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 1

The manuscript entitled "Anomaly-Based Fault Detection in Wind Turbine Main Bearings" deals with a very interesting topic, which is perfectly adequate for the scientific objectives of the journal.

In a nutshell, the authors propose a PCA-based alarm raising method for diagnosing incoming damages to the main bearing of wind turbines. The method is based on SCADA data mining.

The work is well written and well presented. The workflow is very clear and presented in detail, such that it can be replicated by scholars.

The peculiarity of the work is that only exogenous variables (environmental) and the temperature of the component of interest (main bearing) are employed.

Therefore, in general I have a very positive opinion on this work. Nevertheless, there are some aspects which could be discussed more in deep.

Author's reply: Thank you for the positive feedback on the manuscript entitled "Anomaly-Based Fault Detection in Wind Turbine Main Bearings". We are grateful to hear that you consider the topic to be both interesting and well-suited to the scientific objectives of the journal. We also appreciate your comments regarding the clarity and replicability of the workflow, as well as the use of exogenous variables and temperature exclusively in the proposed method. Finally, 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.

1. A considerable number of studies has been recently devoted to this topic. Therefore, I recommend that the authors highlight more clearly the innovative contribution and the points of strength of their work.

Author's reply: We appreciate your suggestion to highlight the innovative contribution and strengths of our work. In particular, the following paragraph has been added in the Introduction Section.

> Although the topic of fault detection in main bearings of wind turbines has been the focus of numerous studies, as can be seen from the aforementioned references, in this paper a novel approach to this problem is presented based on principal component analysis (PCA) and data mining of only SCADA data. It should be emphasized that the stated methodology relies only on exogenous variables (ambient temperature and wind speed) and the temperature of the main bearing (internal variable most related to the target component, the main bearing), facilitating to isolate the faults that influence that one internal variable. In addition, all variables used in the strategy are readily available in all industrial-size wind farms (both older and newer), making it a practical and cost-effective solution for early fault detection.

2. The authors employ almost three years of data for model training. For the necessities of real-time wind farm monitoring, it is not obvious that such amount of healthy data is available. Could the authors discuss their models' performance with shorter training data sets? I suggest the following reference: Turnbull, A., Carroll, J., & McDonald, A. (2022). A comparative analysis on the variability of temperature thresholds through time for wind turbine generators using normal behaviour modelling. Energies, 15(14), 5298

Author's reply: We appreciate your suggestion to examine the performance of our method with shorter training data sets. In response to this comment, the following paragraph has been added to Section 3.1 in the revised manuscript.

> It is acknowledged that the availability of almost three years of data

may not always be feasible. However, a data length of this magnitude was deemed necessary to fully capture the normal operating behavior of the main bearing and to establish a reliable baseline for fault detection. It was observed that when using one year of training data, the results were similar, but when the training data was reduced to only six months, the method was incapable of learning a normality model robust to all wind turbine operating scenarios, see Turnbull et al. (2022). Therefore, for the proposed approach, a minimum of one year of data is strongly recommended, and the methodology will significantly benefit from two or three years of available data.

Furthermore, the results for one year of training data, and only six months of training data are shown in Figures 1 and 2. These figures have not been incorporated into the manuscript, given that their inclusion would not suffice to provide a comprehensive analysis of the impact of distinct training periods. On the other hand, such analysis falls beyond the scope of the paper.

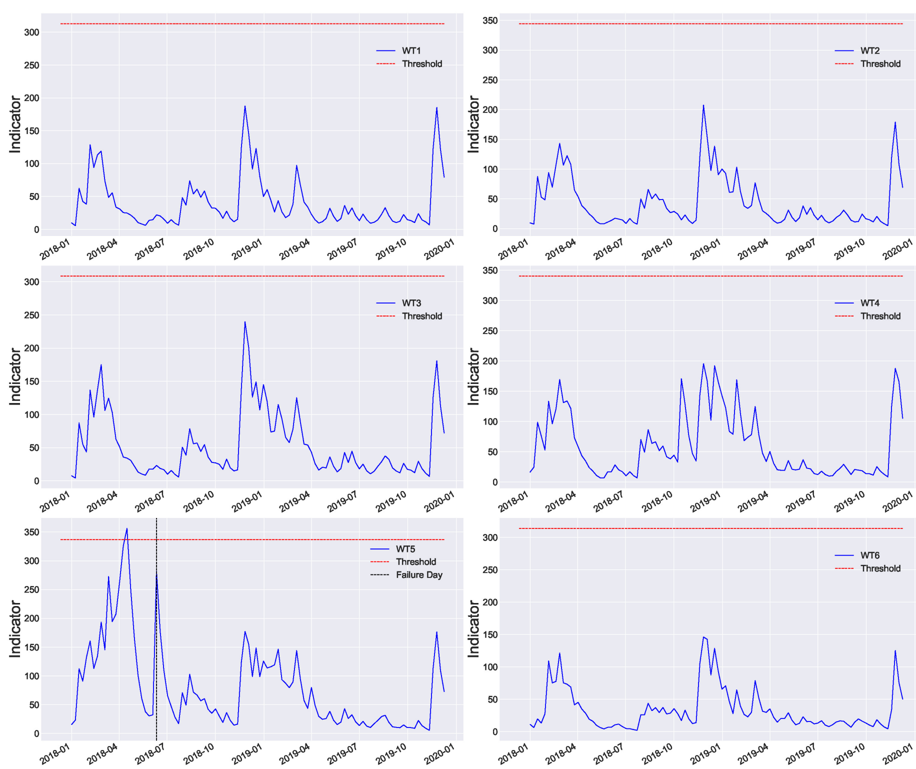

Figure 1: Results for WT1 to WT6 using one year of trainig data.

