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A survey of failures in wind turbine generator systems with focus on a wind farm in China

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Abstract

Component failures are a critical factor that causes unscheduled outage of wind turbine generators (WTG) and a loss of generation. To quantify the WTG failures, a survey which includes data collection and statistical analysis is conducted in this paper. The method applied in the survey has been compared with the previous approaches. The paper demonstrates that there has been a lack of consistency in previous approaches to analysis of failure data and that the proposed method applied here can better ensure data homogeneity. The method is then applied to a wind farm in China which has 134 WTGs, each with a capacity of 1.5 MW in China. Results show that 32.25% of total failures occurred in the pitch system, while cable failures accounted for over 2,033 hours of downtime (29.29% of total downtime), the highest among all causes. It is estimated that 87% of cable failures were due to third party damage (stolen). It is concluded from the analysis that if the wind farm management was improved so that the cable theft was avoided then the wind farm generation could have increased by 0.35% during the period.

Keywords: Wind turbine generator, failures, downtime, capacity factor

1. Introduction

The world's cumulative wind power generation capacity was over 282 Gigawatt (GW) by the end of 2012. Of this capacity, 44,609 MW was newly added, representing the highest rate of annual installation [1]. The trend in growth is set to continue as the World Wind Energy Association (WWEA) predicts a global capacity of more than 500,000 MW by 2016, and 1,000,000 MW by 2020 [1].

Nevertheless, the predicted power generation figures must also take into account operational factors which apply to wind turbines. Some surveys reported that the wind farm capacity factor, which indicates how much electricity wind farms could produce, is less than 35% [2], [3]. One factor which affects the capacity factor is that wind turbine failures cause unscheduled outage of wind turbine generators (WTG) and a loss of generation [2].

WTGs are subjected to different sorts of failures and the extent and impact of failures can be measured through values of frequency of a particular fault type and the downtime that results from the given failure. Surveying the databases of information from operational wind farms is a basic method to collect and analyze the failure data. Therefore, the statistics of wind turbine failures can be studied by considering both failure frequencies and downtimes [4]. Comparing causes of failure and effect of these on generation output with previous surveys is challenging as different methods are used to collect and analyze data on failure frequencies and downtimes of wind turbines and different types of turbine are involved. Some WTGs do not have gearboxes, and some WTGs are able to pitch the angle of blades [5]. In addition, different names have been used to distinguish different parts of wind turbines, such as the electronic control and control systems [6], [7].

This paper aims to clarify the confusions in previous surveys with a comparison of methods in the

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literature before proposing and applying a revised methodology to survey on the failures of WTGs in a wind farm in China. Definitions of all concepts and the behavior of same types of WTGs will be illustrated. In addition, this paper qualifies the percentage of capacity factor that could be improved by avoiding failures of WTGs.

2. Related Work and Methodology

2.1. Related work

The relevant literatures which include surveys of failures will be reviewed in two groups: one is on complete surveys of WTGs [6],[7]; the other is on the reliability analysis of WTGs including results of surveys [3], [5].

An investigation of WTG failures from two Swedish surveys (one involving 723 WTGs, the other involving 786 WTGs) was based on annual reports for the period from 2000 to 2004 [6]. The Swedish survey has been compared with a Finnish survey and a German survey in [6]. In a separate study, Faulstich *et al.* [7] discussed the frequency of failures and duration of downtimes for various WTG subassemblies. The data was extracted from 64,000 maintenance and repair reports in which 1500 WTGs have been analysed, covering approximately 15,357 operational turbine-years [7].

A survey [3] which is a part of the operational analysis carried out for a wind farm in India includes information of electrical generation, wind turbine availability, capacity factor, failure frequency and downtime. Spinato *et al.* [5] have investigated the reliability of over 6000 modern onshore WTGs and their subassemblies in Denmark and Germany over 11years and particularly changes in reliability of generators, gearboxes and converters in a subset of 650 turbines in Schleswig Holstein, Germany. The data of [5] were collected by operators on hand-written or computer-written report sheets.

