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Improving the reliability of industrial multi-MW wind turbines

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Abstract

Although wind turbine gearboxes are designed to remain in-service for 20-25 years, this is not normally the case due to defects initiating and developing prematurely. A large number of gearboxes fail after 7 to 8-years in service. In offshore wind farms gearbox failures have been reported after only 1-2 years in service leading to noteworthy production losses. Reliability issues associated with wind turbine gearboxes are yet to be resolved. Within this paper the quality of materials used for manufacturing wind turbine gearbox gears and bearings has been evaluated. The damage mechanisms affecting gearbox materials have been investigated based on metallographic analysis carried out on failed samples removed from in-service industrial wind turbines. Finite Element Analysis (FEA) has been carried out in order to simulate damage initiation and propagation under in-service conditions. The results have been compared with the experimental observations made on the failed field samples and have been found to be in good agreement. The applicability of acoustic emission in detecting and identifying defects in different wind turbine gearbox components remotely has been assessed following measurements in the field.

Keywords: Wind turbines, gearbox, FEA, condition monitoring, acoustic emission

1. Introduction

Wind energy has grown substantially in recent years with global installed capacity having exceeded 430 GW [1] as of the end of 2015. Several thousands of industrial multi-MW wind turbines have been installed both onshore and offshore throughout the world. These complex industrial systems consist of several critical devices and structural components including the drive-train, power electronics, pitch control, yaw system, blades, tower and foundation. Utility-scale wind turbines can be classified either as direct-drive (gearless) or geared. Approximately 75% of all wind turbines are geared. Replacement of gearboxes is a lengthy process and requires heavy-lifting capacity equipment to be in place. Particularly for offshore wind farms, gearbox maintenance costs are a major contributor to increased Levelised Cost of Electricity (LCOE) generated in comparison with onshore wind farms.

The wind turbine drive-train, particularly the gearbox, has always been a source of concern due to the long downtime and loss of production that its failure can cause, as well as the high costs associated with repair and replacement [2]. In the early days of industrial wind energy production, most gearbox failures arose from design deficiencies which resulted in frequent and costly repairs. Often the complete replacement of the gearboxes affected was necessary. Despite the improvements made in gearbox designs along also with the revision of the IEC-61400 international standard concerning the technical requirements of industrial and utility-scale wind turbine gearboxes [3], there are still technical challenges that are yet to be overcome. This is particularly evident in the case of offshore wind farms employing geared wind turbine models.

There are a number of important reasons behind the wind energy industry's preference in geared over gearless designs. Apart from the fact that they normally cost less to procure, their generator requires significantly less rare earth magnets in comparison with direct-drive wind turbine models. Their nacelles weigh less and also the rotor speed can be kept lower since the generator rotational speed is accelerated by the gearbox at the required ratio. Gearless designs have also more complex power electronics which is another wind turbine component exhibiting high failure rate [2, 4-5]. Albeit power electronics failures result in lower downtime per failure event, they occur much more often. Hence, they tend to result in significant downtime cumulatively. For offshore wind turbines which are not easily accessible the failure of power electronics may be as difficult to resolve as a gearbox fault due to adverse weather conditions preventing maintenance crews from attending the wind farm.

Operating and Maintenance (O&M) costs of onshore wind farms do not normally exceed 20-25% of the overall LCOE. However, in the case of the offshore projects current experience has shown that O&M costs can be as high as 40% of LCOE or even exceeding this. Although onshore wind turbines are designed with a 20-year operational lifetime in mind this has been proven to be practically impossible to achieve without serious repairs taking place as damage evolves with increasing operational time. Offshore wind turbine designers face more complex operational challenges, since these devices are required to remain in operation under adverse environmental conditions for at least 25 years to justify the higher Capital Expenditure (CAPEX) of offshore wind energy projects. It is generally acceptable that an onshore wind turbine may need to have its gearbox repaired or even replaced two or three times during its anticipated operational lifetime. In the case of onshore wind farms this is largely attributed to the inadequate understanding of continuously variable loading conditions arising from turbulent wind, which consequently has a negative effect on the structural components comprising the gearbox.

For offshore wind turbines there has been an underestimation of the loading conditions prevailing out in the open sea. Thus most gearbox designs have experienced significant unexpected problems very early in their operational lifetime [6-8]. The majority of wind turbine gearbox failures have been reported to initiate in the bearings (planetary, intermediate and high-speed shaft) [9]. Oil cleanliness and lubrication quality have also been highlighted as part of the problem. Poor lubrication quality can contribute to excessive wear, surface distress, fatigue spalling and pitting [10-11]. Moreover, there is still a necessity to increase current understanding with respect to the fundamental loading conditions and how these influence wear and fatigue lifetime of gearbox components.

