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Reliability prediction of bearings of an offshore wind turbine gearbox

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ABSTRACT: A model is presented to estimate the failure rate of bearings of an offshore wind turbine gearbox based on data available for similar, known onshore wind turbine systems. The gearbox is one key element of the system since its failure may cause long downtime and consequently high operational and maintenance costs. Various research studies concluded that failure of bearings is predominant in gearbox failures, accounting approximately for 70% of total failures in gearboxes. First, a detailed Failure Mode and Effects Analysis is conducted and then the main Reliability Influencing Factors on the failure causes are identified. The reliability method is then illustrated stepwise to estimate total failure rate of a bearing of an offshore wind turbine gearbox.

1 INTRODUCTION

As the demand of renewable source of energy is increasing, the energy industry is moving towards wind turbines as alternative for energy production. Due to location and environmental constraints inland, offshore wind turbines are becoming one of the most significant choices for energy production. Furthermore, oceans offer good opportunities for sustainable economic development and for this reason the offshore wind turbines have experienced notable development, towards optimizing the exploitation of the resources. It is believed that around 2030 in Europe up to 7.7% of overall electricity consumption will be covered by electricity generated from offshore wind turbines by an installed power of 66 GW capacities (Bagbanci et al. 2012; Corbetta et al. 2015).

Most wind turbines contain speed-increasing gearboxes to convert the slow main rotor speed into the 1000-rpm range for convenient generator operation (Uzunoglu et al.2016). This is accomplished through using larger gears and bearings than that used in a normal gearbox. However, many wind turbine gearboxes influence wind farm performance due to their poor reliability. Previous studies show that gearboxes usually do not reach their design lifetime of 20 years (Sheng 2013, Liu 2013 & Lantz 2013). In addition, various studies show that gearbox is one critical component of wind turbines (Santos et al. 2015a; Reder et al. 2016). According to Spinato (2009) gearboxes come second in the downtime per failure due to their size and robust link to other components making it harder to access, repair, or even replace. The mean downtime per failure is in the range of 6–15 days for studied land-based European wind turbines over a 13 year time period with a failure rate of 0.1–0.15 failure/turbine-year (Tavner 2012). They need replacement after 6–8 years that is much less than expected failure free operational life (Asmus & Seitzler 2010, Mandic et al. 2012).

However, offshore conditions limit the accessibility to the turbines. Also, offshore wind turbines withstand randomly changing weather conditions, temperature, wind shear, wind speed, and load. Hence, such system demands very high reliability because any intervention during operational phase leads to long production downtime and consequently production loss. The offshore wind industry lacks availability of representative data for accurate reliability predictions. The main reasons are short application of this technology; constantly changing turbine designs with technological advancement and site-specific environmental conditions. The last reason affects failure behavior significantly and increases uncertainty in reliability prediction.

There are various reliability prediction methods available in literature for specific equipment or applications, such as, Proportional Hazard (PH) models, Accelerated Failure Time (AFT) models, Mechrel model, Barrier and Operational Risk Analysis (BORA), among others. The present paper adopts the approach by Rahimi & Rausand (2013) originally developed to predict the failure rates of subsea equipment. This approach is used to predict the failure rate of an offshore wind turbine gearbox component using data from similar wind turbines working onshore. This paper describes the approach and its application to predict the failure rate of bearings taking into account the contribution of relevant Reliability Influencing Factors (RIFs) on the failure causes.

2 RELIABILITY STUDIES ON WIND TURBINE GEARBOXES

There have been several studies on reliability of onshore wind turbine through analysing operational data from real wind farms in different countries for varying period and identifying failure data and downtime for subassemblies (Reliawind 2011, Langniss 2006, Ribrant 2006, Stenberg & Holttinen 2010 & Tavner et al. 2007). The field data of offshore wind turbines are limited in public domain (Karyotakis & Bucknall 2010). Power rating and environmental stress factors for mechanical systems (Davidson 1994) have been used as an empirical approach to obtain the offshore failure models of the turbine's components from characteristic onshore failure distributions (Santos et al. 2015b). However, the offshore wind turbines are subjected to higher environmental and power utilization stresses than onshore turbines resulting from the marine environment. Therefore, they have higher failure rates of their subsequent components (Santos et al. 2015a). Hence, the onshore failure models are not appropriate for modelling the operation and maintenance of offshore turbines.