2.2. Confusions

It is difficult to make a comparison among the above surveys due to three major aspects. Firstly, the quality of the WTG data differs. Table 1 shows the information of WTGs in the literature compared with that used in the analysis data for this work. Three of the papers [5], [6] and [7] use data from multiple types of WTGs, e.g., 'Stall- or pitch-regulated' relates to whether the attack angles of blades could be controlled or not and 'direct or indirect drive' indicates whether turbines have gearboxes. However, within the literature there is no indication that the different types of WTGs are analysed in different groups, each of which at least has same configured WTGs. It is not proved that whether the sample is consistent in the time intervals, e.g., the number of surveyed WTGs increased over the studied years in [6]. Therefore, because the homogeneity of the data is questionable, the analysis presented is open to question. Although the type of wind turbine being analysed in [3] is of a single construction type, there is limited information available.

Table 1. Information on wind turbines considered in different data sources

Data Source	The present paper	Ref. [3]	Ref. [5]	Ref. [6]	Ref. [7]
Location	Southeast coastal region in China	South India	Schleswig Holstein (Germany)	Sweden	North German Plain; German coast; German highlands.
Stall- or pitch-regulated	Pitch-regulated	Stall-regulated	Both	Both	Both
Direct or indirect drive	Indirect drive	Indirect drive	Both	Both	Both
Fixed or variable speed	Variable speed	Fixed speed	Both	Both	Both
Number of wind turbines	134	15	650	1509	1500
Rated power(kW)	1500	225	300, 600, 1000	N/A	N/A
Rotor diameter (m)	77	29.8	N/A	N/A	N/A
Hub height (m)	70	45	N/A	N/A	N/A

The second aspect which needs to be addressed is that various terminologies used for different wind turbine parts. A wind turbine is made up of a number of key parts, and a data source provides failure information for each part [8]. Different data sources have slight variations in the name used for each part, and there is no agreed description, definition or explanation of each part in the literature. As there is no evidence to prove that the parts which have a same name in different papers have same configuration, it is questionable whether the results of the literatures could be compared.

The third aspect is to be considered is that there are differences in conclusions in the results of previous surveys. Because of impact of differences in data quality and various terminologies, it is difficult to take a broad approach to analysis to explain the cause of differences. Although four surveys showed that the electrical system had the highest failure frequency, there is no common definition of what components were in the electrical system.

2.3. Methodology

A survey includes the processes of data collection and data analysis. The former process was not emphasized in the literature. However, it is also important for a survey to collect and pre-process data, because inhomogeneous data will limit the application of statistical modelling, such as Weibull model, in further work.

The method applied in the present survey has covered the following steps.

- *System selection and data collection*. A single type of WTGs sited at a single location was chosen as a surveyed sample in this paper. As a result, being at the same wind farm, each WTG has the same configuration and is subjected to similar conditions in the same wind farm. In this survey the primary source of data collection is 181 daily operational reports written by the wind farm operators. The reports include values of power generation, wind velocities, stoppage time due to low wind speed, all events and state of each WTG.
- *Preprocessing of data*. A proper knowledge and understanding of failures, subsystems, equipment and components of the WTGs was developed in this step. A table which contains information including when WTGs shut down due to failure events, when WTGs restarted producing, where the failures located, what actions were carried out for the failures and how much generation lost during per downtime has been made in this survey. Therefore, the failure frequencies and downtimes could be directly obtained by calculations. It is noted that "Loss of generation per failure" was calculated using the difference between the output from a failed WTG and the average generation of neighboring WTGs.
- *Data analysis and comparison*. In this step all the parts of a WTG are classified in three levels: subsystem level, equipment level and component level. The level of analysis moves from the subsystem level to the equipment level, and further on to selected critical components of these subsystems. Failure frequencies and downtimes are two criteria to judge which subsystem or component failures are critical. These criteria were also used in the literatures. As introduced above, although it is hard to compare the results of different surveys, it is possible to find areas of commonality.
- *Identification of failure modes and failure causes in the critical components*. In the survey presented here a detailed study for the critical subsystems or components will be conducted. It is possible to find out a root cause of critical component failures with results of the survey. A possible method to avoid the failure is explored.

