Wind Turbine Failures - Tackling current Problems in Failure Data Analysis

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Abstract. The wind industry has been growing significantly over the past decades, resulting in a remarkable increase in installed wind power capacity. Turbine technologies are rapidly evolving in terms of complexity and size, and there is an urgent need for cost effective operation and maintenance (O&M) strategies. Especially unplanned downtime represents one of the main cost drivers of a modern wind farm. Here, reliability and failure prediction models can enable operators to apply preventive O&M strategies rather than corrective actions. In order to develop these models, the failure rates and downtimes of wind turbine (WT) components have to be understood profoundly. This paper is focused on tackling three of the main issues related to WT failure analyses. These are, the non-uniform data treatment, the scarcity of available failure analyses, and the lack of investigation on alternative data sources. For this, a modernised form of an existing WT taxonomy is introduced. Additionally, an extensive analysis of historical failure and downtime data of more than 4300 turbines is presented. Finally, the possibilities to encounter the lack of available failure data by complementing historical databases with Supervisory Control and Data Acquisition (SCADA) alarms are evaluated.

1. Introduction

Over the past decades, the wind energy sector has been growing significantly and efforts are being made to minimise the overall cost of a wind farm. One of the main cost drivers is directly related to operation and maintenance (O&M) actions. Current tendencies in O&M practice are shifting from rather costly corrective strategies to preventive and predictive approaches. Crucial for setting up these cost effective strategies is to understand profoundly when and how wind turbine (WT) components fail. Moreover, the failure severity, in terms of caused downtime and repair cost, as well as the frequency of failure occurrences need to be known. These can be obtained from analysing historical failure databases and maintenance logbooks provided by manufacturers and operators. The components and their sub-assemblies have to be classified regarding their physical location and functionality, using a so called *taxonomy* or *component breakdown*. Then, the frequencies of component failures and the resulting WT downtimes are derived from the failure database. The outcome of the analysis can then be used to build reliability models and failure prediction tools in order to estimate the WT component degradation over time and to anticipate failures. A considerable amount of research has been done in this area, nonetheless, there are still serious problems regarding recent practices. Three main issues have been identified and will be addressed in this paper.

2. Problem Statement

2.1. Data Treatment - Taxonomy

As stated by Kuik *et al.* in [1], one major issue is related to the non-uniform data treatment within the different analyses. In order to facilitate the comparison of different studies, failures have to be assigned to the affected components using a clear and uniform taxonomy. Several WT taxonomies have been developed in the past. Among these are for example a report from the SANDIA Laboratories presented in [2], and a component breakdown by the VTT Technical Research Centre of Finland stated *inter alia* in [3]. In [4] the differences between some of the existing taxonomies and the problems arising with non-uniform data treatment in failure analyses are explained. Two of the most recent approaches are the RDS-PP taxonomy, published by the VGB PowerTech e.V. in [5], and the ReliaWind taxonomy, see e.g. [6]. The ReliaWind taxonomy, a very sophisticated approach which was applied to an extensive failure data analysis, was chosen as a basis for this study. Nonetheless, certain drawbacks have been identified and will be tackled. The most severe drawback is that the complete WT taxonomy is not publicly available. Additionally, having ended in 2011, most of the 350 WTs used for the ReliaWind study were built before 2008 and represent older WT technologies. Besides the rotor diameters, hub height and capacity, also the WT configuration changed over the past decade, see [7]. Thus, there is a significant need for verification and modernisation of this taxonomy.

2.2. Failure Data Analysis - Failure Rates and Downtimes

Another serious problem is to understand the frequency of component failures and the caused downtimes. Several failure analyses have been carried out, yet, most of them are based on very few wind turbines and/or old WT technologies. For example [8] analysed failure data of 72 wind turbines located in Finland between the years 1996 and 2008. In the WindStats Newsletters, see e.g. [9], extensive data from operating WTs in Denmark, Sweden and Germany are published. Detailed information on the wind turbine size, age and type are not available, though. Ribrant *et al.* [10] compared failure statistics from Swedish, Finish and German databases. Hahn *et al.* [11] presented some results of the WMEP project containing failure data of operating WTs between the years 1989 and 2002. The WMEP continued until 2006 and further studies were published, e.g. [12]. Also, the previously mentioned ReliaWind project [6] analysed failure histories of 350 wind turbines over a varying period of time. Recently, modern approaches have been carried out, for example in [13], the failure rates of WTs equipped with doubly fed induction generator (DFIG) and permanent magnet generator (PMG) technologies, based on around 2200 onshore WTs with nominal power between 1.5 and $2.5MW$ are compared. In [14], the failure data of approximately 350 offshore turbines with nominal power between 2 and $4MW$ are analysed.

