Energy Reports 9 (2023) 3273–3281

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Reliability of electrical and hydraulic pitch systems in wind turbines based on field-data analysis

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ARTICLE INFO

Article history:
Received 7 July 2022
Received in revised form 27 September 2022
Accepted 4 February 2023
Available online 15 February 2023

Keywords:
Wind turbines
Reliability analysis
Pitch system
Failure rate
Field data

ABSTRACT

The pitch system is notably one of the critical subsystems of a wind turbine, supporting its effective control towards maximising wind capture and at the same time protecting its integrity in cases of excessive loads. A pitching mechanism is also responsible for operational downtime, hence its reliability performance needs to be carefully evaluated so as to ensure operational availability. This study aims to derive failure rates of two configurations of pitch systems, namely the electrical and hydraulic, based on statistical analysis of a large population of onshore assets, followed by a classification of findings by turbine rating, effect of seasonality, and reliability performance of different manufacturers. The data sets underlying the present analysis are based on maintenance reports and comprise 1847 operational years of wind turbines with electrical and 848 operational years of turbines with hydraulic pitch system. Results of this study show high failure rates in pitch systems of both types, with hydraulic systems performing slightly better than electrical (0.54 vs. 0.56 failures per turbine per year), a significant variation between turbines of different manufacturers, and a tendency for higher failure rates for larger turbines.

1. Introduction

With increasing deployment of wind energy and especially with the rapid development of offshore wind farms, it is crucial to reduce operation and maintenance (O&M) costs of wind turbines. Since O&M costs sum up to 25% to 40% of levelized cost of energy (LCoE), reliability is one of the main levers for further LCoE reduction (Shafiee et al., 2016; Ioannou et al., 2018).

Several reliability studies have been conducted in the past. A comprehensive overview of available reliability data is given in Cevasco et al. (2021) and Pfaffel et al. (2017). The pitch system has been identified as one of the most critical sub-systems of a wind turbine (WT) with regard to failure rate and downtime, see e.g. Gayo (2011), Carroll et al. (2016) and SPARTA (2017). The RELIAWIND project analysed a data set covering 373 WTs with 1115 operational years and found the pitch system to be the main contributor to the overall failure rate of the WTs with 22% (Gayo, 2011). In addition, within the project a Failure Modes Effects & Criticality Analysis (FMECA) was performed in order to determine the most important failure modes of the critical sub-systems. Carroll et al. published a reliability study analysing around 350 offshore WTs with over 1768 WT years of operation and found the sub-system “pitch/ hydraulics” to stand out with most failures per WT per year (Carroll et al., 2016). The System Performance, Availability and Reliability Trend Analysis (SPARTA) initiative identified the blade adjustment system with the second highest monthly repair rate analysing 1045 offshore WTs located in UK waters (SPARTA, 2017). In comparison, a study from Moog and DNV GL conducted a specific pitch system failure analysis including electrical and hydraulic pitch systems and failure rates for different subsets of data were determined based on a data base of 1330 WTs from North America, Europe and China (Padman et al., 2016). However, most of those studies used data which had been recorded before 2010. Moreover, neither these system-level studies nor the pitch-system specific study presented by Padman et al. (2016) differentiate between hydraulic and electrical pitch systems or analyse underlying failure patterns and related failure rates of the pitch systems' components. At the same time, understanding which failure modes drive the failure rate is key to develop countermeasures. Therefore, this work presents a deepened reliability analysis of both electrical and hydraulic pitch systems including failure rates of the respective components.

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https://doi.org/10.1016/j.egyr.2023.02.007

Table 1
Information about the data sets considered in the analysis.

	Electrical pitch system	Hydraulic pitch system
WT operational years considered	1847	848
Number of WT OEMs covered	6	3
Rated capacity considered	500–6000 kW	600–3000 kW
Available failure data period	2006–2015	2013–2017

Additionally, temporal patterns are investigated to gain further insights into the failure behaviour. Outcomes of this work will be of value to further researchers and practitioners who aim to evaluate and optimise design and operational management of wind turbines, as well as for supporting further technological improvements of next generation pitch systems. Obtained failure rates can be utilised for O&M simulation tools such as the Operation and Maintenance Cost Estimator (OMCE) of the Energy Research Center of the Netherlands (ECN) (Braam et al., 2009), the Norwegian Offshore Wind cost and benefit (NOWIcob) tool presented by Hofmann and Sperstad (2013), the openO&M tool (Kolios et al., 2019), or OffshoreTimes, a simulation tool developed by the Fraunhofer Institute for Wind Energy Systems IWES (Wiggert et al., 2018).

Modern WTs use pitch regulation to control operations. Pitch systems allow changing the blade pitch angle dependent on incoming wind speed. From cut-in wind speed to rated wind speed, the pitch angle is adjusted actively so that optimal power output is achieved. From rated wind speed onwards, power production is limited by rotating the rotor blades out of the wind. Therefore, the pitch system is not only responsible for maximising power output but also functions as an aerodynamic break. Due to safety requirements, there is a pitch system for each blade axis and the systems are entirely independent. There are electrical and hydraulic pitch systems: Electrical pitch systems can be divided into AC or DC systems which drive the pitch motor. In case of interruption of voltage supply, batteries feed the system to guarantee that the WT can be stopped by pitching the blades out of the wind. In comparison, hydraulic pitch systems are driven by hydraulic cylinders. Additional components ensuring its operation are hydraulic valves, accumulator units and oil tanks. A further description of both systems can be found in Hau (2013).

