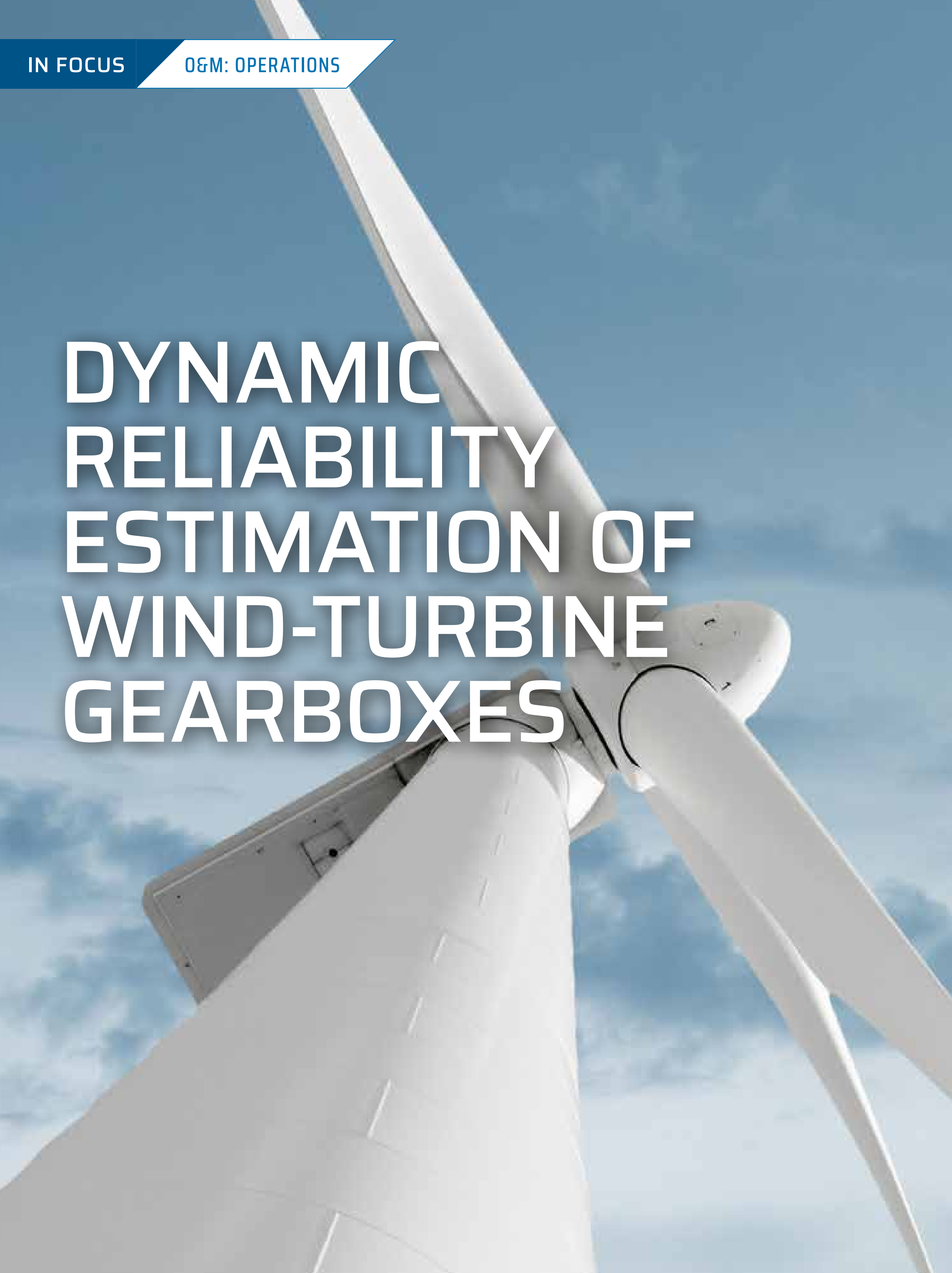

DYNAMIC RELIABILITY ESTIMATION OF WIND-TURBINE GEARBOXES

This study presents a novel method to improve the reliability estimation of wind-turbine gearboxes by using real-time measurements of the operating conditions.