2. Materials for wind turbine gearboxes

Wind turbine gearbox gears and bearings are manufactured from surface-treated ferrous alloys [12]. According to the international standards for wind turbine gearboxes (IEC 61400-4 [3] or ANSI/AGMA/AWEA 6006-A03 [13]) all gears and bearings are required to be made from grade 2 or MQ materials. Therefore, industrial wind turbine gears and bearings are widely made of nickel-chromium-molybdenum low-alloy steels, such as SAE4320, SAE4820, SAE9310, 18CrNiMo7-6, 3CrMo, 3CrMoV and 3NiCrMo [14]. Carburising has been widely applied to gears and bearings to improve fatigue strength and wear resistance. Replacing carburising with nitriding in gear treatment has great potential. This is due to the fact that the treating temperature involved in the nitriding process is lower, allowing more flexibility during surface treatment.

3. Wind turbine gearbox failure mechanisms

Onshore wind farm availability has increased substantially reaching 95-98% on average. However, for offshore wind farms, much lower availabilities have been recorded which reduce the overall average to as low as 80-85% [15]. One of the main reasons for the lower availability of offshore wind farms have been the reliability issues associated with the gearbox resulting in frequent faults. There is also evidence from several European wind farm operators that the quality of repairs can influence considerably the Mean Time Between Failures (MTBF) and hence, the requirement for further maintenance. Also, the way maintenance is carried out can influence the extent that damage may evolve and how it affects the overall wind turbine operation in the future.

Oil cleanliness and lubrication quality plays a crucial factor in the deterioration rate of gearbox rolling elements. It is estimated that poor oil cleanliness can reduce the lifetime of new gearbox components by up to 50% in comparison with a well lubricated gearbox [10]. One report has suggested that 82% of machine wear is particle-induced and related to oil cleanliness [16]. Hence, it is crucial that wear particles are removed using appropriate filters in order to increase the lifetime of gearboxes.

The most common wind turbine gearbox faults are related to shaft misalignment, gear tooth damage and bearing wear. Bearing failures occur mostly due to micro-pitting, scuffing, false brinelling, and fretting corrosion [17-19]. Micro-pitting is normally a precursor to surface failure. Both gears and bearings are affected by this form of damage. Micro-pitting is related to tangential shear stresses arising from rolling-sliding contact. However, it can also initiate due to moisture ingression in the lubricant. Micro-pitting occurs when the oil layer is not sufficiently thick to keep the contact surfaces separated and when they are sliding against one another [20-21]. Micro-pitting has particularly adverse effects on the structural integrity of bearings since it changes the geometry of the raceways and rollers. These geometrical changes result in an increase of the internal clearance generating edge stresses which eventually lead to macro-pitting and subsequently bearing failure [19].

Scuffing is another type of surface damage mode, often characterised by high levels of plastic deformation. When the thickness of the lubrication film is inadequate (generally due to high or fluctuating input loads), local frictional heating will occur at the contact surfaces, giving rise to scuffing. Even though mitigation methods are fairly well established for this form of damage, better understanding is needed, since scuffing-related failures occur frequently [20-21].

Particle contamination can cause abrasive wear and initiate surface fatigue spalling. Moreover, it can reduce the useful lifetime of the lubricant [21-22]. Smooth surfaces, surface-hardened gears and high viscosity lubricants contribute to the reduction of the generation of wear debris [23].

4. Operational characteristics of wind turbines and their effect on gearbox

Conventional rotating machinery, such as pumps in oil refineries, is designed to operate at specific loads which are set to be constant throughout operation. Although the operator may adjust the load that a certain pump operates over a specific time period, this will remain constant without any variations until the user changes again the operational parameters of the pump. In addition, there is better knowledge of the exact materials employed for manufacturing the subcomponents of the pumps. This is not the case for industrial wind turbines operating under constantly varying load conditions regardless of the output they generate. This by default increases the complexity of operation at system and component level.

The consistency of the lubrication quality is an important factor influencing fatigue lifetime which is also better understood in these machines. Unless moisture or other detrimental factors have affected the lubricant condition, then lubrication quality can be considered as deteriorating at a certain expected rate during operation. The lubricant condition can be further ascertained by taking oil samples at pre-determined intervals ensuring that no moisture is present. With gradual wear, debris in the form of ferrous and non-ferrous particles will accumulate in the lubricant. Such particles will contribute to the fatigue damage accumulation in bearings and gears. Oil data obtained using online sensors and/or oil samples retrieved by maintenance engineers can be used to evaluate the overall particle population present in the lubricant of a particular machine as well as their average size and type. The evaluation of the average size of particles however, is not entirely reliable since larger particles not captured in oil filters will gradually be milled to smaller size every time they move through the contact surfaces of two rolling elements. Heavier particles may not be captured during oil sample retrieval simply because they can sink to a lower level from where the oil sample has been taken.