For reliability of wind turbine gearboxes some industrial initiatives are eminent (IEA 2017, NREL 2018). Fault tree analysis was conducted by Marquez et al. (2016). Smolders et al. (2010) have also analyzed and predicted the reliability, but lacking real-time data for failure and repair rates. Dabrowski & Natarajan (2015) have studied the reliability of a gearbox of 5 MW offshore wind turbine under extreme wind loads.

Other studies provide an early fault detection such as by condition monitoring systems (Siegel et al. 2014) or SCADA (Supervisory Control and Data Acquisition) information (Tautz-Weinert & Watson 2016) but not prior information about failures.

The costs for maintenance and replacement of gearboxes, along with the production losses due to non-functioning gearboxes, constitute a large share of the expenses of operating wind power farms (Spinato et al 2009). Shafiee & Dinmohammadi (2014) & Kahrobaee & Asgarpoor (2011) using CPN (Cost Priority Number) indicators, also confirmed that gearbox is the second top most critical assembly in wind turbines. Figure 1 illustrates the expected costs of failure against wind turbine component (Tazi et al. 2017). For these reasons the wind turbine industry effort focuses on reliability of gearboxes.

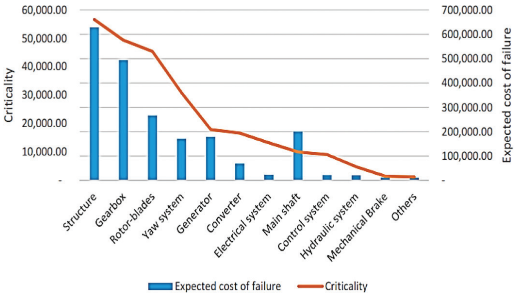

Figure 1. Expected costs of failure and criticality for wind turbine assembly.

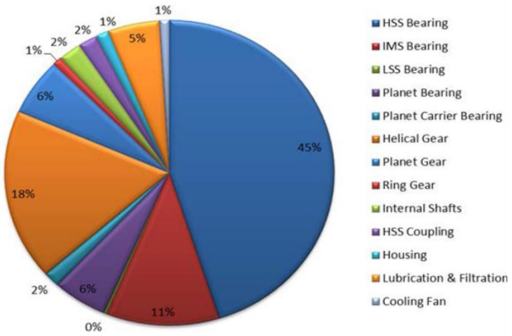

Figure 2. Gearbox failures based on 257 damage records released in (Sheng 2014).

Other studies (Sheng 2013, Zhao et al. 2012, Zhou et al. 2013) focused on wind turbine gearbox failures confirm that bearing failure is the most frequent cause. Especially (Sheng 2014) covered 289 gearbox failure incidents with 257 confirmable damage records. The main outcome of the study shows that 70% of the failures in gearboxes occur in the bearings followed by 26% gear failure and 4% other failures (Figure 2).

In general a gearbox bearing exchange cost can be from 15 k€ for a simple up-tower replacement to even more than 1 M€ for a larger (+5 MW) gearbox exchange. Maintenance offshore is obviously more costly than that onshore.

Bearings are susceptible to special environments like corrosive, high temperature, power, speed and vacuum zone. In offshore environment, they are exposed to the extreme weather conditions with wind speeds larger than 25 m/s. This gives rise to events such as emergency stops, wind gusts and grid losses. Also, the offshore environment is corrosive and humid. The offshore wind turbines may be fixed or floating still, their structure undergoes vibration caused by waves and currents. These events have a significant impact on the reliability of bearings.

So it is clear from the above discussion that reliability of bearings in gearboxes must be high and they should work perfectly during its designed life. As per authors knowledge no comprehensive study on reliability of bearings of offshore wind turbine gearboxes considering failure mechanisms, causal factors and their effect is available in public domain.