3. Concepts and System Description

3.1. Failure

The International Electrotechnical Commission (IEC) has defined a failure as the termination of the ability of an item to perform a required function [9]. Failures could be classified according to the failure modes and causes [10] which should be understood prior to failure analysis.

A failure mode is identified through a symptom by which a failure could be observed [10]. A failure cause is a root cause which can lead to the occurrence of a failure, and has been defined as the circumstances during design, manufacture or use, which has led to a failure [9].

3.2. Components, equipment and systems

According to the IEC 60050 International Electrotechnical Vocabulary (IEV), a component is a constituent part of a device which cannot be physically divided into smaller parts without losing its particular function [9]. Statistically, components are not repairable, have a finite life and usually have a single failure mode [11]. The operational life characteristics for a population of identical components can be represented fairly well by one of the standard statistical distributions.

A piece of equipment is an assembly of components that operate to a specific function [11]. Any component failure could lead to the equipment failure; therefore the equipment may have multiple failure modes. Equipment can be restored to operation by replacement of the failed components [11].

In this paper, systems, the most complex among the three terms, generally are made up with a combination of equipment and components. During the system lifetime, components may be replaced and the equipment may be repaired in situ or replaced [11]. It is worth noting that the term "system" should be qualified when it is not clear from the context to what it refers, such as control system. Hereafter subsystems are defined in the same way as systems except that level of subsystems is lower than level of systems, i.e., a system could be divided into subsystems which could be also divided into several equipment and continue.

3.3. A description of wind turbine generator system (WTG)

In this paper, the objects being surveyed are pitch-regulated variable speed wind turbines with doubly fed induction generators (DFIG). Fig. 1 (a) shows the schematic of the WTG which contains a DFIG, a gearbox and a partially rated converter [12]. During operation, the main shaft transmits the mechanical power from the rotor to the gearbox which drives the generator rotor to rotate. The generator stator is, via a transformer, directly connected to the electric power grid. The generator rotor connects to the transformer through a partially rated converter which allows the generator rotor speed to vary by 30% above and below synchronous speed [12].

In this paper, the whole WTG is regarded as a system which includes:

- Six subsystems, i.e., blade pitch system, yaw system, hydraulic system, lubrication system, braking system and control system;

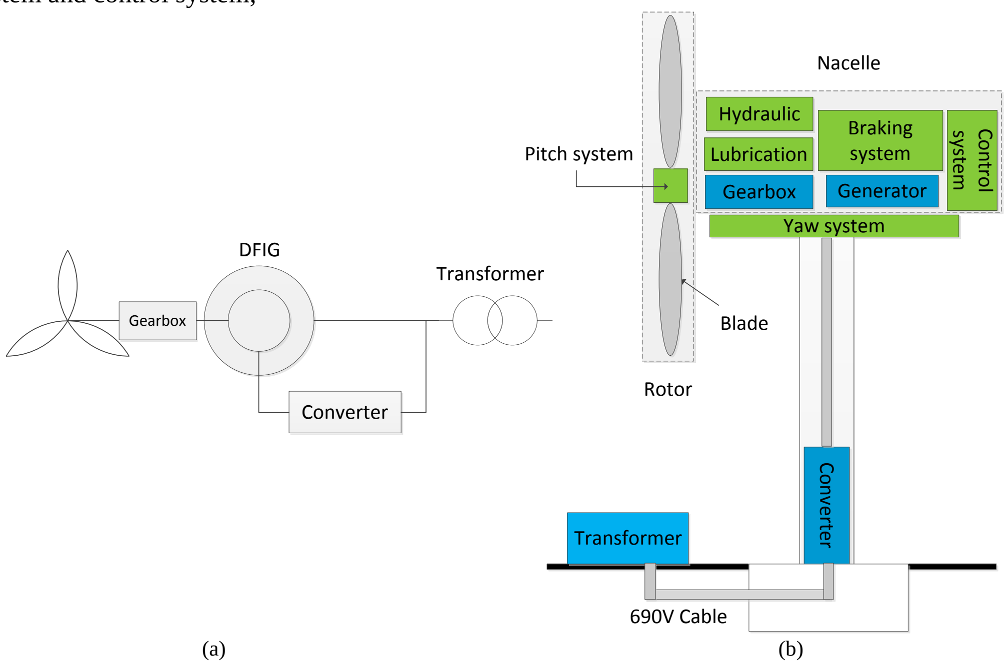

Fig. 1. A schematic of the WTG system: (a) structure of the WTG and (b) subsystems, equipment and main components in the WTG.