The paper is outlined as follows: First, an introduction of the used methods is given and the analysed data set is described (Section 2). Afterwards, the paper presents findings of a deepened statistical analysis for WTs with electrical and hydraulic pitch systems and compares those with previously published results of field-data analysis summarised above. Next to failure rates of the pitch systems' components for different subsets, seasonal patterns are evaluated (Section 3). Last, a summary of main conclusions as well as an outlook to future work are given (Section 4).

2. Methodology and data sets

2.1. Methodology

Within this study, a failure is defined as a fault that leads to downtime of the wind turbine and is not resettable remotely but requires maintenance and the use of spare parts. In case repeated maintenance activities are needed to resolve the same technical problem, the activities are assigned to one failure event. The failed components are classified using the reference designation system RDS-PP for wind turbines (VGB PowerTech, 2014). From all maintenance measures recorded for a wind turbine only maintenance events which are related to the pitch system are analysed in this study.

In order to compare the reliability of different components, their average failure rates are calculated as follows:

$$f = \frac{\sum_{i=1}^{I} N_i}{\sum_{i=1}^{I} X_i T_i} = \frac{N}{T} \tag{1}$$

Herein, N_i is the number of failures of the analysed component in the time interval i, X_i is the number of WTs considered in this time interval and T_i is the duration of the time interval. Therefore, the average failure rate is equal to the quotient of the sum of all failures N and the total amount of analysed WT operational years T.

Additionally, the corresponding confidence intervals are determined to quantify the uncertainty of the calculated failure rates resulting from the size of the data sets (Bain and Engelhardt, 1991; Fischer et al., 2019b):

$$\left[\frac{\chi^2(\frac{\alpha}{2}, 2N)}{2T}, \frac{\chi^2(1-\frac{\alpha}{2}, 2N+2)}{2T}\right] \tag{2}$$

Herein, $\chi^2(\alpha/2, 2N)$ is the $(\alpha/2)$-quantile of the χ^2 distribution with $2N$ degrees of freedom. In this paper $\alpha = 0.1$ is used so that the 90% confidence intervals are provided. These can be interpreted as follows: If a large number of samples (in this case failure data sets of WTs) would be analysed, in 90% of the cases the given confidence intervals would cover the real value of the failure rate.

2.2. Data sets

The data sets underlying the present analysis are based on maintenance reports and comprise 1847 operational years of WTs with electrical and 848 operational years of WTs with hydraulic pitch system. All WTs are located onshore. Detailed information about the data sets is presented in Table 1. While for the electrical pitch system data from turbines of six different original equipment manufacturers (OEMs) with turbine capacities ranging from 500 to 6000 kW are considered, for the hydraulic pitch system data from turbines of three different manufacturers with capacities from 600 to 3000 kW are evaluated. A total number of 2695 WT operational years stemming from 1022 WTs is underlying the present study.

3. Results and discussion

3.1. Comparison of failure rates for hydraulic and electrical pitch systems

3.1.1. Electrical and hydraulic pitch system comparison

Figs. 1 and 2 present the resulting component failure rates along with the overall pitch-system failure rates for the electrical and the hydraulic pitch systems, respectively. For the presentation of results, component categories are chosen based on frequency of failure and level of detail of the available maintenance reports. All pitch-system components that do not fail often and are of no specific interest for the analysis are summarised in "Other Components". Note that the sum of the component failure rates is higher than the overall failure rate of the system, as there are failure events involving the exchange of components from several categories.

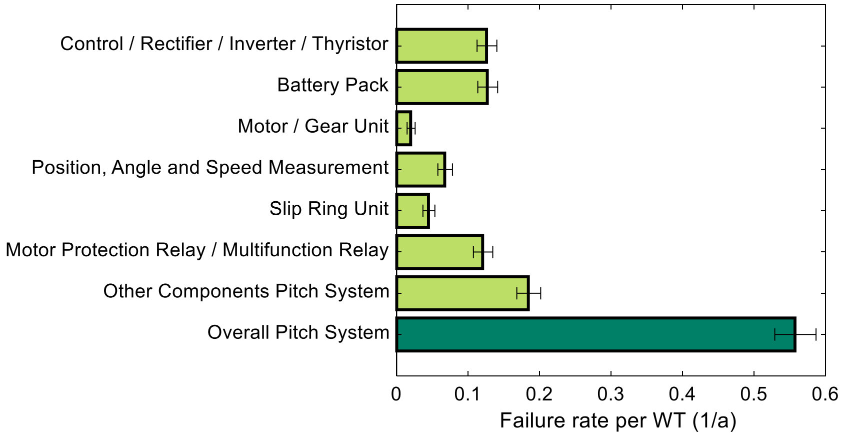


Fig. 1. Average failure rates of the electrical pitch system.