3 FAILURE RATE PREDICTION METHODS

There are various reliability prediction methods available in the literature, most of them have been developed for electronic components, but there is scarcity of methods for predicting the reliability of mechanical component. The most common methods of failure rate prediction are:

- MIL-HDBK-217F mainly for electronic equipment (MIL-HDBK-217F 1991);
- Proportional hazard (PH) models (Cox 1972);
- Accelerated failure time (AFT) models (Lawless 1983);
- Brissaud's approach (Brissaud et al. 2010);
- MechRel (NSWC 2011);
- BORA project (Vinnem et al. 2009).

The above methods have their field of applicability and respective advantages and disadvantages. Prediction of failure rates for mechanical system is difficult because they have large number of complex failure mechanisms. Also, such systems are sensitive to loading, operating mode, and utilization rates (NSWC 2011 & Foucher et al. 2002).

Reliability requirements may be stated according to standards like ANSI/AGMA/AWEA 6006-A03—for design and specification of gearboxes for wind turbines which was adopted without change in 2005 as ISO 81400–4, an international standard(AGMA 2004). The new draft by International Electrotechnical Commission (IEC) IEC 61400–4:2012(E) expands on preceding standards so it is more encompassing (IEC 2012). This standard applies to wind turbines installed onshore or offshore. For bearings in gearboxes, specific industrial documents such as SKF (1997) can be used for specifications and design.

To use the available field data from onshore wind turbines to offshore wind turbines, Rahimi & Rausands (2013) approach is well suited. This approach has the following 8 steps:

1. New system familiarization;
2. Identification of failure modes and failure causes;
3. Reliability information acquisition for the similar known system; comparison of the new and the known system;
4. Selection of relevant RIFs;
5. Scoring the effects of the RIFs;
6. Weighing of the contribution the failure causes to failure modes;
7. Determination of failure rate for similar failure modes;
8. Determination of failure rates of new failure modes and calculation of new total failure rate.

The approach is illustrated in the next section, focusing on an offshore wind turbine gearbox bearing.

4 FAILURE RATE PREDICTION OF THE BEARING

4.1 *Bearing in offshore wind turbine gearboxes*

The main function of gearboxes in wind turbine is to transform slow speed, high torque rotation to higher speed required by the generator, which converts the mechanical power to electricity. The bearing in a typical gearbox is represented in Figure 3. It should be noted that the arrangement may alter for different wind turbine gearboxes.

The ReliaWind taxonomy can be used to classify the wind turbine system (Tavner 2012), which divides all the wind turbines elements into 5 levels as follows for bearings:

System	Wind turbine generator
Sub-System	Drive Train Module
Assembly	Gearbox
Sub-Assembly	Bearings
Component	Planet carrier Bearing (PLC)
	Shaft Bearing
	○ High speed shaft (HSS);
	○ Intermediate shaft (IMS);
	○ Low speed shaft (LSS).
	Carrier Bearing (PL)

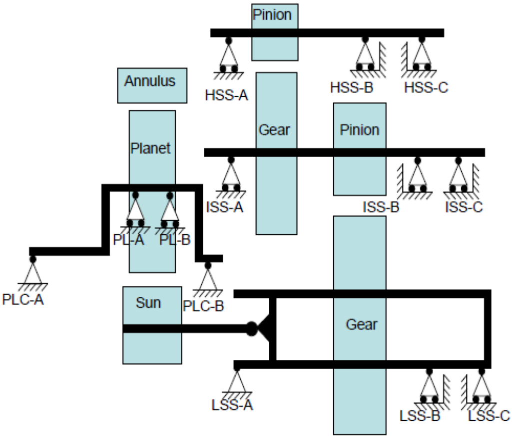

Figure 3. Topology of bearing in a wind turbine gearbox (courtesy NREL 2011).