By GEORGO ANGELIS and LAURENS KRUDDE

Wind turbine gearbox often fail to reach their expected lifetime of 20 years. This causes great maintenance costs and unexpected downtime. Similarly, gearboxes that do reach their expected lifetime are often replaced while they might be able to stay in operation for longer, missing out on revenue. There is a need for a reliability estimation based on the operating conditions such that premature failure and extended lifetime risks can be assessed. This work proposes a method to dynamically compute the gearbox's reliability based on real-time measurements of the operating conditions. This is done by introducing the concept of "used capacity," which denotes the accumulated damage on the gearbox during operation. It generalizes the traditional Weibull model by allowing for varying operating conditions that cause damage to accumulate similar to Miner's rule. This results in a more accurate reliability estimate than commonly used static estimates. Furthermore, other key performance indicators such as the mission risk and the remaining useable life can be derived from the model. The approach was tested using synthetic data for a Siemens Gamesa G97 2MW Turbine as part of a research project together with National Renewable Energy Laboratory (NREL) and Siemens Gamesa. Furthermore, the approach was applied to real wind-turbine data from a Penmanshiel wind park. The results demonstrate realistic reliability indicators for the gearbox and its components. Using this result, one can improve maintenance strategies, optimize resource allocation, and assess risk more accurately. Moreover, the approach is adaptable to other types of rotating machinery, offering broad applications beyond wind turbines.

1 INTRODUCTION

Wind energy has become an important component in the global transition to sustainable energy. As wind turbines are increasing in size and capacity, it is becoming more important to ensure the reliability of critical components as failures and downtime become more expensive. From all components in a wind turbine, the gearbox has been shown to be the component that experiences the greatest number of failures [1]. Wind-turbine gearboxes frequently fall short of their expected 20-year lifespan and few make it past the 10-year mark [2, 3]. Wind-turbine gearbox failures are one of the main reasons for significant increase in operation and maintenance (O&M) costs and wind turbine downtime

While there is a wide variety in failure prognostic models, reliability assessments are commonly performed using the L_{10} life formula and the Weibull distribution due to their simplicity and ease of use [4]. The reliability calculation is done using expected average operating conditions such as torque and rotational speed. Based on the expected operating conditions and the time of operation, a reliability estimate can be calculated. However, once a wind turbine is in operation, the operating conditions naturally vary due to wind conditions, grid interaction, and environmental factors. This can lead to deviations from the initial assumed reliability distribution, resulting in an unreliable reliability estimate.

This article proposes a novel dynamic reliability assessment by integrating real-time operational data in a stochastic model. This model introduces a 'used capacity' metric, extending Weibull-based reliability estimation to account for variable operating conditions. By keeping track of the used capacity, an accurate estimate of the reliability can be calculated. Based on the used capacity formulation, additional key performance indicators can be calculated, such as the mission risk and the remaining useful life. The proposed method is applied to real operational data of wind turbines to compare it to traditional methods and to show the application to a wind park. This work aims to provide improved reliability metrics that can be used for predictive maintenance and lifecycle management and ultimately reduce O&M costs for wind turbine operators.

2 BACKGROUND

In this section, we recall the common reliability calculation methods; the L_{10} formula, the Weibull distribution and Miner's rule.

2.1 L_{10} formula

The basic rating life, L10, is the millions of revolutions that the bearing can be expected to endure with 90 percent probability, where failure is defined as the appearance of subsurface material fatigue as per ISO 15243 [5]. In the case of gears, tooth pitting and bending fatigue are considered as per ISO 6336 [6]. The basic rating life, from Lundberg and Palmgren in 1924 as cited by [7], is given by Equation 1:

$$L_{10} = \left(\frac{C_p}{F}\right)^p$$

Equation 1

with C_p the dynamic load capacity, F the load and p the life exponent. The parameters C_p and p are often known from literature (i.e. given by bearing or gear manufacturers) or can be determined analytically or experimentally. The L_{10} formula is an initial estimate for the expected life but cannot provide an adapted estimate during operating.