Misalignment can further contribute to increased fatigue rates due to the change in the contact angles of rolling elements. Hence, misalignment results in higher stresses being sustained by the rotating components. Paris-Erdogan law, Miner's rule or specifically adapted power laws can be used in combination to estimate the remaining lifetime of rotating components showing evidence of damage due to increasing noise and vibration levels. Nonetheless, it is important to understand that even in this case where several of the variables needed to estimate the remaining lifetime of a particular component are known, the available metal fatigue data can exhibit significant scatter. Therefore, it is only possible to refer to a minimum fatigue damage threshold which can be subsequently related to the actual risk of failure. Hence, a probabilistic approach needs to be employed in order to assess the remaining lifetime of such components.

There are several patterns of probability of failure. Certain components in conventional rotating machinery are expected to follow a normal bathtub curve (pattern I in figure 1). Actually, in modern maintenance theory different components can exhibit different probability of failure patterns. Thus, assuming that the bathtub curve is applicable to all sub-components of the system will most likely involve some level of inaccuracy. The normal bathtub curve predicts an initial stage with increased number of failures which is known as the infant mortality stage. Probability of failure will gradually stabilise with time as infant mortality issues are gradually resolved. Towards the end of life of the component failure rate increases again due to wear and fatigue (wear out time). Certain studies have shown that the bathtub curve is applicable for describing the overall reliability of wind turbines [24-26]. However, this has been based on data analysis gathered from various wind turbine models and wind farms rather considering individual models separately. The quality of different wind turbine types produced from different manufacturers is not the same. This results in variability of the reliability levels attained for different wind turbine models. Also the maintenance regime is not uniform across the wind turbine fleet. Therefore, reliability analysis needs to be more detailed and specific to subcomponents and turbine types, limiting the effects of generalisation in the results obtained from the data available.

Pattern II assumes an increasing probability of failure during the break-in period which then becomes stable with time. Pattern III is based on wear-out predicting a relatively stable initial probability of failure followed by a gradually increasing rate towards later stages. For wind turbines, Pattern III is the most desirable for wind farm operators as long as initial probability of failure is low and wear out does not generally begin before the intended lifetime of the design has been reached. Pattern IV describes the random probability of failure of certain components throughout their in-service lifetime. Pattern V is based on fatigue assuming a linearly increasing probability of failure which is typical for steady state equipment operating under constant conditions. Finally, Pattern VI is based on infant mortality where initial operation has inherently a high probability of failure followed by a relatively lower and stable probability of failure at later stages.

In general, failures happening at the early stages of operation of a complex system (infant mortality) are attributed either to manufacturing quality deficiencies, assembly mistakes, mis-handling, operational errors or simply insufficient knowledge to optimise design. With increasing experience most of these problems are gradually addressed moving away from early failures.

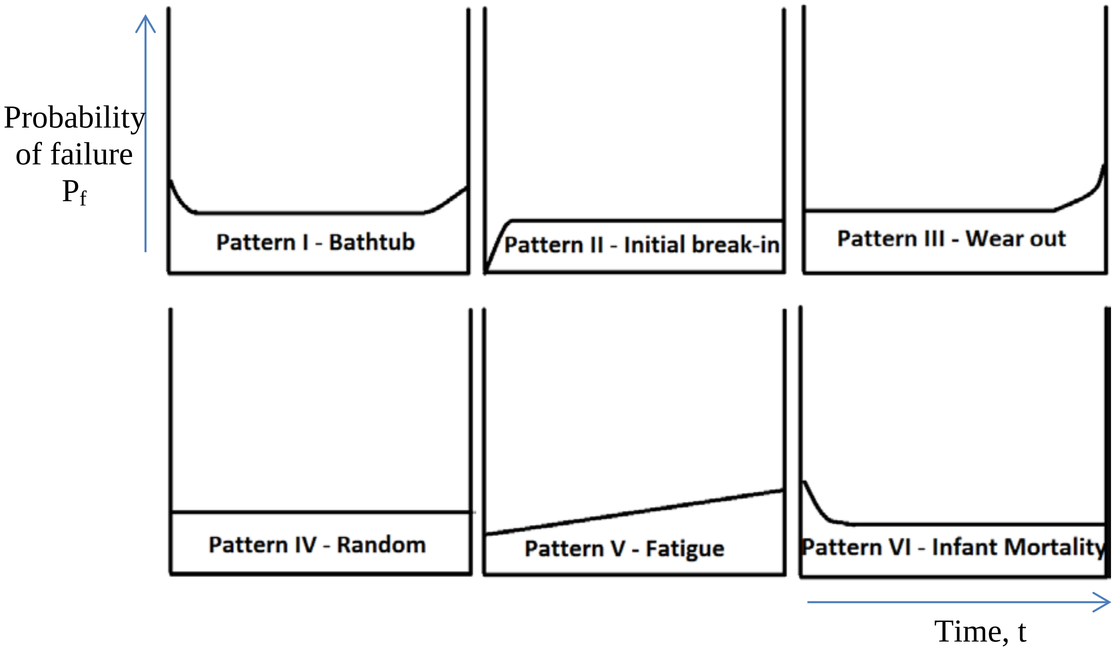

Figure 1: Possible patterns of probability of failure with time.