4.2 *FMEA of gearbox bearing*

Failure mode and effect analysis (FMEA) is a powerful tool for risk and reliability that provides a means of comparing and assessing the system configuration (Tague 2004). This methodology breaks down system to component level and identifies their failure modes and their effects on system function and other system components. FMEA has been used in different industries. The present FMEA is conducted on sub assembly level (bearings) rather than component level since all components in subassembly exhibits same failure modes. It is also assumed that offshore and onshore wind turbine bearings have exactly same failure modes. Table 1 presents detailed FMEA for bearing of offshore wind turbine gearbox.

4.3 *Reliability information acquisition for the similar known system*

In general bearing life can be calculated with supplier models or ISO 281(2007) while operational data are site and design specific. It is assumed that data are available from a known onshore wind turbine system that performs similar functions and has a similar design and structure as the offshore wind turbine system. Secondly, reliability information about the known system must be acquired as much as possible. There are different sources of reliability data for onshore wind turbine like research papers, technical reports, operational data, engineering magazines, etc. which can be used to determine the base failure rate of turbine components.

The present study aims at demonstrating the application of the reliability prediction method on offshore wind turbine gearbox bearing in general and for comparison. Therefore, the use of exact site specific data is beyond the scope of present study. For sake of representation the onshore failure rate of the bearing component corresponding to each failure mode is represented as "λ_i" where $i = 1$ to number of failure modes.

4.4 *Selection of relevant RIFs*

Reliability influencing factors (RIFs) are factors that influence the equipment reliability. A RIFs represents a condition that when changed, produces a positive or negative effect on the reliability of the equipment. The RIFs should be identified and should, as far as possible, be quantified and monitored. The RIFs for bearing in offshore gearboxes are presented in Table 2 are related to; design and manufacturing, operation and maintenance, and environmental factors. The RIFs here are identified focusing on the offshore wind turbine system only. Like RIFs *tower acceleration* (due to waves and current) is characterized only for offshore wind turbines.

In order to get insight related to failures, influencing factors and so, an influence diagram must be

Table 2. Reliability-influencing factors (RIFs).

Category		RIFs
Design and manufacturing		Wind speed/Turbulence
		Quality (manufacturing process, installation, logistics, assembly,)
Operational and maintenance		Improper lubrication
		Accessibility for maintenance
Environmental	External	Temperature
		Tower acceleration
		Corrosive environment
	Internal	Contamination

Table 1. Failure mode and effect analysis of gearbox bearing.

Sub-assembly	Failure modes	Failure causes	Effect
Bearing	Bearing ring creep	Wear	Poor load sharing
	Misalignment	Vibration,	Poor load sharing
		Fracture in groove	
	Loss of function	Contact wear (Scoring)	Power transmission stops/ reduced efficiency
		Scuffing	
		Axial cracking	
		Electrical Damage (Fluting)	
		Fretting corrosion	
		Contact fatigue (spalling/Flanking/pitting)	
		Smearing	
		Brinelling	
	Noise	Vibration,	Reduced efficiency
		Scuffing	
		Fretting corrosion	
	Overheating/seizure	Lack of heat removal	Reduced efficiency

developed. Figure 4 illustrates the potential failure causes and relationship among different RIFs. It is obvious that one RIFs affects many failure causes, but only those with main influences (represented by arrow) are considered. For example *temperature* affects almost all the failure causes but only the causes primarily influenced by it are considered here.

The specific RIFs must next be ranked by experts according to their importance to each failure cause of offshore wind turbine bearings. To each RIF, for a given failure cause should be allocated some weight ε_{kj}. The weights indicate the relative importance of the RIFs and must be scaled such that the sum of all the weights is equal to 1.

For bearings, the number of RIFs is 8 ($k = 1$ to 8) and number of failure causes is 11 ($j = 1$ to 11). The number of RIFs for failure causes is 22 (number of arrows connecting RIFs to Failure causes). In the present study all RIFs are ranked equal and their influences on each failure cause are also considered equal i.e each ε_{kj} (= 1/22 for bearings).