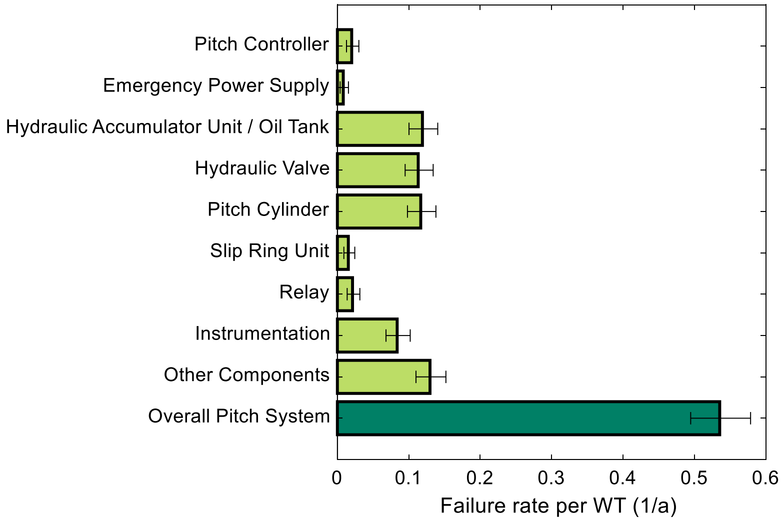


Fig. 2. Average failure rates of the hydraulic pitch system.

The results confirm the occurrence of high failure rates in pitch systems of both types. With 0.54 failures per WT and year, the overall failure rate of the hydraulic pitch system is slightly lower than that of the electrical pitch system with 0.56 failures per WT per year. However, due to overlapping confidence intervals, there is not sufficient evidence to conclude that hydraulic pitch systems are more reliable than electrical pitch systems. While for the electrical pitch system the component categories “Battery Pack”, “Control/ Rectifier/ Inverter/ Thyristor” and “Motor Protection Relay/ Multifunction Relay” are identified as most critical, the hydraulic pitch system shows the highest failure rates in the component categories “Hydraulic Accumulator Unit/ Oil Tank”, “Pitch Cylinder” and “Hydraulic Valve”. This highlights that main concerns of the hydraulic pitch system are related to the hydraulic system itself. An interesting finding in the context of electrical pitch systems is that, in contrast to the main power converters of WTs where power electronics are subject to frequent failure (cf. Bartschat et al., 2018; Fischer et al., 2019b), they are only a minor contributor to failure of pitch systems. A possible explanation for that could be the significantly lower rated power of the pitch drives. A more sophisticated design better withstanding the harsh environmental conditions could be another reason.

3.1.2. Comparison with literature

When comparing those results with the reliability studies mentioned in the introduction, similarities can be identified. While the RELIAWIND project provides only normalised failure rates, the study by Padman et al. (2016) found an average failure rate of 0.7 per WT per year for a combined data set of 545 WTs with electrical and 785 WTs with hydraulic pitch system all being installed onshore. This number is slightly higher in comparison to the average failure rates presented above even when considering the confidence intervals. Also (Carroll et al., 2016) have identified a higher failure rate of 1.076 failures per WT per year. However, the comparison can only be made with caution since Carroll et al. used a sub-system category which combines the pitch system with all other hydraulic components within a turbine since only hydraulic pitch systems were analysed. In the RELIAWIND project, a FMECA was conducted identifying the top five failure modes of the critical sub-systems of which the pitch system has been one. For the electrical pitch system, “battery failure”, “pitch motor failure” and “pitch motor converter failure” were mentioned as most important failure modes, whereas for the hydraulic pitch system different kinds of leakages were described as top three failure modes (Gayo, 2011). Carroll et al. (2016) described oil issues, valve issues and accumulator problems as

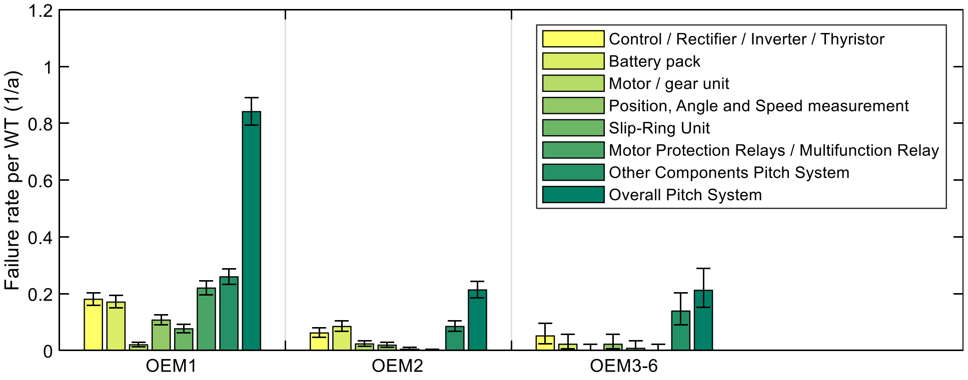


Fig. 3. Failure-rate comparison across wind turbine OEMs for electrical pitch systems.