In the present study an extensive analysis of a very big wind farm portfolio including over 4300 onshore turbines is presented. This contains both, very old technologies and recently installed ones with rated capacities between $300kW$ and $3MW$. Not only geared drive turbines will be considered, but also direct drive technologies. With this, the authors want to contribute to the availability of WT failure analyses and enable further research to access reliable data.

2.3. Lack of available Failure Data - Complement with SCADA Alarms

Due to the lack of available data, many reliability models and maintenance decision tools are based on assumed failure rates - not representing sufficiently well the reality. Very recent studies [15] and [16] are proposing the use of Supervisory Control and Data Acquisition (SCADA) alarms to complement available failure logs with additional information. Most modern WTs are equipped with SCADA systems, generating a huge amount of information that can be obtained mostly free of additional cost. Nonetheless, there is very few research conducted on determining the value of this information for failure analyses. In [17], an extensive analysis of the Sandia CREW database is presented, with the aim of finding frequent SCADA events contributing to downtimes and component failures. These events are exclusively taken from SCADA systems and no work-orders, historical failure logbooks or other sources are considered.

In this study, historical failure logs and component related SCADA alarms are combined. It is evaluated to which extend SCADA data can add information to the logbooks, and for which components this is especially the case. This will permit studies, which are suffering from failure data scarcity or need more information on the component state, to use an additional source.

3. Database Composition

3.1. Data for Failure Rate and Downtime Analysis

To analyse the failure rates and downtimes, as well as to verify the modified taxonomy, a very big failure database was considered. This includes three years of operational data of three bladed onshore WTs with nominal power between $300kW$ and $3MW$ each. Both, geared and direct drive technologies have been considered. The latter have rated capacities between $600kW$ and $2MW$ per WT, and will be presented separately in order to draw useful conclusions. WT failure logbooks from 14 different manufacturers are represented in the database, including most major manufacturers currently having turbines installed in Europe. The composition of the database is given in table 1. As the number of WTs in operation changed slightly throughout the years, the average yearly number is displayed. In comparison to previous studies, discussed in section 2.2, a significantly higher amount of operating turbines is examined. Furthermore, only turbine shut downs due to component failures are considered - shut down events due to grid restrictions, weather conditions, etc. are not included. In total, around 7000 failure events were analysed.

Table 1: Data used in this study

Avg. yearly number of wind farms	230
Mean yearly installed capacity (MW)	5818
Avg. number of failure events per year	2280
Avg. yearly number of WTs considered	over 4300
Containing:	
Avg. yearly number of WTs under 1 MW	2130
Avg. yearly number of WTs equal or over 1 MW	2270
Number of direct drive turbines	215

3.2. Data for SCADA Alarm Analysis

In order to investigate the correlation between the alarms extracted from the SCADA system and the actual failure occurrences, the data had to be analysed differently than it was for the second task. A smaller part of the above explained data was used, containing the WT technologies displayed in table 2 and representing some of the most widely installed modern technologies. As older turbines are not necessarily equipped with SCADA systems or only operate relatively limited ones, they were excluded. The different technologies are indicated by their rated power and drive train setup - being either direct drive or geared WTs. As for confidentially reasons no manufacturer names can be published, the WT makes are indicated by the letters A to G. The respective SCADA system used within these turbines is referred to with the numbers 1 to 5. Turbine types A, D, E, F, G are equipped with a DFIG and types B and C with a synchronous generator. In total 440 WTs were analysed over a period of three years, resulting in 1320 operational years. An overall number of 653 failures and 1345036 alarms were registered and processed. The failures and alarms per turbine are displayed as rounded values.

Table 2: Data used for the SCADA Alarms and Failure Analysis

SCADA System	WT Make	Technology	Rated Capacity (kW)	Nb of Turbines	Failures per Turbine	Alarms per Turbine
1	A	Geared	1500	55	0.709	4170.07
2	B, C	Dir. Drive	2000	57	0.632	1120.35
3	D	Geared	850	77	2.208	2778.78
4	E	Geared	2000	168	1.780	4704.57
5	F, G	Geared	1800 & 2000	83	1.313	572.14

4. Approach and Methods

4.1. Enhanced Taxonomy

With the aim of creating a taxonomy applicable to the available data, one of the most sophisticated existing WT taxonomies developed for the ReliaWind project, has been carefully reviewed. Using detailed manufacturer information on recent WT technologies, it has been rearranged and extended considering the components' functionality and physical location. The objective was not to develop an entirely new taxonomy, but rather to extend and modernise an existing one. The latter has been verified with a big database of around 4300 turbines, including a variety of different WT technologies and ages.