4.5 *Scoring the effects of the RIFs (η_{kj})*

First the relevance of each RIFs is judged by an indicator "ν_{kj}" that can assume binary values from 0 to 1. In the Table 3 the indicator values (0 or 1) for each RIFs against corresponding failure cause are presented against the row "*Relevance*". For example *wind speed/turbulence* is a relevant factor both onshore and offshore, so "ν" assume value 1 both against the corresponding failure causes (like *contact fatigue*), whereas *tower acceleration* is relevant on offshore only so indicator (ν) has value 0 against onshore while 1 against offshore.

The effects each RIFs has on the offshore system are then compared with the effects the same RIFs has on the onshore system. For each failure cause and RIFs, an influence score (η_{kj}) is used to indicate how much higher/lower influence the RIF has on failure cause for the offshore system compared with the onshore system. Seven point scale (+3 to −3) is used here to represent the influence score (η_{kj}), shown in Table 3 against "*Score*". For example, it is believed that *wind speed/turbulence* influence is higher on offshore than onshore so its influence is high "$\eta = 2$" on *contact fatigue*.

4.6 *Weighing the contribution of the failure causes to failure modes (w_{ji})*

How much the failure cause contributes to failure mode for an offshore or onshore wind turbine is specified as a weight "w_{ji}". The failure causes are assumed disjoint, such that the sum of the weights for each failure mode is equal to 1. The bearings have $i = 1$ to 5 failure modes. The weights can be deduced from statistical data from reliability studies or expert judgments, technical reports, operational data, feedback from engineers, knowledge etc.

Table 4 presents different weights assigned to failure causes corresponding to each failure mode. It was observed from literature study that *axial cracking* is major cause of failure followed *fretting*

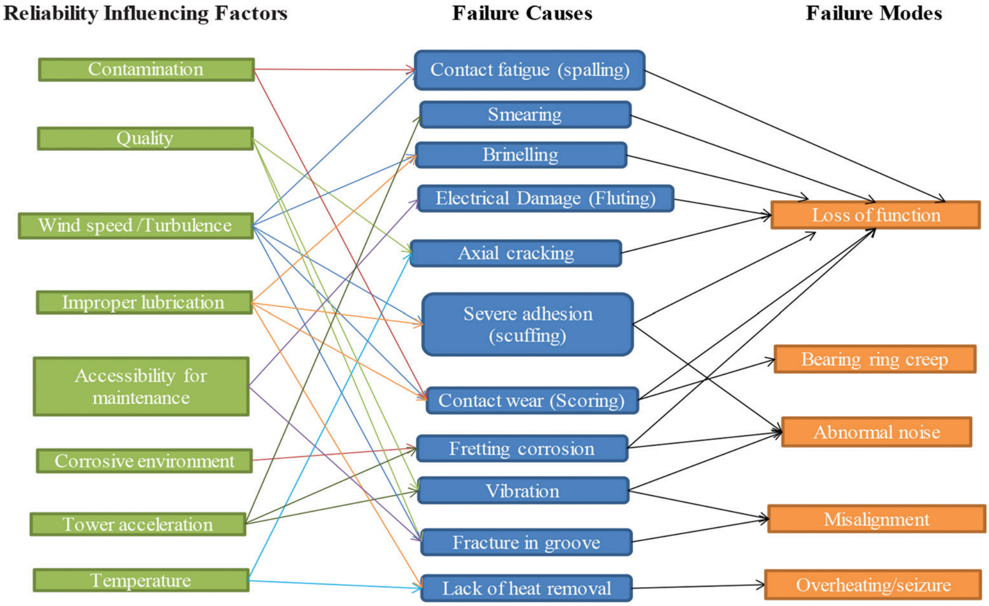

Figure 4. Influence diagram for bearings RIFs, failure.

Table 3. Scoring the effects of the RIFs on bearing failure causes.