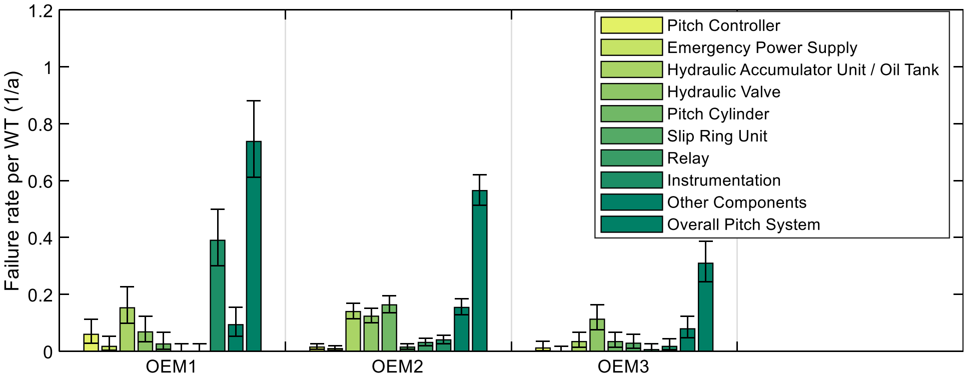


Fig. 4. Failure-rate comparison across wind turbine OEMs for hydraulic pitch systems.

the most common failure modes in the component category "pitch/ hydraulic". Furthermore, based on the quantitative study of Carroll et al. (2016) and Liniger et al. (2017) performed a case study for fluid power pitch systems in which a fault tree analysis (FTA) and FMECA revealed valves and accumulators as most critical components. Those findings are in line with the components' average failure rates shown in Figs. 1 and 2. Even though criticality of the faults cannot be derived directly from the presented results, all component failures need to be considered as critical since the pitch system is part of the emergency shut down system of turbines. Additionally, instead of giving just a ranking for top failure modes, in this study the determined average failure rates of the components can be used to quantify to which extent a certain component drives the overall failure rate of the pitch system analysed.

3.2. Failure-rate comparison across WT OEMs

While it is common practice to provide average failure rates calculated from mixed fleets containing different types of turbines as in Section 3.1, this practice is afflicted with risks: One is that certain WT types with a particularly low or high reliability level might bias the result. Another one is that providing only a group-averaged failure rate without further elaboration masks such reliability differences that are important indicators to trigger root-cause analysis and design improvements. Therefore, more detailed analyses based on subgroups of turbines are presented in the following.

3.2.1. Electrical pitch systems

Further analyses have shown that there are significant differences in pitch system failure rates when comparing failure rates across different WT manufacturers or when clustering WTs according to their rated power. Fig. 3 shows the results for average failure rates for the electrical pitch system and its components for three different OEM categories. The data set of the category OEM1 is characterised by an average rated power of 1511 kW and 1011 operational years analysed in which 850 failure events have been recorded, thus having an average failure rate of 0.84 per WT per year. The analysis for OEM2 is based on 700 operational years with an average rated capacity of 1686 kW and results with 149 logged failures in a lower failure rate of only 0.21 per WT per year for the overall pitch system. The last analysis combines the failure events of four different OEMs as the data sets available for each OEM separately would have been too small for sufficient interpretation of the results. Therefore, the last category OEM3-6 includes 137 operational years of WTs from four different OEMs with 29 failures recorded. The WTs within this data set have an average rated capacity of 1996 kW. Even though the confidence interval is slightly larger due to the smaller data set evaluated, also for this category there is an average failure rate of 0.21 per WT per year. Moreover, it can be noted that the distribution of most contributing components varies slightly dependent on the OEM. While for OEM1 the component category "Motor Protection Relays/ Multifunction Relays" plays a significant role, this is not the case for OEM2 and OEM3-6.

3.2.2. Hydraulic pitch systems

The same evaluation has been conducted for the hydraulic pitch system. In this case three OEMs are compared. Results are presented in Fig. 4. The data-subset of OEM1 comprises 118 operational years. With 87 failures counted, an average failure rate of 0.74 per WT per year for the overall pitch system is calculated. The WTs within this subset can be characterised by an average rated capacity of 1420 kW. The category OEM2 contains 552 operational years and WTs within this subset have an average rated capacity of 2004 kW. With 312 failures noted in this period, a lower average failure rate than for OEM1 of 0.57 per WT per year is determined. The analysis for OEM3 is based on 178 operational years and the subset has an average rated capacity of 1226 kW. For this subset 55 failure events have been recorded resulting in an average failure rate of 0.31 per WT per year. Comparing the failure rates of the components it can be noted that the component categories "Hydraulic Valve" and "Pitch Cylinder" have higher failure rates for WTs of OEM2 whereas the overall pitch system failure rate of OEM1 is driven by the component category "Instrumentation". In comparison to OEM1 and OEM2, the component category "Hydraulic Valve" is the only component category that plays a significant role for OEM3.