4.2. Failure Data Analysis

The failure data analysis was realised by applying the taxonomy to the historical failure database, explained in section 3. For this, the data set has been cleaned and structured; occurring failures have been assigned to the affected *subsystem*, *assembly* or *subassembly.* Then, using historical data and maintenance logs, the failure rates per turbine and year have been calculated for each component and the downtimes have been determined.

4.3. Additional information using SCADA Alarms

A 'dictionary' classifying the alarms according to the taxonomy has been developed. This, allows a fast and effective categorisation, making the alarms comparable to the previously analysed failure data. More information can be obtained from a parallel study by the authors [18], including a time sequence analysis of alarms before failures. The SCADA system uses sensor information and sends out alarms if predefined thresholds are exceeded. The sensors are implemented in different parts of the WT and indicate component states such as temperature, rotational speed, etc. As the systems of different manufacturers vary highly in the amount of possible alarms, they were analysed separately. Some manufacturers divide the alarms in warnings and faults, respectively indicating a problematic or failed component. As this is not the case for all manufacturers, the term *alarm* will be used in the further indicating SCADA entries for any given *subsystem*, assembly or *subassembly.* Only alarms describing a problem or failure were considered. SCADA events reporting e.g. *yaw cable unwinding* were excluded, as they do not affect any component negatively and would lead to a misinterpretations. The classification has been carried out automatically in R and a profound study has been performed comparing alarm and failure frequencies.

5. Results and Discussion

5.1. Wind Turbine Taxonomy

The wind turbine system has been divided into seven main *subsystems* and several *assemblies* were assigned to each *subsystem.* Then, a certain number of *subassemblies* has been assigned to each *assembly*. Figure 1 shows the results for the *subsystems* and *assemblies*. The *subassemblies* will not be presented here. For a better understanding the *subassembly* failure rates and downtimes will be grouped within the respective *assembly*, to which they belong to. The objective was to enable the taxonomy to be applied to both, older and modern WT technologies.

Subsystem	Assembly	Subsystem	Assembly	Subsystem	Assembly
Power Module		Control & Communications		Auxiliary System	
	Frequency Converter		Sensors		Cooling system
	Generator		Controller		Electrical Protection and Safety
	Switch Gear		Communication System		Human Safety
	Soft Starter		Emergency Control & Communication Series		Hydraulic Group
	MV/LV Transformer		Data Aquisition System		WTG Meteorological Station
	Power Feeder Cables	Nacelle			Lightning Protection
	Power Cabinet		Yaw System		Firefighting System
	Power Module Other		Nacelle Cover		Cabinets
	Power Protection Unit		Nacelle Bed plate		Service Crane
Rotor & Blades		Drive train			Lift
	Pitch System		Gearbox		Grounding
	Other Blade Brake		Main Bearing		Beacon/Lights
	Rotor		Bearings		Power Supply Auxiliary Systems
	Blades		Mechanical Brake		Electrical Auxiliary Cabling
	Hub		High Speed Shaft	Structure	
	Blade Bearing		Silent Blocks		Tower
			Low Speed (Main) Shaft		Foundations

Figure 1: Taxonomy used for the Failure Data Analysis

The taxonomy is quite similar to the ReliaWind taxonomy, nonetheless, several changes have been made. These include the enclosure of components of modern WTs and rearrangements of already assigned ones. If possible, new *sub-assemblies* were assigned to existing categories - if not, new categories were established. Furthermore, in some cases higher priority was given to classify components rather according to their functional similarity than to their physical location. Due to limited space, only the most remarkable changes are explained in the following. Many components for operational safety and control have been added. Also, several sensors have been attached to the control & communication system, including the condition monitoring system (CMS). Contrarily to the ReliaWind taxonomy, for example the *sub-assemblies* related to the control of the components, such as the converter control unit, the yaw and pitch control, *etcetera* are assigned to the control & communication system to which they functionally belong to - not to the component they are controlling. This was performed similarly for the cooling systems, which are classified as auxiliary systems. Only minor changes were performed to the hydraulic group. Functional classification is of great advantage in some cases, especially when e.g. analysing different WT technologies or the effects of weather conditions on components, as for example hydraulic and electric components are affected differently.