- Four pieces of equipment, i.e., gearbox, generator, converter and transformer;
- Four main component classes, i.e., blades, sensors, cables and others.

Fig. 1 (b) illustrates the subsystems, the equipment and main components which are independent in the WTG. The large number of sensors distributed throughout the WTGs means that it is not possible to represent them in the figure. Subsystems and equipment are classified depending on where they are located. For example, the pitch system that is mounted in the hub includes controllers, but the pitch controller is not classified into control system. In this paper, there are some components which have the same name but are present in the different subsystems or equipment, such as bearings which exist in gearboxes, generators and pitch systems [12]. However, those subsystems and equipment are still independent, and the qualified item will be used, such as gearbox bearing and generator bearing.

There are two advantages on this definition of WTGs. Firstly, it is easily understood and accepted. Components of each independent equipment or subsystem are gathered in the specific area. The components of the pitch system are mounted in the hub, and similarly, a component found in the master control cabinet belongs to the control system.

Secondly, components of each subsystem are subjected to same environment in the WTG. For example, all the components of pitch system are mounted in the hub and rotate with the rotor. It is possible to say that it is more difficult to access the pitch system components than the components in the converter, which is static at the bottom of the WTG.

4. Results and Discussions

4.1. Source for statistical data

The surveyed wind farm is an onshore wind farm, located in the southeast coastal region in China. There are 134 DFIG-WTGs each with a capacity of 1.5 MW. All the WTGs have been commissioned since the end of 2010. In this paper, 307 failures which occurred in those 134 WTGs from January to June in 2011 are investigated.

In this case the WTGs have been remotely monitored. If a failure occurs inside the WTG, an alarm is sent to the wind farm operators. Often the WTG can be restarted because many alarms are not crucial. However, if the failure of the WTG is severe, a visual inspection of the WTG has to be made. At the same time, maintenance and repair personnel are sent to repair or replace the damaged components.

4.2. Failure frequency and downtime

Fig. 2 shows the percentage breakdown of failures that occurred from January to June in 2011. The majority of failures (32.25%) were linked to the pitch system followed by control system (15.64%) and sensors (12.7%).

Fig. 3 illustrates the distribution of downtime per part in the wind farm during the six months. The results show that the cable failures cause the most amount of downtime (2,033 hours or 29.29%) followed by pitch system (14.74%) and control system (14.02%).

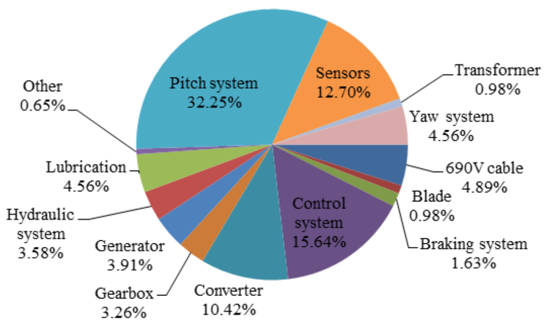

Fig. 2. Proportion of failure counts for each subsystem, equipment and component.

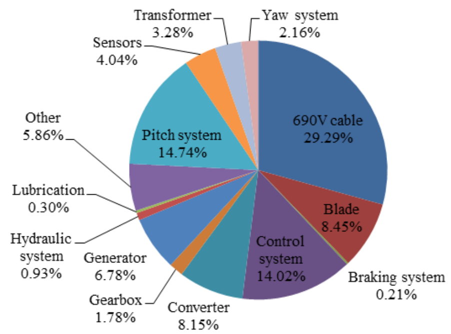

Fig. 3. Proportion of downtimes per subsystem, equipment and component.