3.3. Failure-rate comparison: Role of WT rated power

3.3.1. Electrical and hydraulic pitch system

In a next step, the pitch-system failure rates of WTs with different ranges of rated capacity are compared. In order to ensure comparability, a data-subset is chosen in which only one OEM is considered, and which allows for splitting the available failure data in different capacity classes.

For the electrical pitch system this is only the case for OEM2. Fig. 5 shows the failure-rate comparison for this case. Because of using a subset for this evaluation, the number of operational years considered is reduced to 164 which leads to larger confidence intervals. The category "low WT rated capacity" comprises WTs with rated capacities below 1500 kW, whereas the category "medium to high WT rated capacity" contains WTs ranging from 1500 kW to 6000 kW.

A similar analysis is performed for two subsets with WTs with a hydraulic pitch system. Results can be seen in Figs. 6 and 7. For the first case the comparison is made for a data-subset comprising 112 operational years since only failure events of OEM1 are considered for comparability reasons. While the category "low WT rated capacity" contains WTs with rated capacity below 1500 kW as for the electrical pitch system, the category "medium WT rated capacity" consists of WTs ranging from 1500 kW to 2500 kW. The second case analyses a data-subset containing WTs of OEM3 which considers 178 operational years. The category "low WT rated capacity" describes WTs with rated capacity below 1500 kW, whereas the category "medium WT rated capacity" comprises WTs with rated capacity ranging from 1500 kW to 2500 kW as for OEM1.

While there is not in all cases clear evidence due to the overlapping confidence intervals, a trend of failure rates increasing with the WT rated power can be observed both for the hydraulic and the electrical pitch systems. Besides the component category "Position, Angle and Speed measurement", there is a trend for all other components of the electrical pitch system failing more often in larger turbines as well. For the components of the hydraulic pitch system of OEM1 no clear trend can be observed. Comparing the two categories of OEM3 for the hydraulic pitch system, a distinct tendency of higher failure rates for WTs with higher rated power can be seen. However, it has to be noted that only three failure events for the category with low WT rated capacity have been recorded within 125 operational years resulting in the low average failure rate. Considering this, it becomes clear that the lower average failure rate of OEM3 in comparison to OEM1 and OEM2 in Fig. 4 is mainly driven by the majority of small WTs being represented in the data-subset of OEM3.

3.3.2. Comparison with literature

The findings above can be compared with the study of Padman et al. (2016) which also differentiated into two categories of turbine sizes. One turbine class was defined with rated power ranging from 1.5 MW to 2.5 MW, and the other turbine class included WTs with a rated capacity between 2.5 MW and 3 MW. The same trend was identified: The larger the turbine, the greater the failure rate of the pitch system. However, the failure rate of 1.6 failures per WT per year obtained for the larger turbine class differs from the ones in this study. While for the electrical pitch system significantly lower failure rates are found (compare Fig. 5), the upper boundary of the confidence interval of the hydraulic pitch system for medium WT rated capacity differs only slightly (compare Fig. 6). Since no confidence intervals are presented in the study of Padman et al. (2016), it is difficult to judge how the smaller data set affects the calculated failure rate.

3.4. Seasonal patterns in the failure behaviour

Next to comparing failure rates under consideration of design factors (OEM, size of turbine, type of pitch system), it is evaluated if any seasonal patterns can be identified in the failure behaviour. For this purpose, component failure rates are calculated for each month. In order to allow a comparison of the failure behaviour with the environmental conditions the WTs have been exposed to, monthly averaged wind, temperature and humidity conditions derived from ERA5 reanalysis data are included for each evaluated wind farm. (ERA5 provides hourly estimates of a variety of atmospheric and oceanographic variables based on global modal

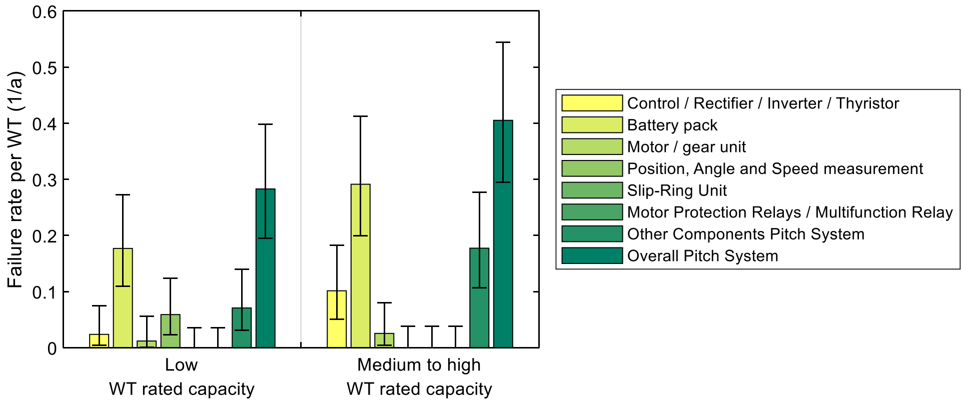


Fig. 5. Failure-rate comparison for wind turbines with different categories of rated power for electric pitch systems.