5.2. Failure Rates and Downtime Analysis

A failure and downtime analysis, applying the taxonomy shown in section 5.1 has been carried out. In general, direct drive turbines had significantly less failures and downtime than geared turbines. The total failure rates per year and turbine for each WT type are shown in table 3, displaying the rounded values for geared WTs with rated capacity below 1 MW ($G < 1MW$), equal/above 1 MW ($G \geq 1MW$) and direct drive turbines (DD). Also, the average downtime per WT and year and per failure are displayed. Compared to former studies the obtained failure rates are in the lower range. For example in [10] the following failure rates were collected: 0.402 for Swedish, 1.38 for Finnish and 2.38 for German WTs. An important difference to earlier studies is that this study focuses exclusively on component failures. Thus, grid problems, wind farm tests, vandalism and similar causes are not considered. Furthermore, failures due to "unknown" or "other" reasons, which hold a big share of the failure rates in previous studies, were excluded. They do not complement to the aim of comparing the share of component failures. The total failure rates for DD turbines are similar to previous studies, see e.g. [13].

Table 3: Total Failures and Downtimes per Turbine per Year for the different WT Technologies

WT Technology	Failures/Turb./Year	Downtime/Turb./Year	Downtime/Failure
$G < 1MW$	0.46	78.46 h	151,46 h
$G \geq 1MW$	0.52	44.51 h	112.67 h
DD	0.19	20.50 h	34.98 h

Figures 2, 3 and 4 show the results for the failure rates and downtimes per component for $G < 1MW$, $G \geq 1MW$ and DD respectively. The colours in the graphs represent the *subsystems* as displayed in the taxonomy. The failure rates are given as failures per turbine and year, normalised to the total number of recorded failures. The downtimes are presented as the component's contribution to the overall downtime. The results for the *subsystems* indicate clearly that DD turbines were more likely to suffer from power module and control & communication system failures than geared turbines. Direct drive turbines suffered from hardly any drive train failures, except for some torque limiter problems. This is, certainly also due to the absent gearbox, which is the major contributor to the failure rates and downtimes. Regarding the WT *assemblies*, it can be highlighted that for all three technologies the generator was one of the biggest contributors to the overall failure rates and downtime.