It is widely accepted that wind turbines exhibit a bathtub pattern when describing failure probability for these systems. This has also been the traditional approach to failure for most complex machinery and systems. In reality, this does not seem to be the case for wind turbines, particularly for those installed in offshore environments. In addition, different components will exhibit a different pattern of failure.

Taking into account global failure data for both onshore and offshore wind turbines it can be safely assumed that failure would have very likely occurred much more rapidly than anticipated by design standards [2, 26-30]. Since the loading conditions offshore are normally much more severe than onshore, damage propagation can also be expected to progress more rapidly than onshore.

It is important to take into consideration that previous research has largely focused on different types and makes of wind turbines [2, 8-9, 25-27, 30]. The fact that wind turbines have been growing in size and complexity with time, intensifies the problem of correctly analysing the failure data available from these studies. It appears that only limited effort has been expended on the correlation of failures with environmental parameters prevailing at local level such as average wind speed, turbulence, terrain morphology, icing conditions, maximum wind speed, time spent at maximum power output, etc. It should be stressed that these parameters are only a small fraction of the considerations that need to be taken into account to fully describe the problem of assessing accurately the actual condition and risk of failure of gearbox components in industrial wind turbines.

5. Condition monitoring

Vibration analysis based on different signal processing methodologies, such as moving RMS, moving kurtosis, spectral kurtosis, high frequency resonance technique (HFRT), power spectral and cepstral analysis can help to identify the exact components that have been damaged. Having also knowledge of the exact loading conditions and operational history of a particular machine it is possible to predict the risk of failure and extent of structural damage with reasonable probability of success. The results of the analysis oil samples can further increase the confidence levels in predicting the risk of failure.

Acoustic emission (AE) offers significant advantages over conventional vibration analysis testing since damage can be detected much earlier. This can potentially be achieved with fewer sensors since noise is transmitted more efficiently throughout the gearbox structure in comparison with vibration.

Oil analysis using online eddy current (EC) sensors is particularly beneficial since it can provide information regarding the nature of the wear particles, their size as well as population present in the lubricant. This information combined with the results of vibration and/or AE monitoring systems can provide a solid indicator with respect to the extent of damage present in the gearbox and the likelihood of failure. Hence, the combined results from oil, vibration and AE analysis can be used to make efficient maintenance decisions, minimising the risk of unpredictable downtime and associated costs.

6. Finite Element Analysis

The highest stresses are concentrated in the contact area between two rolling elements, e.g. two gears. The contact and bending stresses between two gear teeth in contact can be seen in figure 2. For this gear pair and input torque, the bending stress is much lower than the contact stress, as observed in the contour plot.