				Failure causes										
RIF	Category	Inter-pretation		Contact fatigue (spalling)	Smearing	Brinelling	Electrical damage (Fluting)	Axial cracking	Severe adhesion (scuffing)	Contact wear (Scoring)	Fretting corrosion	Vibration	Fracture in groove	Lack of heat removal
Wind speed/ Turbulence	*Onshore*	20 m/s	*Relevance*	1	0	1	0	0	1	1	0	0	1	0
	Offshore	25–30 m/s	*Relevance*	1	0	1	0	0	1	1	0	0	1	0
			Score	2	0	1	0	0	2	2	0	0	1	0
Corrosive environment	*Onshore*	Normal	*Relevance*	0	0	0	0	0	0	0	1	0	0	0
	Offshore	High	*Relevance*	0	0	0	0	0	0	0	1	0	0	0
			Score	0	0	0	0	0	0	0	0	0	0	0
Improper lubrication	*Onshore*	Normal	*Relevance*	0	0	1	0	0	1	1	0	0	0	1
	Offshore	High	*Relevance*	0	0	1	0	0	1	1	0	0	0	1
			Score	0	0	2	0	0	2	2	0	0	0	2
Contamination	*Onshore*	Normal	*Relevance*	1	0	0	0	0	0	1	0	0	0	0
	Offshore	More	*Relevance*	1	0	0	0	0	0	1	0	0	0	0
			Score	1	0	0	0	0	0	1	0	0	0	0
Temperature	*Onshore*	Normal	*Relevance*	0	0	0	0	1	0	0	0	0	0	1
	Offshore	Little more	*Relevance*	0	0	0	0	1	0	0	0	0	0	1
			Score	0	0	0	0	1	0	0	0	0	0	1
Quality	*Onshore*	Normal	*Relevance*	0	0	0	0	1	0	0	0	1	1	0
	Offshore	Normal	*Relevance*	0	0	0	0	1	0	0	0	1	1	0
			Score	0	0	0	0	0	0	0	0	0	0	0
Tower accelaration	*Onshore*	None	*Relevance*	0	0	0	0	0	0	0	0	0	0	0
	Offshore	Highe	*Relevance*	0	1	0	0	0	0	0	1	1	0	0
			Score	0	1	0	0	0	0	0	2	2	0	0
Accessibility for maintenance	*Onshore*	Easy	*Relevance*	0	0	0	1	0	0	0	0	0	1	0
	Offshore	Difficult	*Relevance*	0	0	0	1	0	0	0	0	0	1	0
			Score	0	0	0	3	0	0	0	0	0	3	0

corrosion and *contact fatigue* for *loss of function* (failure mode) in bearing onshore, hence they are assigned with weight "*w*" 0.15, 0.12 and 0.08 respectively. But *contact wear* and *fretting corrosion* are more predominant failures for *loss of function* (failure mode) in bearings offshore, hence they are assigned with weight "*w*" 0.18 and 0.16 respectively.

4.7 *Determination of the failure rate for similar failure modes*

The failure rates for the failure modes of the offshore system can be determined by adjusting the corresponding failure rates for the onshore system based on the influences of the RIFs. If "λ_i" is the failure rate of the onshore wind turbine bearing corresponding to each failure mode, then using Rahimi & Rausand (2013) approach the failure rate for the corresponding failure mode can be given as:

$$\lambda_i^{(offshore)} = (1 + \kappa_i) \cdot \lambda_i^{(onshore)} \tag{1}$$

where $\kappa_i > -1$ is a constant scaling factor to understand how much various failure causes affect the failure modes of the offshore wind turbine compared with the onshore wind turbine. This influence is determined as a weighted average of the scores of the RIFs given by:

$$\kappa_i = c_i \bullet \sum_{j=1}^{r} w_{ji} \bullet \bar{\eta}_j \tag{2}$$

for $i = 1, 2 \ldots. 5$ (number of failure modes). w_{ji} is given in Table 4. It should be noted that w_{ji} for offshore is to be taken. $\bar{\eta}_j$ is the weighted average of the scores of the RIFs that influence failure causes and it is given by:

$$\bar{\eta}_j = \sum_{k=1}^{p} \varepsilon_{kj} \bullet \nu_{kj} \bullet \frac{\eta_{kj}}{3} \tag{3}$$

for $j = 1, 2 \ldots\ldots r$ failure causes and $k = 1, 2 \ldots. p$ RIFs. $\varepsilon_{kj} = 1/22$ (explained in section 4.4); η_{kj} and ν_{kj} are given in Table 3. It should be noted that ν_{kj} values for offshore are to be used.

