Anomaly-Based Fault Detection in Wind Turbine Main Bearings

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Response to reviewers

General comments of the authors

Dear Editor and the Reviewers,

We sincerely thank you for your constructive comments. Under the reviewers' comments and suggestions, the manuscript has been significantly strengthened both in contents and clarity. Below, you can see the changes that we made in response to each reviewer's comment.

The editor and reviewers found the paper of interest, yet they felt that several issues needed to be improved and clarified before the paper could be accepted for publication. In the revised manuscript:

- The changes made in response to Reviewer 1 are marked in blue.
- The changes made in response to Reviewer 2 are marked in red.
- The changes made in response to Reviewer 3 are marked in brown.

Reviewer 3

The authors developed a method to detect wind turbine main bearing failures in an early stage, hence the work fits good to the scope of the journal. They used an anomaly detector based on principal component analysis to detect failures of a main bearing with the help of SCADA data. To train the model and to evaluate the results they used the data of 18 turbines.

The structure is clear, and the steps are described in detail. The overall quality is very good, some minor suggestions in the technical comments may help to improve it a little bit.

It is perfectly fine that the focus is on the model, the selection of data and data processing. Nevertheless, in my opinion the technical background could be highlighted more.

Author's reply: Thank you for taking the time to review our paper. We are glad to hear that you find our work relevant to the scope of the journal and that the structure and description of the steps are clear. We also appreciate your positive comments on the overall quality of our work.

Regarding your suggestion to highlight the technical background more, we agree that it is an important aspect of our work. We revised the manuscript to better explain the underlying concepts and methodologies.

We acknowledge your suggestions for discussing certain aspects of the work in greater detail. We will address them in this point-by-point answer to the suggestions given for improvement.

Special comments

E.g. the work of Carrol et. al. (DOI: 10.1002/we.1887) could help to underline the importance to prevent failures and downtimes.

Author's reply: Thanks for bringing this issue to our attention. In our revised manuscript, we included in the Introduction Section a discussion of the importance of early detection of wind turbine main bearing failures in reducing downtime and maintenance costs. We referenced the work of Carrol et al. as an example of related research in the field. In particular, the following paragraph has been added to the revised manuscript.

> Early detection of main bearing failures of wind turbines is crucial to guarantee the reliability of the element, as well as a safer and more efficient operation in wind farms. The main bearing is one of the most critical components in a WT, and a failure in it can cause significant damage to other components, such as the gearbox, generator, and blades, and result in downtime and expensive repairs, see Carrol et al. (2016). Early detection of main bearing failures enables predictive maintenance, giving maintenance crews time to plan and schedule repairs during low wind periods, minimizing the impact on energy production.

To give technical details of a WT is not necessary. In my opinion the power curve in figure 1 does not give any contribution to this work. The lines from 97 to 102 could be deleted. Here a reference to other publications like Hansen would be possible as well. However, the authors do not give information about main bearings. Possible questions are: Which kind of suspension do the turbines have? Why do I need a bearing and what are possible bearing types? Maybe its not necessary to explain it in detail, but at least a reference would be welcome (Wenske 2022 DOI: 10.1049/PBPO142F or Hau . . . .). A cross reference to figure 2 can be done, too.

Author's reply: We appreciate your suggestion that the power curve may not be necessary for this work and agree that a reference to other publications may be more appropriate. Therefore, we removed the lines from 97 to 102 of the original manuscript and referenced Hansen's work in our revised manuscript.

We understand the importance of streamlining the manuscript to focus on the core contributions of our research and appreciate your input in this matter. In particular, the following paragraph was added in Section 2.

> Technical details of the wind turbines under study are out of the scope for the analysis presented in this paper. However, it should be noted that wind turbine design and operation can impact the performance of fault detection methods. The book of Hansen (2015), on the aerodynamics of wind turbines, provides a comprehensive overview of wind turbine design and operation, including factors that can impact the accuracy of fault detection methods. Therefore, we encourage readers who are interested in the technical details of wind turbine design to refer to this resource.

In regard to the main bearing given information, we appreciate your suggestion that additional information or a reference to relevant literature would be beneficial. In response to your feedback, the following paragraph has been added in Section 2.

> Regarding the drivetrain configuration, three-point and four-point suspensions, which refer to one or two main bearings, respectively, are the most common wind turbine drivetrain architectures. In the three-point suspension configuration, which is the one used in the wind farm under study, the rotor is rigidly connected to the main shaft, which is supported by a single main bearing near the rotor. A shrink disk typically connects the downwind side of the shaft to the low-speed stage of the gearbox. The gearbox is supported by two torque arms that are connected to the bedplate elastically. These two torque arms, along with the single main bearing, provide a total of three points of support. Furthermore, there are different types of state-of-the-art main bearings, as fully explained in Wenske (2022). In particular, the turbines of this park are equipped with the so-called spherical roller bearing (SRB) type. SRBs are characterized by their outer raceways being a portion of a sphere. The rollers, in turn, are shaped so that they closely conform to the inner and outer raceways. This results in a bearing that is internally self-aligning and has a high radial load carrying capacity, please see Hart et al. (2019) for a more detailed explanation.

There are plenty of possible bearing damages (fatigue, wear cracks… they can occur at the rings, raceways, rollers or at the cage) which can have an effect on the bearing lifetime. This is not considered. Here I can recommend e.g. the work of Hard like DOI: 10.1002/we.2386. As a reference about bearing damages e.g. the work from Harris and Kotzalas could be used. The fact that just one main bearing failure occurs in the data, may raise the question if other main bearing failures can be detected. At least in the discussion or in the outlook I would expect a discussion on that.