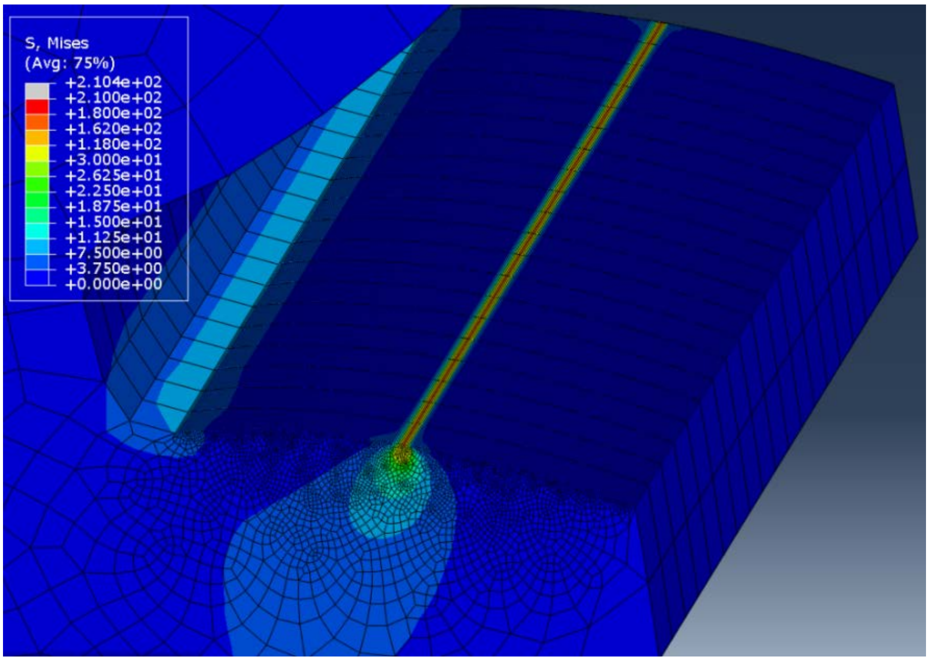

Figure 2: Von Mises contour plot for gear pair, lateral view. The mating gear was removed for better visualisation.

The contact stress levels will be influenced by a number of variables but primarily it will be a function of the coefficient of friction and contact area. From calculations carried out it is possible to see that higher coefficient of friction value results in much higher contact stresses (figure 3). Similarly, the effect of angular misalignment on contact stress amplitude has also been evaluated.

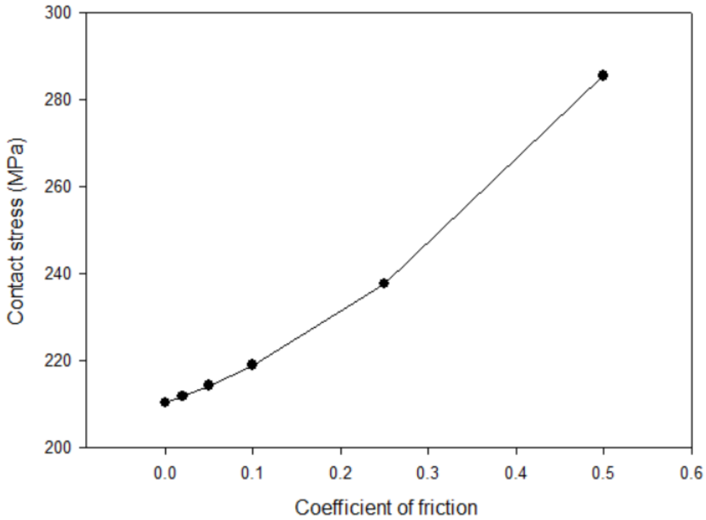

Figure 3: Plot showing the effect of the coefficient of friction on contact stress.

In order to test the effect of angular misalignment, one of the simulated gears was rotated along its y-axis, between 0° (figure 4a) and 1° (Figure 4b). The results of the effect of misalignment on contact stress level can be seen in the plot of figure 5.

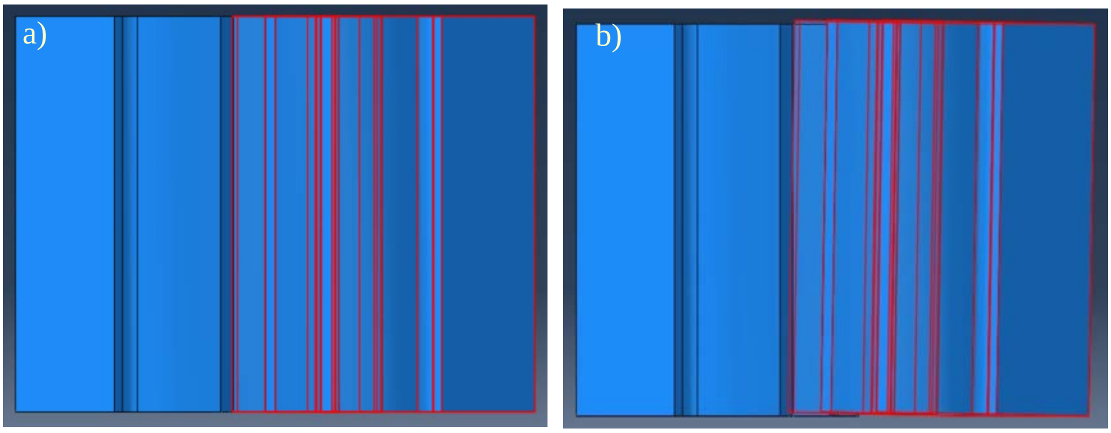

Figure 4: a) Gear pair in perfect alignment (left); b) Gear pair in angular misalignment (1°) (right).