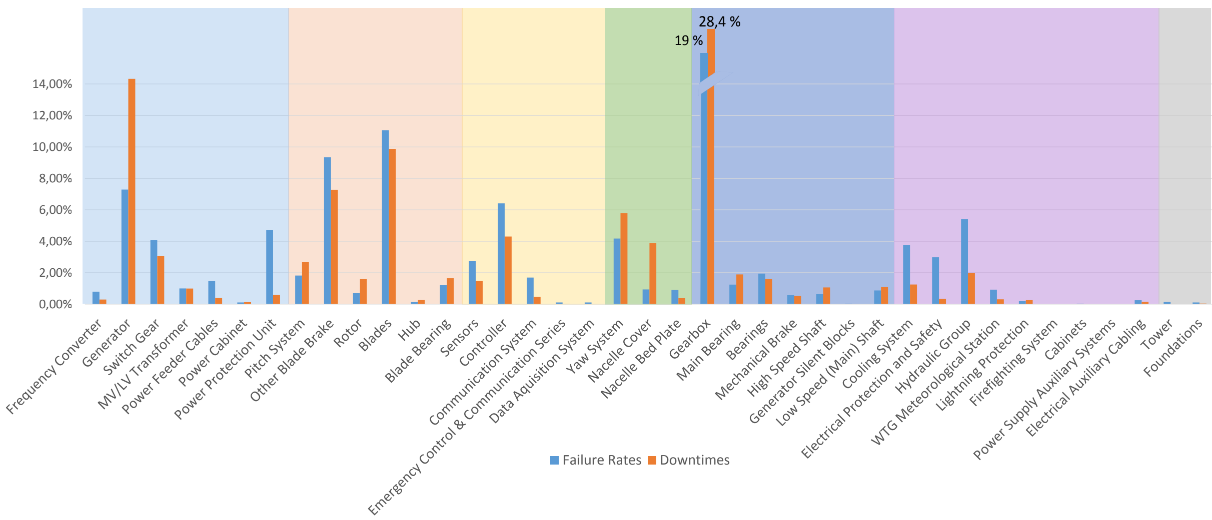


Figure 2: Normalised Failure Rates and Downtimes for Geared $G < 1MW$ Turbines

Especially DD turbines showed the highest downtimes due to generator failures. Geared WTs suffered from extremely high gearbox failure rates and downtimes. At the same time, by virtue of their energy conversion principle, the DD turbines showed a higher share of power module and the control system failures. They also suffered from very few blade failures, which however, contributed significantly more to the WT downtime than for the other two technologies. This indicates that blade failures are more severe for DD WTs than for geared ones. The fact that the generator and transformer are contributing more to the failures and downtimes of DD WTs could be explained by the elevated stress on these components due to the missing gearbox. The pitch system failed relatively often in $G \geq 1MW$ and DD turbines. The older $G < 1MW$ turbines are often not equipped with a pitch system instead with another blade brake, which also failed quite often. Newer WT technologies are using significantly more complex control

& communication systems that are contributing more to the overall failure rates. Especially the DD turbines show an extremely high share of controller failures. The controller could be challenged more due to the missing gearbox. Geared turbines $G \geq 1MW$ and $G < 1MW$ had notably more problems with the cooling system than DD technologies. This could be related to the fact, that the gearbox has a more failure-prone cooling system than other components.

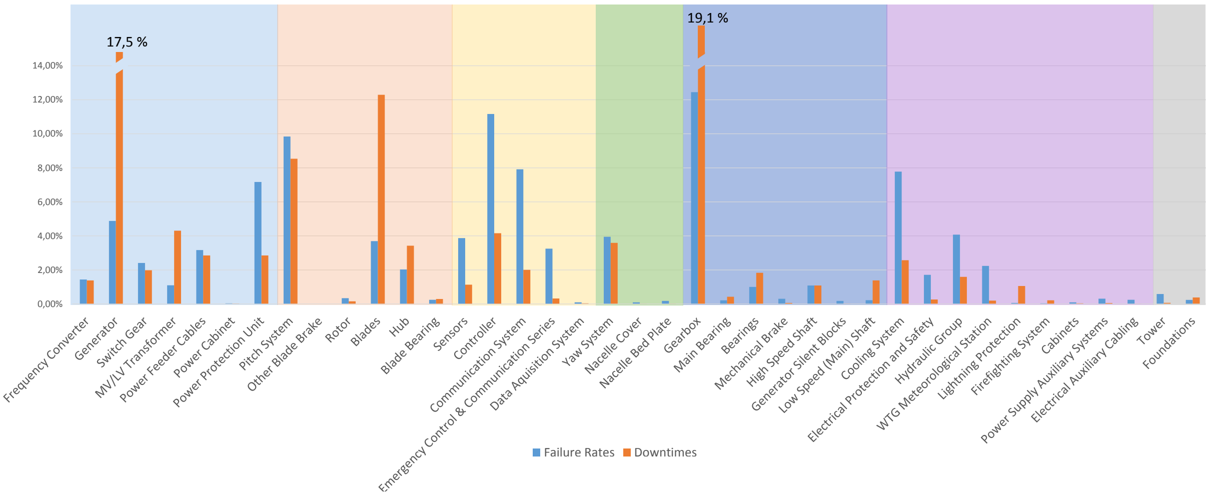


Figure 3: Normalised Failure Rates and Downtimes for Geared $G \geq 1MW$ Turbines