Author's reply: Thank you for your comments on the potential different types of bearing damage and locations. In response to your feedback, we included a brief discussion in the manuscript on the possible bearing damage modes, such as fatigue, wear, and cracks, and their impact on the bearing lifetime. We referenced the works of Hard (DOI: 10.1002/we.2386) and Harris and Kotzalas to provide additional information on these topics. In particular, the following paragraph has been added to the Introduction Section.

> Bearing damage in wind turbines can occur in different locations, including the rings, raceways, rollers, and cage. The most common types of bearing damage are related to heat release, which can result from friction, wear, and cracks, see Harries et al. (2006). All of these damage modes can significantly impact the lifetime of the bearing, which in turn can cause significant downtime and maintenance costs. Early detection of bearing damage through monitoring and detection of heat release can allow for timely repairs and maintenance, minimizing the impact on the bearing and other components, and reducing downtime and maintenance costs. The methodology proposed in this work aims to detect heat release in the bearings, allowing for early detection and diagnosis of potential bearing damage.

Furthermore, in the Results Section the following paragraph has also been added (highlighted in red color as Reviewer 2 also commented on this issue).

> It is significant that the proposed approach is designed specifically to detect (using only standard SCADA data, which are usually 10-minute averaged) the possible heat generated from an initial failure mode, such as the initiation or propagation of the crack, friction, electrical discharge and other failure modes associated with heat release. These types of failure typically result in a gradual and sustained increase in temperature (while they evolve), rather than sudden spikes or drops, which makes them detectable even with low sampling rates, as temperature variables have a low dynamic and still contain the information of the fault after being 10-minute averaged.

Regarding the occurrence of only one main bearing failure in our dataset, we acknowledge that this may raise questions about the generalizability of our approach in detecting other main bearing failures. We addressed this concern in the revised manuscript by including the following paragraph in the Conclusions Section.

> The results demonstrate that the stated approach is effective in detecting a main bearing fault that resulted in a significant increase

> in temperature. Although only one failure was available in the investigated wind park data, which is insufficient for statistical analysis, any bearing fault leading to heat release might be detectable by the proposed strategy. However, to more extensively investigate the performance of the model, it is necessary to apply the model to other wind parks with main bearing failure issues. Therefore, future work will test the model on a larger dataset to assess its performance in different scenarios and draw more generalizable conclusions.

The mentioned counteractions to prevent a bearing failure after detection stay very vague.

Author's reply: Thank you for your comment about the counteractions to prevent a bearing failure after detection. In response to your comment, the following paragraph was added (in red color as this issue was also commented by Reviewer 2) to the Results Section of the revised manuscript.

> Note that after peaks (Figure 11, WT5), the signal drops sharply again for a long period. This is because the heat created from an initial failure mode (heating from an initial crack, friction, wear,...) is detected by the methodology, but its appearance is not continuous over time until the final breakdown. In contrast, when the failure mode advances, for example, when a crack propagates, the generated heat appears. When the crack remains still, no further heat is generated; thus, the alarm is set off. However, cracks are already present and can advance at any time, leading to the possible failure of the component. Thus, in this methodology, whenever the alarm is on (even when it is set off after a few weeks), it is highly recommended to check the specific WT.

Technical comments
In Table5 and figure 5 units are missing.

Author's reply: Thank you for pointing out that units are missing in Table 5 and Figure 5. We apologize for this oversight. We ensured that the missing units are included in the revised manuscript.

In figures 11, 12, and 13 a same y-axis scale would make it easier to compare the individual turbines.

Author's reply: We appreciate your feedback and understand your suggestion of using a consistent y-axis scale for comparison. However, we decided to use different y-axis scales for each figure as the models were trained on data with different characteristics and had different ranges of normal and faulty data. Using a consistent y-axis scale could potentially cause misleading visual comparisons of the data.

We have, however, kept the threshold value in the same position in each figure to provide a clear comparison between the actual and predicted values of each turbine, making it easier to see whether a turbine is operating normally or has a fault. The position of the threshold value is independent of the y-axis scale and is used to classify the data points, making it a crucial reference for the reader.

We hope that this explanation clarifies our reasoning for using different y-axis scales but maintaining the same position for the threshold value in each figure. If you have any further suggestions or comments, please let us know.

To reduce the number of plots it could be a good idea to summarize a few turbines in one plot. Different colors could be used.

Author's reply: Thank you for your suggestion to summarize multiple turbines in one plot and use different colors. While we appreciate your idea, we would like to keep one plot per wind turbine for the sake of clarity and ease of interpretation. Our aim is to provide a clear and detailed presentation of each turbine's performance, and we believe that this would be better achieved through individual plots. By doing so, readers can easily compare the performance of each turbine and identify any differences or patterns that may arise.

Sometimes shorter sentences would increase the legibility. As one example would separate the sentence (in line 326) after the first date.

Author's reply: Thank you for your suggestion to use shorter sentences for improved legibility, and for highlighting the sentence in line 326 as an example. We will separate the proposed sentence and also thoroughly review the entire manuscript to identify and address similar issues to ensure that the text is presented in a clear and concise manner.

Finally, we would like to thank the reviewer for the valuable feedback and the time to review the paper.