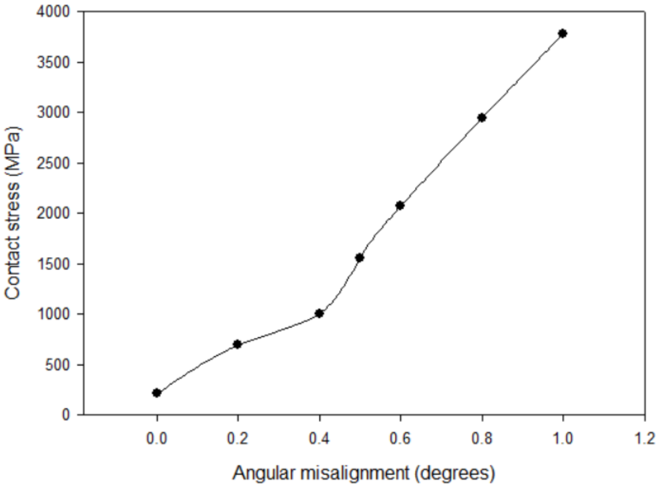

Figure 5: Plot showing the effect of angular misalignment on contact stress.

Angular misalignment has a significant effect on the amplitude of the contact stress. Even a small amount of misalignment, such as 0.20° can produce contact stresses as high as 692.7 MPa, which is almost 3.3 times the contact stress level obtained from two gears in perfect alignment. At 1° of angular misalignment, the contact stress can be almost 18 times higher than the initial contact stress. Such high contact stresses could lead to severe plastic deformation, causing initiation and subsequently rapid propagation of damage.

7. Characterisation of damaged gearbox components retrieved from the field

Tests on reference materials from failed bearings and gears provided by wind turbine operators participating in the OPTIMUS FP7 project consortium have revealed that the cleanliness of steel plays an important role in the initiation and subsequent propagation of fatigue cracking in rolling elements. The presence of inclusions, such as manganese sulphides (MnS), has a detrimental effect on the fatigue lifetime of gearbox components. This is due to the fact that fatigue cracks due to contact and bending stresses can initiate from MnS inclusions and then propagate along them. The initiation of the cracks can also be related to the MnS inclusion distance from the surface. Therefore, depending on the cleanliness of the steels employed damage can propagate faster or slower following a path outlined by inclusions present in the microstructure. This failure mechanism has been observed in samples obtained from defective gearboxes (Figure 6) and verified using finite element analysis (FEA) simulations.

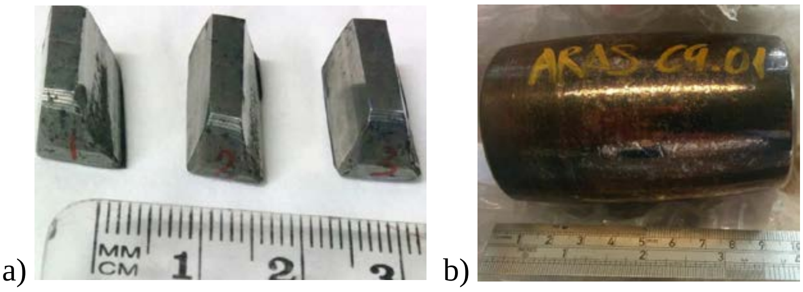

Figure 6: Damaged a) gear teeth and b) roller removed from gearbox.

Figure 7 shows crack propagation in one of the damaged gear teeth evaluated using optical and Scanning Electron Microscopy (SEM). The SEM micrographs in Figure 8 show that the crack propagates along inclusions which have been established to be MnS.

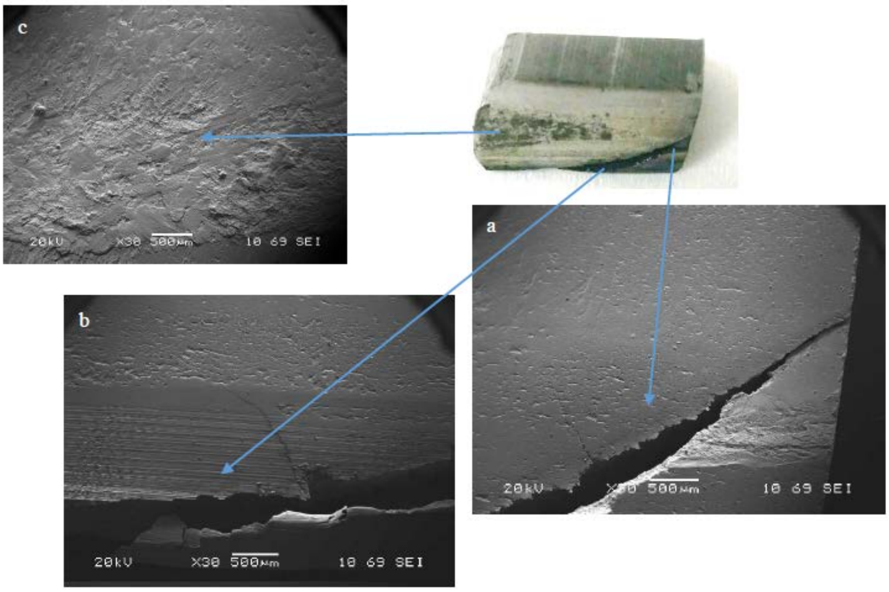

Figure 7: SEM evaluation of cracked tooth sample.