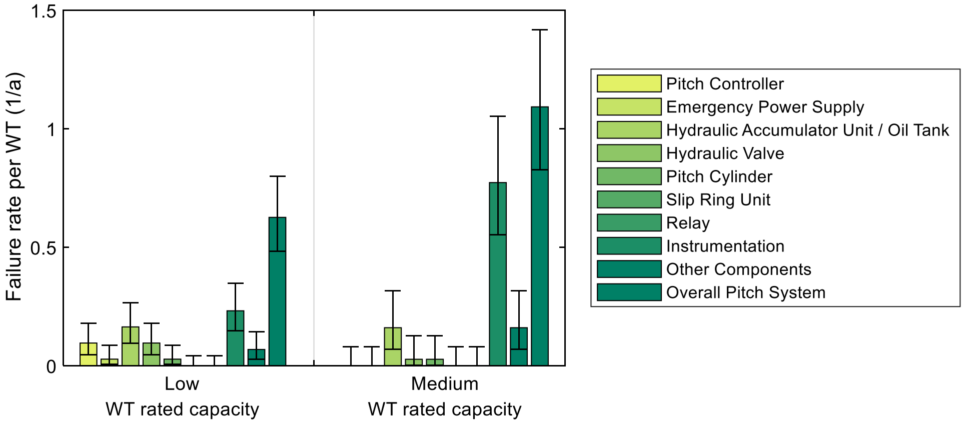


Fig. 6. Failure-rate comparison for wind turbines of OEM1 with different categories of rated power for hydraulic pitch systems.

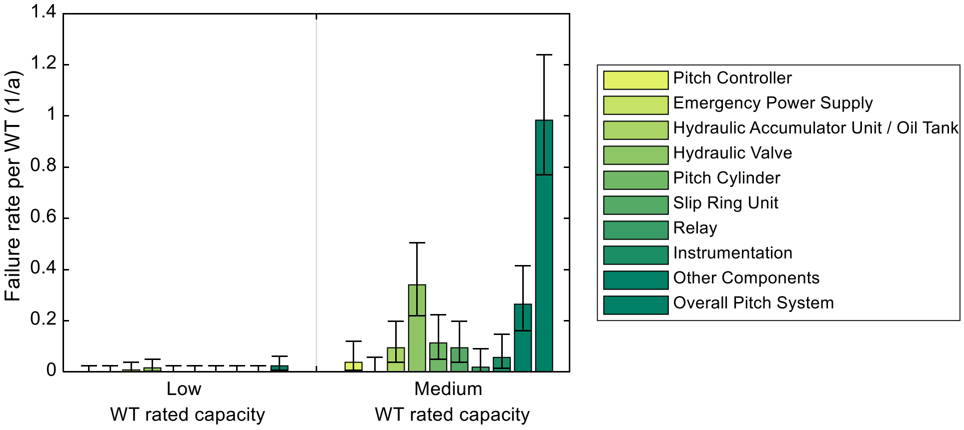


Fig. 7. Failure-rate comparison for wind turbines of OEM3 with different categories of rated power for hydraulic pitch systems.

data. The data set covers the earth on a grid of approximately 30 km × 30 km. For detailed information on the ERA5 reanalysis data, please refer to Hersbach et al. (2020) and European Centre for Medium-Range Weather Forecasts ECMWF (2022), for information on how this data is processed to Fischer et al. (2021)).

Fig. 8 shows the component failure rates through the year and respective ERA5 data from the same wind farms and time periods failure data has been available for. Each line indicates the environmental conditions at one analysed wind farm location. Results for the electrical pitch system are shown on the left and for the hydraulic pitch on the right side, respectively. It can be observed that the WTs operate within similar climatic conditions whereas the wind characteristics for each site can differ significantly. Looking at the overall pitch-system failure rates, no pronounced seasonal patterns can be identified.

When the same analysis is repeated for specific components of the electrical pitch system, the situation looks different. Fig. 9 presents component failure rates through the year for selected components for which seasonal patterns can be identified:

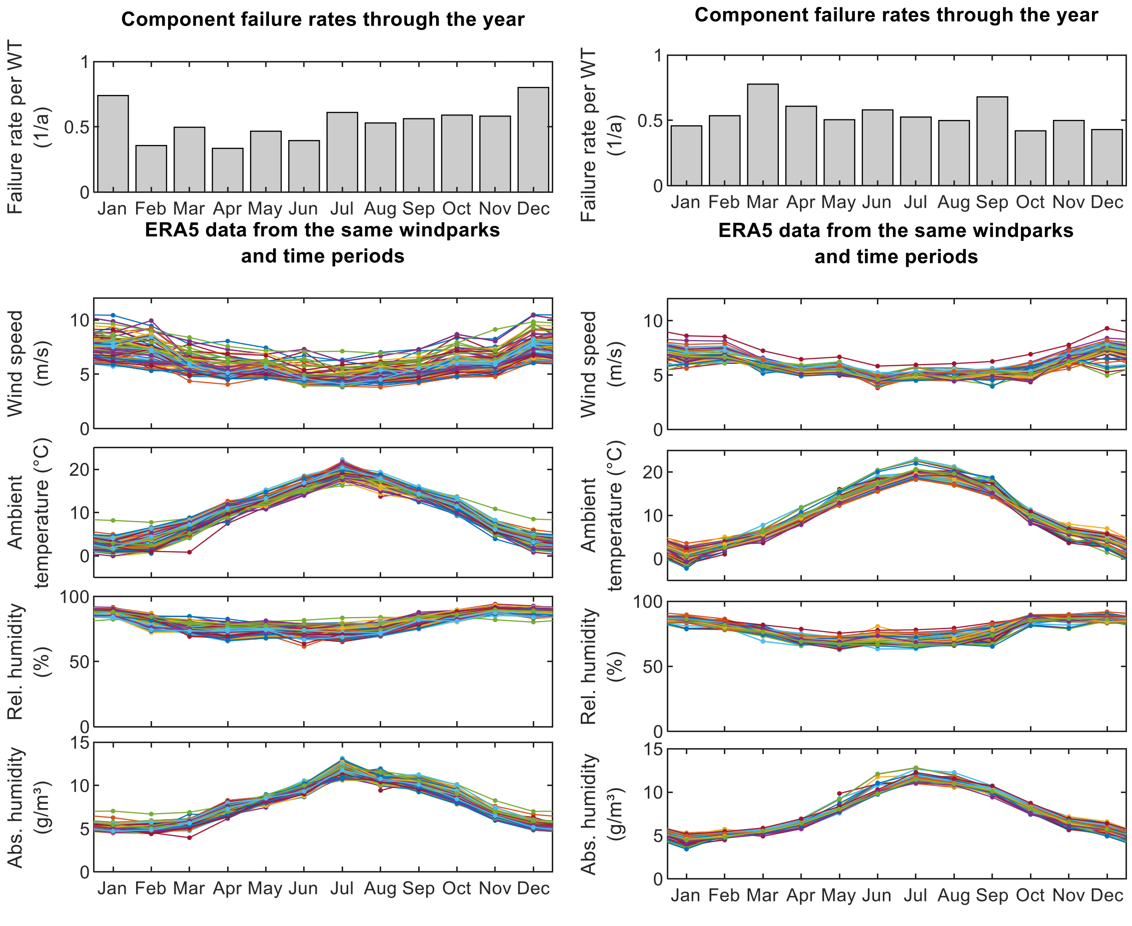
The battery packs have higher failure rates from September to January in comparison to the summer months. This could partially be related to low ambient temperatures (compare Fig. 8). The colder it is, the lower is the battery voltage and the higher the probability that required minimum voltage values are not met anymore. Consequently, the battery pack needs to be replaced.

Motor protection relays and multifunction relays show two different trends. On the one hand, failure rates are higher from July to October which could be explained with a correlation with higher temperature and absolute humidity. On the other hand, there are peaks in the winter months of December and January which likely have a different cause.

Slip ring units are found to have the highest failure rates in December and January. Those are the months with highest average wind speed but also low temperatures (compare Fig. 8). A correlation with high wind speeds could be explained with more pitch activity and possibly increased friction related to the higher main-shaft speed during operation at or close to rated power. Consequently, the slip ring unit faces increased wear and needs to be replaced more often.

In comparison to the three components mentioned above, electronic and power-electronic components of the electrical pitch system, namely control, rectifier, inverter and thyristor, do not exhibit any seasonal clusters. This is an interesting finding since for power electronics in main power converters of WTs pronounced seasonal patterns have been reported in Fischer et al. (2019a), which could be related to their climatic operating conditions in Fischer et al. (2021).

The same evaluation is conducted for the hydraulic pitch system and its components. Fig. 10 shows component failure rates through the year for selected components. No pronounced seasonal patterns are found for components of the hydraulic pitch system. This can partially be related to the fact that the number of operational years covered by this data-subset is smaller in comparison to the one of the electrical pitch system. Especially for



(**a**) (**b**)

Fig. 8. Average failure rates through the year and respective ERA5 data from the same wind farms and time periods. (a) Electrical pitch system. (b) Hydraulic pitch system.

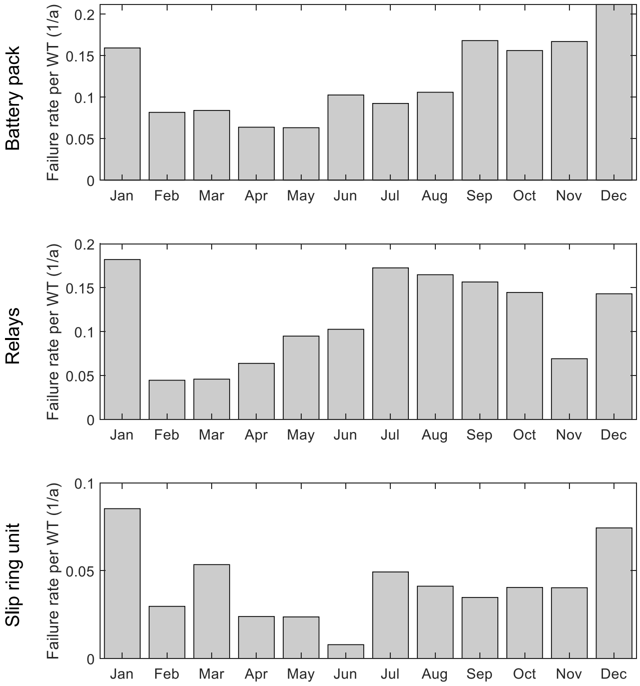


Fig. 9. Component failure rates through the year for different components of the electrical pitch system.