2.2 Weibull distribution

More generally, it has been found that fatigue life follows a Weibull distribution, as first developed by Weibull in 1939 [7]. Which can be written using L_{10} in Equation 2:

$$P(L > l) = S \quad \text{where} \quad \log(1/S) = AL^k$$

Equation 2

where S denotes the survival probability. Substituting $S = 0.9$ for L_{10} allows us to solve for A and rewrite the Weibull equation (Equation 3):

$$S = e^{(L/\lambda)^k} \quad \text{where} \quad \lambda = \frac{L_{10}}{\sqrt[k]{-\log(0.9)}}$$

Equation 3

The Weibull distribution gives more insight in the failures we expect over the course of an operation. However, the Weibull distribution is only dependent on the number of revolutions and is defined for a fixed load. Varying operating conditions cannot be incorporated in this formulation.

2.3 Miner's rule

Miner's rule is a simple method to incorporate varying operating conditions and calculate the accumulated damage. If L_i is the number of revolutions under load F_i and L_i is the L_{10} at load F_i, then the total damage under n stress levels is seen in Equation 4:

$$D = \sum_{i=1}^{n} \frac{L_i}{L_{10}^{i}}$$

Equation 4

According to Miner's rule, failure occurs when the total accumulated damage D is equal to or exceeds 1. This is clearly a conservative estimate, since only 10% is expected to fail at that point, but large margins are common in engineering design to guarantee successful operation. While Miner's rule has been successful in engineering practice, it has been advised to be extended using probabilistic approaches [8, 9].

2.4 Gearbox modelling

The previous reliability models are suited to model a single component. In order to model the reliability of a gearbox as a whole, the components can be modeled separately and combined to derive reliability model for a gearbox [10, 11]. It is common to consider the reliability of the system, i.e. the gearbox, as the product of the reliabilities of the components. However, the reliabilities of the components can also be modeled as being dependent based on the mechanics of the gearbox [12].

Another approach to estimate the remaining useful life of planetary gearboxes is to use a state space model based on the Gamma process [13].

2.5 Conclusion

While these models provide useful reliability estimates, they assume static operating conditions or a deterministic failure threshold. In reality, wind-turbine gearboxes experience fluctuating loads and failure is a stochastic occurrence. The following section introduces a probabilistic approach that adapts reliability estimation to real-time operating data.

3 METHODOLOGY

This section proposes the reliability calculation based on the used capacity variable. First, the used capacity and reliability calculation is done for a single gearbox component; a bearing. Then, the used capacity notion is extended to a gearbox, being a system of certain components. Lastly, the additional prognostic metrics mission risk and remaining useful life are defined.

3.1 Used capacity metric

In order to incorporate varying operating conditions, we define a new random variable, which we call the capacity and is denoted by C. The capacity combines the operating conditions load and speed in a single variable, similarly to Miner's rule. We define capacity C in Equation 5:

$$C = A^{1/k} L$$

Equation 5

meaning that the bearing can last L revolutions under operating condition A. To incorporate varying operating conditions, we let capacity increment in Equation 6:

$$c^{*} = \int_{0}^{L_f} A_f(L)^{1/k} dL$$

Equation 6

as illustrated in Figure 1. Here, the simplifying assumption from Miner's rule that the order of applied loads has no effect is used.

3.2 Reliability

The way that the used capacity accumulates is similar to Miner's rule. However, we treat the capacity C as a random variable. The Weibull distribution from Equation 2 can be written in terms of capacity in Equation 7:

$$P(C > c) = S \quad \text{where} \quad \log(1/S) = c^k$$

Equation 7

and the reliability of the bearing can be determined based on the used capacity. Important is that the distribution now only depends on the capacity C and not on A and l separately. This allows us to incorporate varying operating conditions.