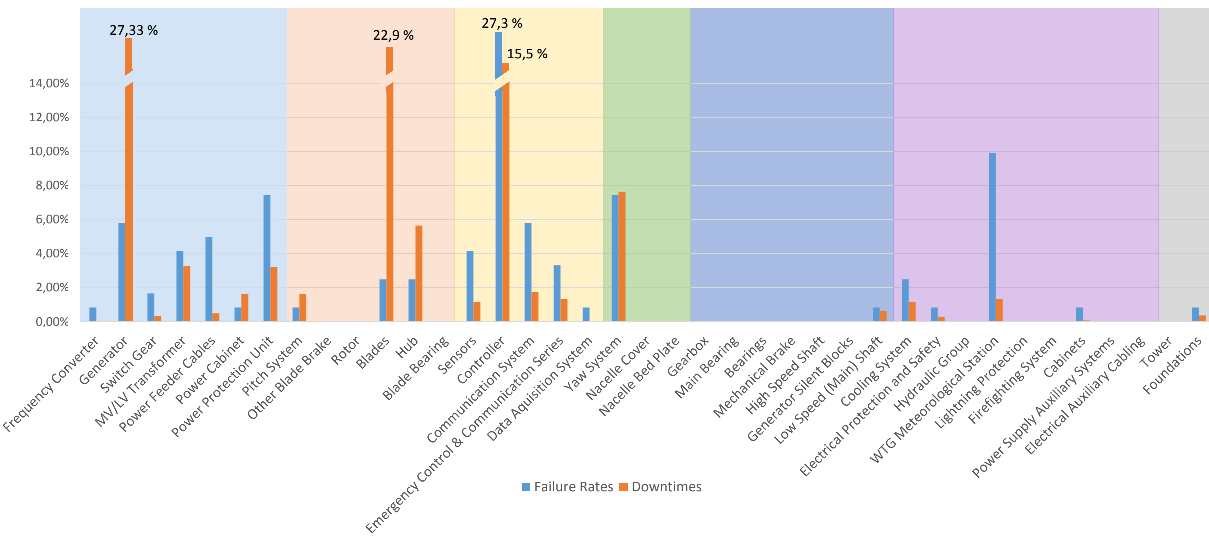


Figure 4: Normalised Failure Rates and Downtimes for Direct Drive WTs

5.3. SCADA Alarms and Failure Analysis

Figure 5 displays the possible alarms for each SCADA system. Figure 6 shows the composition of the alarms actually recorded for each system within the given observation period. They consist of alarms related to a specific WT component, alarms due to extreme environmental conditions, and others that could not be assigned to any component, e.g. grid restrictions. Comparing the two figures, shows that for WT types A, B, C and D many weather related alarms were recorded, indicating extreme conditions, which could be responsible for certain component failures. Turbines B, C and D showed a quite similar share of the three alarm categories recorded. Also the share of possible alarms of these two SCADA systems are alike.