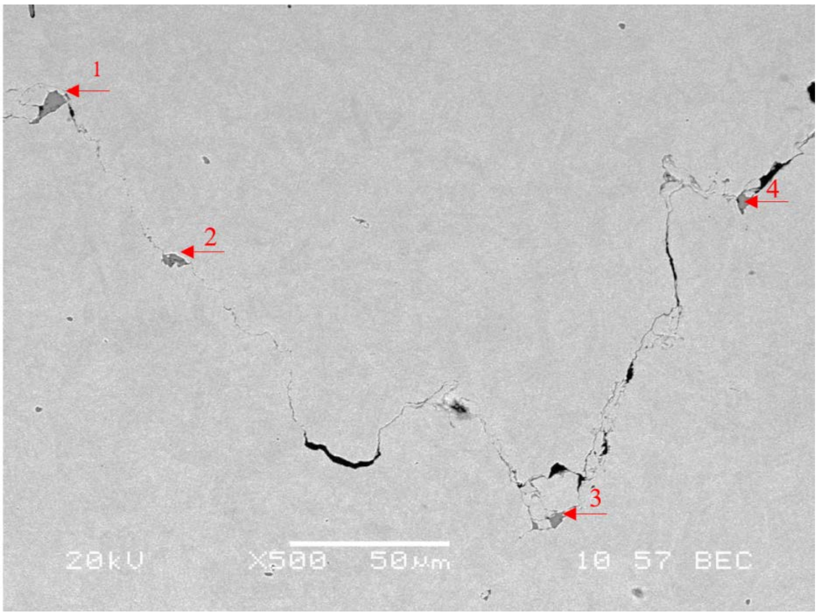

Figure 8: SEM images showing crack propagation along MnS inclusions (direction of crack propagation is from inclusion #4 towards #1).

FEA simulations carried out using Abaqus have also clearly shown that the cracks can initiate at MnS sites in the gear tooth material and subsequently propagate along a path which is outlined by the presence of such inclusions. This is shown in the FEA results of figure 9.

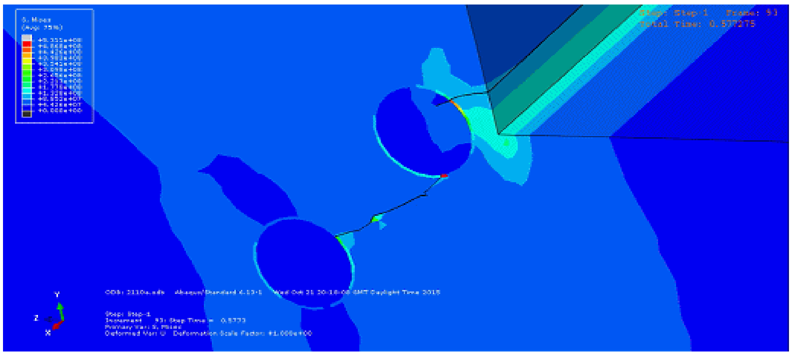

Figure 9: FE model showing crack propagation initiating and propagating on a gear tooth along MnS inclusions.

8. Condition monitoring of wind turbine gearbox using acoustic emission

The use of acoustic emission for monitoring wind turbine gearbox components has been studied previously with very promising results [31-34]. In this paper, the authors report the results obtained following the instrumentation of the three-stage planetary gearbox of an 850 kW industrial wind turbine owned by TERNA Energy installed on the island of Crete, Greece, using a customised 4-channel AE condition monitoring system. The customised data logger was created using Labview® developed by National Instruments. Detailed analysis was carried out using Matlab®. Data were acquired for a period of a few days over repetitive acquisition intervals set to take place every 10 minutes. The acquisition period was 12 seconds and a sampling rate of 500 kSamples/s was employed. One Physical Acoustics Corporation (PAC) R50A AE sensor was installed on the main bearing. Ultrasonic coupling and adhesion of the sensor to the test surface were achieved simultaneously with the use of araldite. Three more R50A AE sensors were installed on the gearbox itself at the planetary, intermediate and high-speed stages. The AE signals were amplified using pre-amplifiers and amplifiers procured from PAC. The total gain was set at 58 dB. Figure 10 shows the wind turbine and gearbox instrumented together with part of the equipment used.

Figure 10: The 850 kW TERNA Energy wind turbine gearbox instrumented in Crete together with the AE sensors and pre-amplifiers employed for its instrumentation.