3.3. Gearbox as a system of components

In the previous sections, we took the example of a single bearing. Now we will generalize to a system of components. For example, a wind-turbine gearbox containing various bearings and gears. Suppose we have n components that define a system such that if 1 of the components fails this implies that also the system fails. In this case the reliability of the system is calculated in Equation 8:

$$S_s = \prod_{i=1:n} S_i$$

Equation 8

Now the used capacity of the system C_s can be computed in Equation 9:

$$C_s = \Big(\sum_{i=1:n} C_i^{k_i}\Big)^{1/k_s}$$

Equation 9

As such, we can define the used capacity of a wind-turbine gearbox and thus calculate its reliability.

3.4 Additional prognostics

The reliability follows directly from the Weibull distribution, but additional metrics can be computed. If the gearbox has been in operation and has exhibited a certain used capacity, then the remaining capacity has a conditional (left truncated) Weibull probability. Formally, the probability of remaining capacity c' with confidence level α after having accounted for evidenced used capacity č is described as follows in Equation 10.

$$P(C \leq \tilde{c} + c' | C > \tilde{c}) = 1 - \alpha$$

Equation 10

This implies that only knowledge of the used capacity č alters the likelihood of the remaining capacity *c'*. Two interesting metrics can be formulated: the mission risk and the remaining useful life, both of which can be determined based on purely the used capacity.

3.4.1 Mission risk

Given some used capacity č and a mission that requires future capacity c', what is the probability α that the bearing can exhibit c' more capacity? We can fix for some capacity c' (the mission) and solve for the probability α. This gives an estimate for the risk of keeping a wind turbine in operation for a certain mission duration.

3.4.2 Remaining useful life

Given some used capacity č and confidence level α. How much capacity c' can the wind turbine exhibit with confidence α? We can fix a confidence level α and solve for remaining useful capacity c'. The most interesting case is the remaining life with 90 percent reliability conditioned on the fact that the bearing has already exhibited a certain capacity. Since L_{10} is often denoted as the useful life of new components, the conditional L_{10} determines the remaining useful life of used components.

Both Remaining Useful Life (RUL) and Mission Risk statements depend on the known used capacity to date and require a prediction into the future, i.e. the capacity needed for the mission or the future operating conditions to estimate RUL in terms of revolutions instead of capacity. The prediction can be based on the expected operating conditions, but can also be done using exhibited used capacity from the past. As such, only the used capacity and its history is necessary to determine all metrics.

4 DATA AND CASE STUDY

Two different datasets, consisting of torque and speed measurements on the wind-turbine rotor, were used to illustrate the proposed method. First, a dataset for a single wind turbine over 20 years was used to compare the proposed method with traditional methods. Second, real measurement data from wind turbines from a 4.5-year-old wind park was used to illustrate its application to a wind park.

4.1.Single gearbox: Synthetic NREL data

A dataset over the course of a wind turbine's typical design life, e.g. 20 years, is appropriate to compare the proposed method with traditional methods. Due to the lack of available data over such a period, a synthetic time series of torque and speed was created based on binned operating conditions. The binned operat-

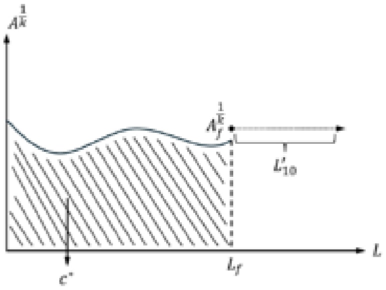

Figure 1. Used capacity accumulation.

Figure 2: Penmanshiel wind-turbine locations on Google Earth [16].