The last scaling factor c_i can be calculated as

$$c_i = \begin{cases} 1 - \theta_{\min,i} & when \quad \sum_{j=1}^{r} w_{ji} \bullet \bar{\eta}_j < 0 \\ 0 & when \quad \sum_{j=1}^{r} w_{ji} \bullet \bar{\eta}_j = 0 \\ \theta_{\max,i} - 1 & when \quad \sum_{j=1}^{r} w_{ji} \bullet \bar{\eta}_j > 0 \end{cases} \tag{4}$$

for $i = 1,2\ldots.5$ failure modes.

Table 4. Weighing the contribution of the failure causes to failure modes for bearing.

	Failure causes										
Failure modes	Contract fatigue (spalling)	Smearing	Brinelling	Electrical damage (Fluting)	Axial cracking	Severe adhesion (scuffing)	Contact wear (Scoring)	Fretting corrosion	Vibration	Fracture in groove	Lack of heat removal
Contributing weight onshore											
Loss of function	0.08	0.2	0.08	0.07	0.15	0.1	0.2	0.12			
Bearing ring creep							1				
Abnormal noise										1	
Misalignment						0.2		0.3	0.5		
Overheating/seizure											1
Contributing weight offshore											
Loss of function	0.1	0.2	0.04	0.06	0.14	0.12	0.18	0.16			
Bearing ring creep							1				
Abnormal noise										1	
Misalignment						0.15		0.2	0.65		
Overheating/seizure											1

Table 5. Scaling factors for failure rate prediction.

Failure modes	c_i	$\Sigma w_{ji} \cdot \bar{\eta}_j$	κ_i	$1 + \kappa_i$
Loss of function	0,2	0,0215	0,0043	1,0043
Bearing ring creep	0,2	0,0758	0,0152	1,0152
Abnormal noise	0,2	0,0606	0,0121	1,0121
Misalignment	0,2	0,0409	0,0082	1,0082
Overheating/ seizure	0,2	0,0455	0,0091	1,0091

When calculating failure rates corresponding to each failure mode, the upper and lower bounds values must be assumed. These limits are defined by the two factors θ_{min} and θ_{max}, for each failure mode such that:

$$\theta_{min} \cdot \lambda^{onshore} \leq \lambda^{offshore} \leq \theta_{max} \cdot \lambda^{onshore}$$

The factors θ_{min} and θ_{max}, must be determined by expert judgment, although in the present study they are assumed as $\theta_{min} = 0.5$ and $\theta_{max} = 1.2$.

The abovementioned scaling factors are calculated corresponding to each failure mode and presented in Table 5.

4.8 *Calculation of new total failure rate of the gearbox bearing*

Finally, the total failure rate for the bearing can be calculated from equation:

$$\lambda_{total}^{(offshore)} = \sum \lambda_i^{(offshore)} \tag{5}$$

Though the contributing failure modes to the total failure rate are not completely independent, it is considered the above equation provides a sufficiently accurate approximation.

5 CONCLUSIONS

This paper describes an approach for predicting the failure rate of bearings of offshore wind turbine gearboxes from data available for similar onshore wind turbines. The main failure modes, failure causes and RIFs of a bearing in a wind turbine gearbox are identified. The influence of RIFs on failure causes, and failure causes on failure modes are illustrated showing the relationships among them. The scoring of RIFs against failure causes and failure causes against failure modes are compared for offshore and onshore wind turbines bearings. Few scaling factors are obtained by these scorings based on the assumption that the scaling factors can be used as correction factors for calculating failure rate of the bearing of the offshore wind turbine based on failure rate of similar onshore wind turbines.

This study can be helpful to understand the relation among various failure modes, their causes and factors affecting reliability for bearings.

The illustrated method is subjected to several assumptions and therefore has some limitations. However with more inputs from experts, industry feedback or data, the model can be further enhanced to better predict the failure rates of equipment in offshore conditions.

ACKNOWLEDGEMENTS

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