Figure 11 shows a raw AE signal acquired from the planetary stage sensor position. From the spiky nature of the signal it is evident that a defect is present. Further in-depth data analysis revealed clear evidence of significant damage present in the planetary stage (planetary bearing) which was also verified by TERNA maintenance personnel. Figure 12 shows the power spectrum of the demodulated signal, indicating the presence of a planetary bearing tone with sidebands and related harmonics.

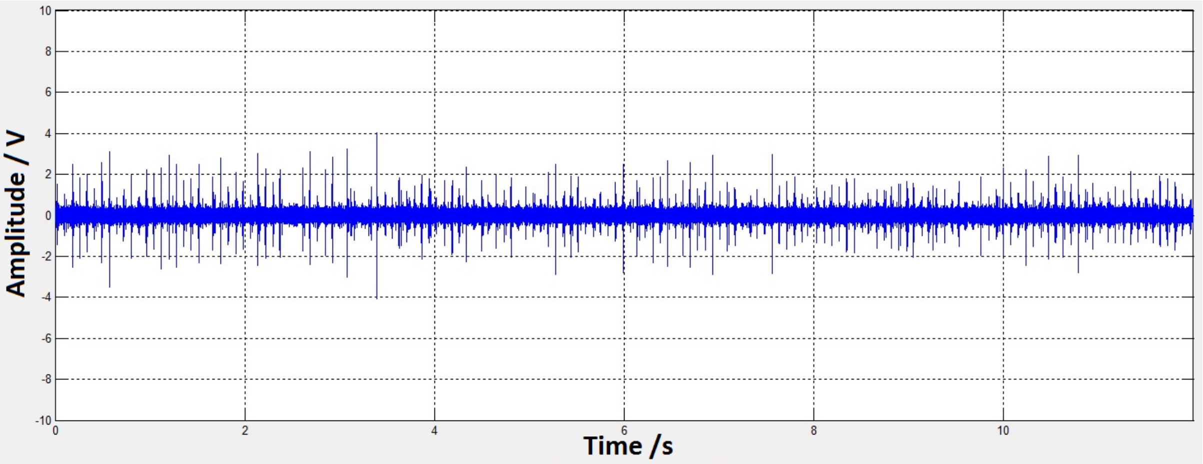

Figure 11: Raw AE signal acquired from the planetary stage sensor showing multiple regular peaks. This is an indication of a possible defect.

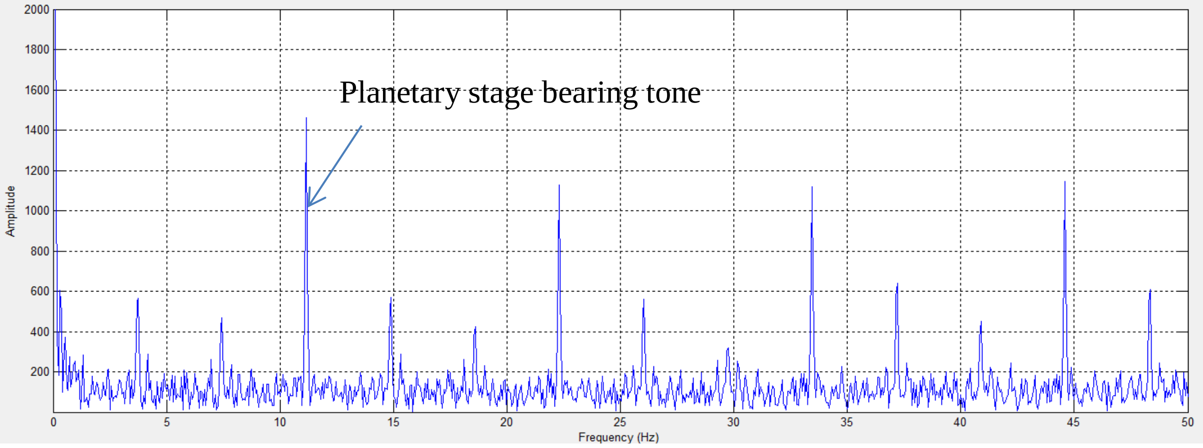

Figure 12: Low frequency power spectrum of the demodulated AE signal showing a planetary stage bearing defect with sidebands.

9. Conclusions

It is undeniable that wind energy has grown profoundly in importance. Its contribution to the global wind energy mix will continue to rise in the forthcoming years. Despite the significant increase in the power output of utility-scale wind turbines, gearbox problems are yet to be fully resolved. This necessitates improved understanding of the operational conditions coupled with efficient condition monitoring capabilities and knowledge of the materials and damage mechanisms associated with wind turbine gearboxes. This study provided an insight of the damage characteristics and condition monitoring results from field tests together with FEA models developed by the authors.

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