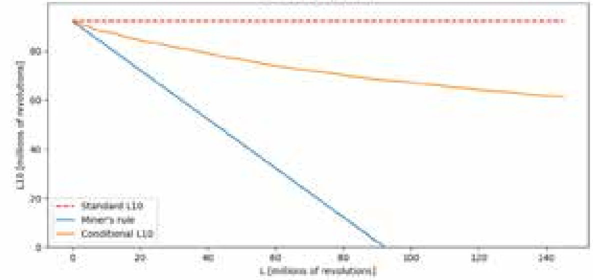

Figure 3: The remaining useful life L10 according to Miner's rule and the conditional L10 from the proposed method based on synthetic data of a wind-turbine gearbox. It shows that a gearbox may have remaining useful life after surviving the initial L10.

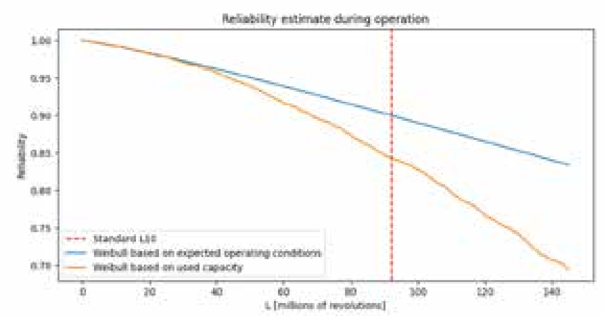

Figure 4: Weibull reliability estimation using the expected operating conditions and the used capacity baed on synthetic data of a wind turbine gearbox. It shows that the reliability estimate based on used capacity takes into account the higher experienced operating conditions.

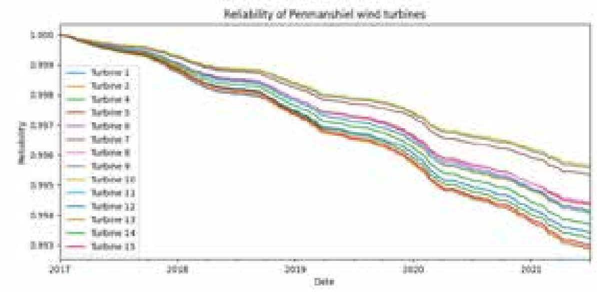

Figure 5: Reliability over time for wind turbines in Penmanshiel wind park, showing how edge turbines degrade faster due to higher loads.

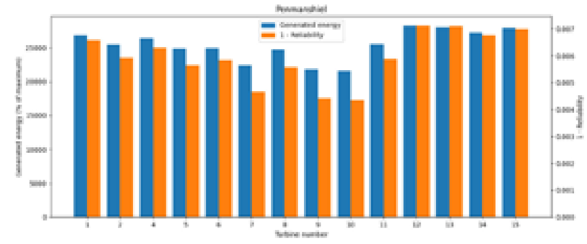

Figure 6: The generated energy and the reliability of the Penmanshiel wind turbines. It shows that turbines with lower generated energy have a larger reliability.

ing conditions were derived from real-time measurements of the operating condition on a Siemens Gamesa G97 2MW turbine as part of a research project together with National Renewable Energy Laboratory (NREL) and Siemens Gamesa, of which these results are a continuation [14]. While the synthetic time series are similar to the binned data, the synthetic data had slightly higher operating conditions.

4.2. Wind park: real-world Penmanshiel data

A dataset of multiple wind turbines is needed to illustrate the different reliability estimates among wind turbines in a wind park as a result of the different operating conditions that they experience. This creates insights that can be used on a wind park management level. As such, the method is applied to open SCADA data of 14 Senvion MM82 2.05 MW wind turbines over 4.5 years from Penmanshiel [15]. Figure 2 shows the relative location of the wind turbines.

5 RESULTS

We present the results for a single gearbox to compare the proposed method with traditional methods and the results for real-world data of a wind park.

5.1 Single gearbox

Figure 3 shows the difference between the traditional L_{10}, Miner's rule and the proposed conditional L_{10}. Since L_{10} is only based on expected operating conditions and not on measurements, it does not change over time. Miner's rule states that failure can be expected after L_{10} is reached. The proposed method is able to calculate the remaining useful life, the life with over 90% conditioned on the accumulated used capacity. It can be seen that, if the gearbox has survived the initial L_{10}, it may still have significant remaining useful life, depending on the accumulated used capacity. This demonstrates the proposed method in providing a more accurate estimation of remaining useful life beyond the initial reliability expectations.