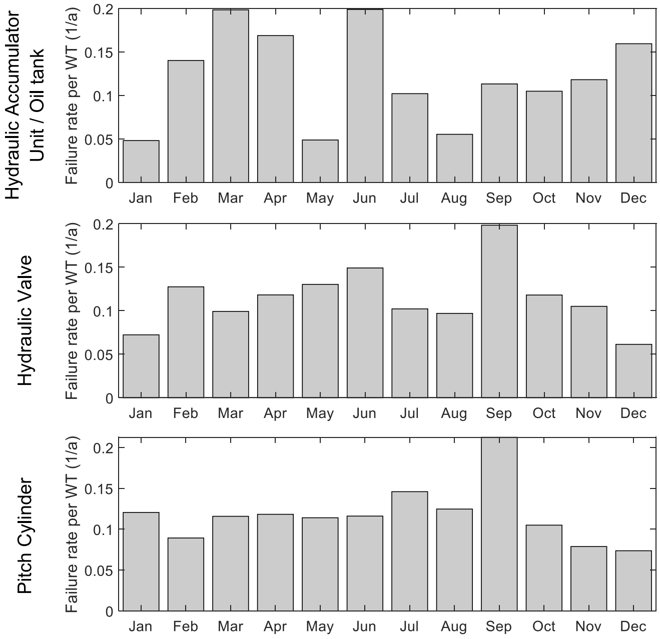


Fig. 10. Component failure rates through the year for different components of the hydraulic pitch system.

components with small average failure rates (compare Fig. 2) only a few failure events have been recorded. Therefore, patterns are more difficult to identify. On the contrary, also components with higher average failure rates (see Fig. 10) do not show seasonal clusters. Solely a peak in September can be observed for the component categories "Hydraulic Valve" and "Pitch Cylinder". However, there is no evident reason found.

4. Conclusions and outlook

This paper has investigated the reliability performance of electrical and hydraulic pitch systems based on a large population of wind turbines with the objective to derive representative failure rates for the overall populations and evaluate the impact of certain parameters to the failure rate values. This can be utilised for more representative availability assessments, optimisation of operational strategies or prioritisation of design improvements. As the study has been performed on a larger dataset than any previous study, its results can be considered more representative. Findings of the study can be summarised as follows:

- Failure rates are high in pitch systems of both types, with hydraulic systems performing slightly better than electrical (0.54 vs. 0.56 failures per WT per year). However, due to overlapping confidence intervals, there is no sufficient evidence to conclude that hydraulic pitch systems are more reliable than electrical ones.
- Among the different OEMs comprised by the dataset, the failure rates have been found to differ significantly depending on OEM, and hence technology.
- The classification of rating to low and medium-high capacity has indicated that the failure rates of the overall pitch system tend to increase with the WT rated power.
- While for the electrical pitch system the component categories "Battery Pack", "Control/ Rectifier/ Inverter/ Thyristor" and "Motor Protection Relay/ Multifunction Relay" have been identified as most critical, the hydraulic pitch system has shown the highest failure rates in the component categories related to the hydraulic system itself, namely "Hydraulic Accumulator Unit/ Oil Tank", "Pitch Cylinder" and "Hydraulic Valve".
- Seasonal patterns in the failure behaviour have been found for components of the electrical pitch system, but could not be identified for hydraulic pitch system's components based on the evaluated dataset. As temporal failure patterns typically become more evident with higher numbers of evaluated failures, further investigations with an extended data base are recommendable especially for components with low average failure rates in the future to reveal potential further conclusive correlations with environmental conditions.

CRediT authorship contribution statement

Julia Walgern: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft. **Katharina Fischer:** Conceptualization, Methodology, Formal analysis, Visualization, Writing – review & editing, Supervision. **Paul Hentschel:** Data curation. **Athanasios Kolios:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgements

The present work was partly carried out within the "Fraunhofer-Innovationscluster Leistungselektronik für regenerative Energieversorgung". The support by the Federal State of Lower Saxony with funds from "Niedersächsisches Vorab, Germany" (grant number VWZN2989) and by Fraunhofer-Gesellschaft, Germany as well as the provision of comprehensive field data by the project partners are gratefully acknowledged. ERA5 reanalysis data were obtained from the Copernicus Climate Change and Atmosphere Monitoring Services. Further financial support was received by EPSRC, United Kingdom through the Wind and Marine Energy Systems Centre for Doctoral Training under the grant number EP/S023801/1.

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