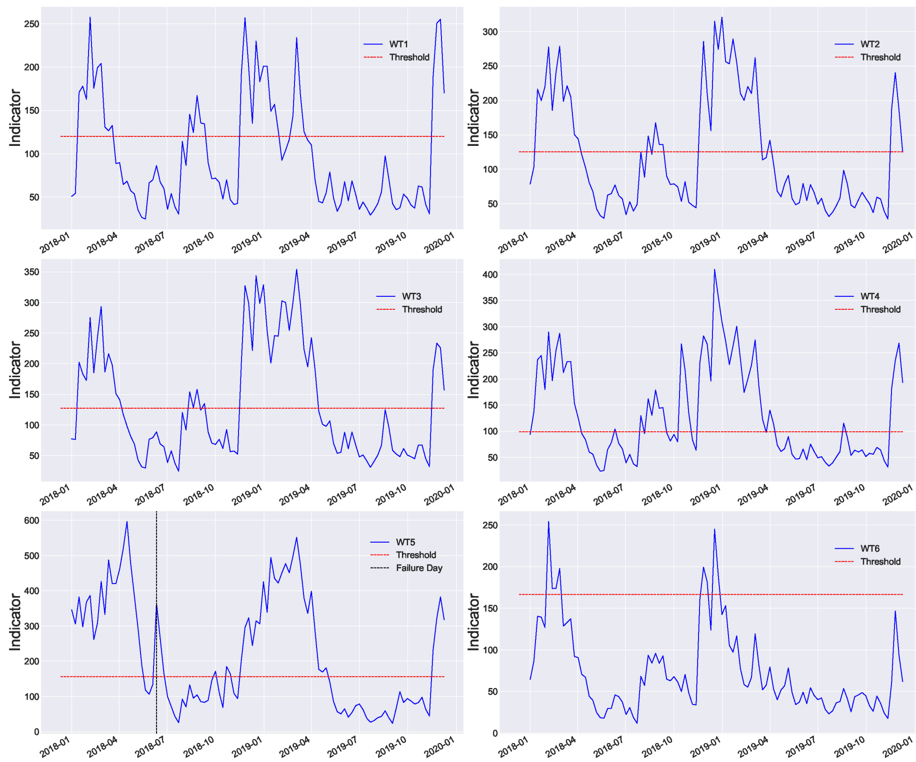

Figure 2: Results for WT1 to WT6 using six months of training data.

3. The authors obtain a result similar to that obtained, for example, in the recent paper Murgia, A., Verbeke, R., Tsiporkova, E., Terzi, L., & Astolfi, D. (2023). Discussion on the Suitability of SCADA-Based Condition Monitoring for Wind Turbine Fault Diagnosis through Temperature Data Analysis. Energies, 16(2), 620. The main bearing temperature is the most adequate target to monitor for raising an alarm, but there is an issue related to the capability of the model in locating adequately the fault. In this work, using the main bearing temperature, a fault regarding the main bearing itself and a fault regarding the gearbox are diagnosed similarly. This occurs also in the paper which I have indicated. Therefore, I am wondering if the authors have ideas for further developments regarding the issue of precise fault location.

Author's reply: Thank you for drawing our attention to the excellent recent paper "Discussion on the Suitability of SCADA-Based Condition Monitoring for Wind Turbine Fault Diagnosis through Temperature Data Analysis" by Murgia et al. In this work, as well as in our study, the main bearing temperature was found to be a suitable indicator for detecting faults in wind turbines. However, we acknowledge the issue you raised regarding the capability of the model in precisely locating the fault. As not being able to adequately locating the fault is a clear limitation of the proposed methodology, in the revised manuscript we added the following paragraph in the Conclusions Section together with a reference to Murgia et al. paper.

> While the main bearing temperature was found to be a suitable indicator for detecting faults in wind turbines, as also stated in a recent paper by Murgia et al. (2023), another limitation of the proposed approach is that it cannot precisely locate the fault or its severity. Further developments could be pursued in this direction, for instance, by incorporating high-sampling data and/or additional sensors to improve the precision of the fault location. However, this may come at the cost of increased complexity and expense, which is trying to be avoided in this work where the main objective is to contribute a cost-effective solution where all variables used are readily available in all industrial-size wind farms (both older and newer).

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