Figure 4 shows the Weibull reliability estimates based on expected operating conditions and based on the synthetic operating conditions for a single gearbox. It can be seen that the reliability estimate based on expected operating conditions perfectly crosses the L_{10} line at 90 percent reliability, as the L_{10} is also determined based on expected operating conditions. The proposed method incorporates the experienced operating conditions, and it can be seen that the estimates decrease faster or slower based on these experienced operating conditions. Furthermore, it can be seen that reliability estimate based on the used capacity decreases faster than the initial Weibull estimate, because the synthetic operating conditions were higher than the expected operating conditions.

5.2 Wind park

Figure 5 illustrates the reliability trends across the gearboxes of the 14 turbines in the Penmanshiel wind park. It can be seen that similar patterns are visible for all turbines, which is what one would expect since the turbines are experiencing similar wind conditions. However, the reliabilities start to diverge over time. Comparing this to the location of the turbines in Figure 2, it is clear that the turbines at the edge of the wind park are experiencing higher operating conditions, as they are more exposed to wind inflow. In contrast, the turbines in the centre are catching reduced wind, leading to lower operating conditions and thus slower decrease in reliability.

Figure 6 shows the generated energy and the failure probability (1 — reliability) of the turbines after 4.5 years. As expected, it can be seen that the turbines that have generated more energy have lower reliability due to increased accumulated stress on the gearboxes. The relationship between energy production and reliability follows an exponential trend, and it can be seen that turbines with lower cumulative energy output exhibit disproportionately higher reliability. This is a direct consequence of the life exponent in the L_{10} formula.

These variations in reliability suggest that a wind park operator can optimize the distribution of reliability across the fleet by strategically managing turbine exposure to wind.

For instance, reducing the workload on turbines with higher accumulated used capacity while allowing other turbines to operate under increased loads can help balance failure risk and maximize overall uptime and energy production.

6 DISCUSSION

This method forms the basis for a new reliability estimate, but some assumptions and limitations should be mentioned. First, this method estimates wind-turbine gearbox reliability based on fatigue failure due to wear on the material. Bearing failure is defined as subsurface fatigue appearance, and gear failure is defined by root pitting or bending fatigue, as per ISO standards [6, 5]. It does not account for early failures or other failure modes such as misalignment, lubrication issues, or material defects.

Also, failure of one component is considered as failure of the whole gearbox and therefore operation with a partially faulty gearbox is not considered. Faulty components would increase the stress on other components and the gearbox as a whole, which complicates a reliability model, but inspiration can be taken from [12]. Second, the reliability estimate relies on measured torque and speed data, making the accuracy dependent on data quality.

Uncertainty in measurements induces uncertainty in the reliability estimate. This uncertainty could be modeled, but it is advised to ensure accurate measurement data. Lastly, it should also be noted the current approach only considers torque on the gearbox carrier, capturing torque-induced loads but ignoring non-torque loads, i.e. disturbance forces, that also contribute to fatigue. Future work should incorporate these additional forces acting on the gearbox, if measurable.

7 CONCLUSION

This study presents a novel method to improve the reliability estimation of wind-turbine gearboxes by using real-time measurements of the operating conditions. By introducing the concept of "used capacity," the proposed approach generalizes traditional Weibull distribution models, making them adaptable to varying conditions that a gearbox experiences over time.

This method provides accurate predictions of key performance indicators such as reliability, mission risk and remaining useful life. This can be the basis for better maintenance strategies and extended operational lifetimes for wind turbines. The application of synthetic data demonstrates the method's effectiveness, laying a foundation for future implementation in real-world scenarios. Future work could extend this approach to other rotating machinery applications, such as offshore turbine drivetrains.

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