
False Positives	0	9	0.0
In depth oil analysis			
Low damage	8	24	33.3
Moderate damage	2	7	28.6
Serious damage	0	1	0.0

Table 4. Summary of prediction of damage with each technique depending on type compared with the boroscopy.

4. - DISCUSSION

The main conclusion drawn in this paper is that boroscopy is the most adequate predictive analysis technique, if the economic aspect is not taken into consideration and the one that provides us with most information. It suggests both type of damage and its seriousness despite its limited scope, given that some elements cannot be observed. Therefore, it is possible that some low levels of damage may remain hidden and unobserved, but should it become moderate or serious, this damage is usually repeated along the raceways and can be detected.

The bearing condition unit vibration analysis technique can always detect serious damage in bearings. However, it is not able to detect low or moderate damage. It must be pointed out, though, that it sometimes produces false positives which must be inspected using boroscopy. On the other hand, it is no so laborious a technique and even though it does require qualified field technicians and, new generation of GB implement on-line monitoring.

Bearing condition unit vibration analysis can be enhanced by using fast Fourier transformation, detective enveloping selection and bearing condition selection analyses to detect the area of damage in each bearing, but bearing condition unit analysis is sufficient to detect the condition of the bearing. Furthermore, it must be pointed out that vibration analysis allows the detection of damage in gears and it is therefore an optimal predictive technique for new gear boxes. In the case of those older gear boxes which are operative and still have considerable service life, this technique can be used to detect serious damage.

Regarding predictive oil analysis, this technique is not reliable to detect damage in bearings and sometimes has not detected serious and grave damage present in the gear box despite a complete oil analysis being made.

As a conclusion it can be stated that bearing condition unit vibration analysis, despite having only predicted low and moderate damage in a few cases, is the only predictive method of those studied which can, with adequate reliability, identify severe damage in the satellite bearings of the gear boxes due to severe flaking. In-depth oil analysis, despite being able to predict damage in a few cases, proved alongside the other methods under study, not to be suitable to the task.

REFERENCES

[1] IEC 61400-4:2012, Wind turbines -- Part 4: Design requirements for wind turbine gearboxes. International Organization for Standardization. (2012)
[2] ISO 81400-4:2005, Wind turbines -- Part 4: Design and specification of gearboxes, International Organization for Standardization. (2005).
[3] M. Grujicic, S. Ramaswami, R. Yavari, R. Galgalikar, V. Chenna, J.S. Snipes, Multiphysics computational analysis of white-etch cracking failure mode in wind turbine gearbox bearings, Proceedings of the Institution of Mechanical Engineers Part L-Journal of Materials-Design and Applications. 240-1 (2016) 43-64.
[4] A. Greco, S. Sheng, J. Keller, A. Erdemir, Material wear and fatigue in wind turbine Systems, Wear. 302 (2013) 1583-1591.
[5] N. Tandon, A. Choudhury, A review of vibration and acoustic measurement methods for the detection of defects in rolling element bearings. Tribology International. 32-8 (1999) 469-480.
[6] Z. Hameed, Y.S. Hong, Y.M. Choa, S.H. Ahn, C.K. Song, Condition monitoring and fault detection of wind turbines and related algorithms: a review, Renewable and Sustainable Energy Reviews, 1 (2009) 1-39.
[7] F.P. Garcia, A.M. Tobias, J.M. Pinar, P. Mayorkinos, Condition monitoring of wind turbines: Techniques and methods, Renewable Energy. 36 (2012), pp 169-178.
[8] B. Li, X.N. Zhang, A new strategy of instantaneous angular speed extraction and its application to multistage gearbox fault diagnosis, Journal of Sounds and Vibrations. 396 (2017) 340-355.
[9] J. Wang, Y.Y. Peng, W. Qiao, J.L. Hudgins, Bearing Fault Diagnosis of Direct-Drive Wind Turbines Using Multiscale Filtering Spectrum, IEEE Transactions on Industry Applications. 53-3 (2017) 3029-3038.
[10] Bruel and Kjaer. http://www.bksv.es/
[11] ISO 15243:2017, Rolling bearings — Damage and failures — Terms, characteristics and causes, International Organization for Standardization
[12] ISO 10825:1995, Gears — Wear and damage to gear teeth, International Organization for Standardization
[13] ISO 15242-1:2015, Rolling bearings — Measuring methods for vibration, International Organization for Standardization
[14] P. Tchakoua, R. Wamkeue, M. Ouhrouche, Wind Turbine Condition Monitoring: State-of-the-Art Review, New Trends, and Future Challenges, Energies. 7-4 (2014) 2595-2630.
[15] P. Gupta, M.K. Pradhan, Fault detection analysis in rolling element bearing: A review. Materials Today: proceedings. 4-2 (2017) 2085-2094.
[16] X. Chen, G. Cheng, H. Li, Y. Li, Research of Planetary Gear Fault Diagnosis Based on Multi-Scale Fractal Box Dimension of CEEMD and ELM, Journal of Mechanical Engineering. 63-1 (2017) 45-55.
[17] X.H. Chen, G. Cheng, X.L. Shan, X. Hu, W. Guo, H.G. Liu, Research of weak fault feature information extraction of planetary gear based on ensemble empirical mode decomposition and adaptive stochastic resonance. Measurement. 73 (2015) 55-67.
[18] Y. Feng, Y. Qiu, C.J. Crabtree, et al., Monitoring wind turbine gearboxes, Wind Energy. 16-5 (2013) 728-740.
[19] ASTM D7691 - 16 Standard Test Method for Multielement Analysis of Crude Oils Using Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES), American Society for Testing and Materials
[20] ASTM D8184, Standard Test Method for Ferrous Wear Debris Monitoring in In-Service Fluids Using a Particle Quantifier Instrument, American Society for Testing and Materials