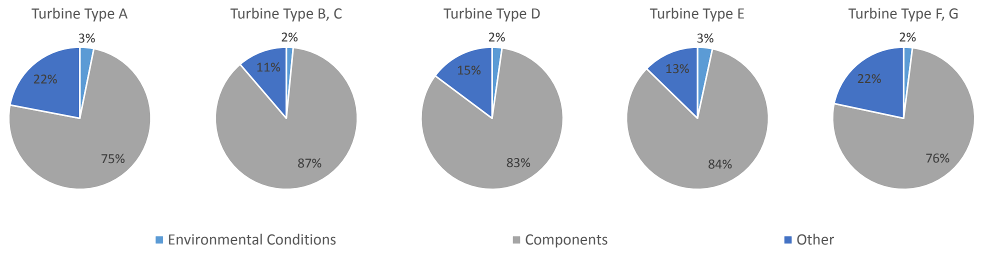


Figure 5: Possible Alarms for the five different SCADA Systems

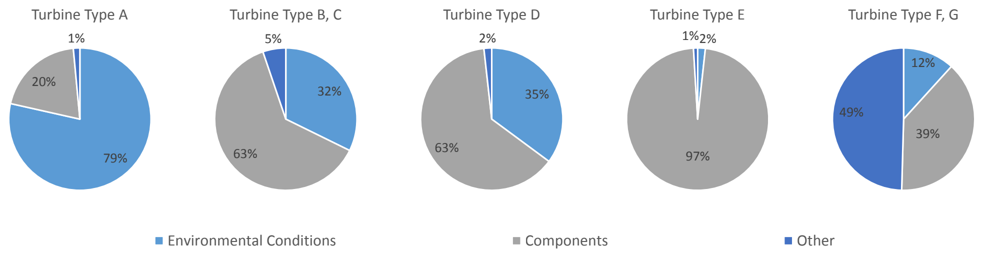
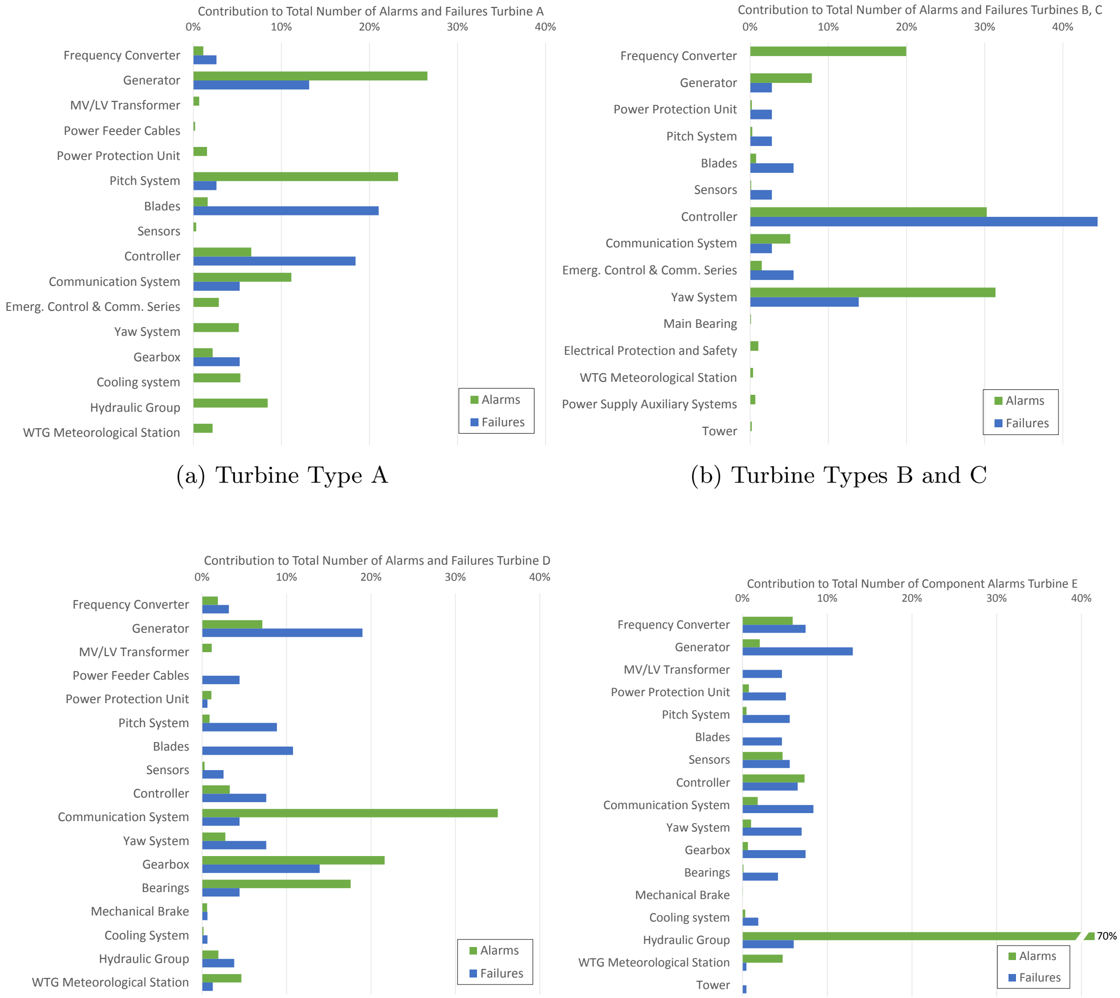


Figure 6: Recorded Alarms for the five different SCADA Systems

Figures 7 and 8 represent the contribution of the component related alarms to the total number of recorded alarms. This is compared to the failures per year and turbine, normalised to the total number of failure occurrences. It is taken for granted that the CMS is connected to the SCADA system and functioning well in monitoring the turbine. This means that high numbers of alarms indicate a problem. Showing many alarms but few failures, indicates that the component is well monitored and failures are prevented by shutting down the turbine before they occur. Wind turbines of type A showed a relatively small number of total failures per turbine, but a very high number of alarms - see table 2. Thus, failures seem to be anticipated by the SCADA system. It is remarkable that many alarms due to environmental conditions but hardly any blades and controller alarms were recorded. At the same time, however, a large number of blade and controller failures appeared in the data set. The generator also showed relatively high failure rates as well as the second highest number of alarms. The alarms assigned to the generator had the highest share of all component related alarms. It is assumed that the generator is equipped with an extensive CMS to prevent failures.

Being direct drive turbines, types B and C showed the lowest total number of failures. Many alarms were assigned to the controller and yaw system. The frequency converter also showed a large number of alarms, however, did not have any failures. The SCADA system actually indicated generator problems fairly well by reporting many alarms while very few generator failures occurred. Similar to type A, a high number of alarms due to heavy weather conditions can be related to controller and blade failures. Hence, it is assumed that for direct drive technologies the controller, yaw system and blades are suffering more likely from unfavourable weather conditions than other components.

Type D turbines, represented the oldest technology with the lowest rated capacity per turbine. They showed the highest number of failures per WT, and a fairly high number of alarms due to environmental conditions. Many blade failures occurred, however, no alarm could be associated to the blades. The number of alarms related to the gearbox, the communication system and the bearings were quite high, indicating that the latter are well monitored by the SCADA system. The pitch system, the controller and the generator, however, did not provoke many alarms, although showing relatively high failure rates. This could be due to the fact, that the SCADA system in the older technology is not as advanced as it is in newer ones.



(a) Turbine Type A

(b) Turbine Types B and C

(c) Turbine Type D

(d) Turbine Type E

Figure 7: Comparing the Failure Rates and Alarms for Turbine Types A to E

The highest number of alarms was registered for WTs of type E. Similar to types A and D, the generator caused many failures whilst very few alarms were registered. Especially the hydraulic system showed an extremely large number of alarms. This leads to the theory, that for type E turbines the hydraulic system alarms can indicate failures of other components. Very few weather related alarms were observed. Like others, type E also showed very few alarms for the pitch and yaw system whilst suffering from many failures of these components.

For WT types F, G no blade alarms but many yaw system and weather related ones were recorded. Vibrations in the foundation were indicated by the SCADA system as well as several failures of this part. Showing many alarms and very few failures, the pitch system, the generator and the hydraulic group seemed to be well monitored. The gearbox showed the most critical behaviour, with very few alarms but very high failure rates, and should be monitored better.

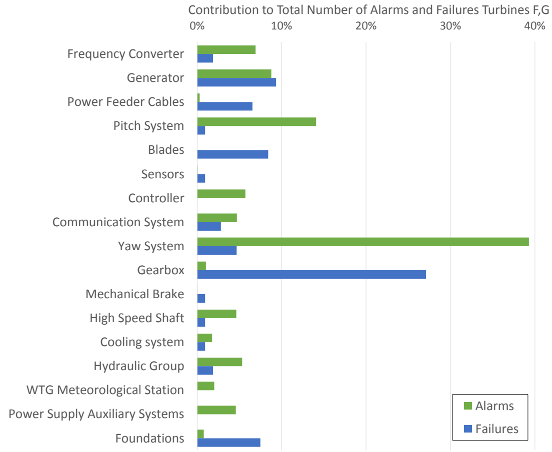


Figure 8: Comparing the Failure Rates and Alarms for Turbine Types F and G

6. Conclusions

This work contributes to solving three major issues currently faced within WT failure analysis and reliability modelling: (1) the non-uniform data treatment, (2) the lack of available failure analyses, and (3) the need for investigating the possibility of using additional data sources to gain information on component failures. For this, firstly, an existing taxonomy was modernised to ensure the comparability of this study to older studies. This shall contribute to the uniformity in data treatment. The taxonomy has been applied to a database of more than 4300 WTs and failure rates and downtimes have been calculated. The analysis showed the values for six *subsystems* and their assemblies in detail, adding to encounter the lack of publicly available WT failure analyses. Finally, the possibility of using SCADA alarms to complement incomplete failure data has been investigated. Recorded alarms and historical failure data for five different SCADA systems and WT types were compared. It was shown that for certain components there are significantly more alarms than actual failures - and contrariwise. In general, high numbers of component alarms and low failure rates indicate that the SCADA system is helping to avoid failures from occurring. Blade and controller failures showed to occur frequently in the presence of alarms indicating harsh environmental conditions. Nonetheless, it is very hard to obtain a global conclusion on how much the SCADA system is adding value to (missing) failure data, as the information provided by the different systems vary strongly. Thus, for each SCADA type the relation between component failures and the respective alarms was demonstrated. This can be used in further studies as an indicator on how much information the different SCADA systems contain for each component and how this is interconnected to its failures. This part of the work served as base for a parallel study by the authors [18], where subsequently recorded alarms 30 days before failure were analysed. In any case, a uniform guideline to WT condition monitoring and SCADA systems for manufacturers could be very helpful and would enable research to advance in great steps. In future studies, the authors will focus on extending the WT failure analysis and strategies to use SCADA alarms in WT performance and reliability modelling will be developed. Also, environmental conditions before failures will be analysed in more detail.

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