It is noted that the downtime does not consider "time to repair" and other factors which influence downtime. The times when staffs are available to carry out repairs will affect downtime, in the wind farm the working day is 7:00 am to 9:00 pm and all work should be conducted in this duration. Finding out the failure types and waiting for new components for replacement also increase the downtime. In addition, environment is also a main factor which influences the downtime, e.g. bad road conditions may cost personnel more time to access the failed WTG and cases where the wind speed is higher than 10 m/s may also delay the repair, because the wind farm regulation forbids repair personnel accessing the nacelles under these conditions.

The majority of cable failures occur on the power cable between the transformer and the converter. It is estimated that 87% of cable failures were due to neutral conductors been stolen, or third party damage. If actions can be taken to prevent cable theft, outage due to "cable failure" would reduce significantly. The rest of cable failures are caused by short circuit. It is calculated that the average downtime per cable failure is 135.57 hours which ranks second among other type of failures, only after blade failures. However, so far there is no warning system of cable failures in the studied wind farm. This justifies the necessity to monitor the power cable of the WTGs.

Table 2. Downtimes and number of failures for each equipment and component in the pitch system

Equipment and components	Number of failures	Downtime (h)	Downtime per failure (h)
Battery sets	8	93.4	11.67
Controllers	24	135.7	5.65
Encoders	28	218.2	7.79
Electric motor	5	214.3	42.86
Slip ring	12	139.6	11.63
Other	16	111.0	6.94
Unknown	6	111.4	18.57
Total	99	1023.6	

This paper carried out a detailed study on types of failures which occurred in the pitch system, as shown in Table 2. The table only considers component types which have failed more than 4 times. It can be seen that encoders have the largest number of failures (28 times), closely followed by that of pitch controllers (24 times). The operators judged that the quality of encoders and controllers is a root cause of the failures. The total downtime caused by electric motor failures is high, close to the total downtime caused by encoders in the pitch system. Although electric motors have the least number of failures, the downtime for resolving this is the longest.

It is noticed that 22.2% of pitch system failures were caused by loosed components. To eliminate the failures due to loose components requires parts to be securely fastened thus, without requiring replacement it would be possible to increase operational time. Similarly, it is estimated that 83.3% of slip ring failures which account for 10% of the total number of pitch system failures are caused by pollution. Debris and dust from wear and tear may contaminate the lube in the slip rings, lowering their ability to transmit power and signals. If maintenance personnel are given guidance to pay attention to the loosed components and the cleanliness of slip rings during scheduled maintenance, 32.2% of the pitch system failures may be avoided.

There was a loss of 2,414.367 MWh which equates to 1.38% of the wind farm electricity generation during the six months. If the failures had been eliminated completely, the capacity factor of the six-month operation would have increased by 0.28%. As introduced above, the 87% of cable failures will cause a loss of 605,967.5 kWh which equals to 0.35% of the wind farm generation during the six months.

In addition, 59 failures (19.2% of total failures) were caused by loosed components. There are 142,803.5 kWh lost (0.08% of the wind farm generation) due to the 59 failures in the six months. Although loosed components may not cause significant loss of generation, it may lead WTGs to frequently restart which will in turn increase fatigue loads on the components [13].

4.3. A comparison between results of this paper and those of literatures

This paper carried out a comparison of the results in different papers. The available statistics from a wind farm in India [3], the WMEP [7], the LWK [5], the Swedish source [6](a), the Finnish source [6](b) and the German source [6](c) have been used to find representative values for downtime of an amount of failures for each subsystem, equipment and component. A compilation of the most interesting values is presented in Table 3.

Table 3. Comparison among quantitative results presented in the literatures.

Data source	The present paper	Ref. [6] (a)	Ref. [6] (b)	Ref. [6] (c)
Average number of failures per turbine per month	0.382	0.0335	0.115	0.198
Average downtime per month	8.64	4.33	19.75	12.42
Average downtime per failure	22.62	170	172	62.6

It is clear to see that the findings are different between this paper and the previous work. The average number of failures per turbine per month is higher in this paper compared to other surveys of data sources. It is noted that all the wind turbines studied in the paper started to operate at the end of 2010 and, according to the bathtub curve which describes a particular form of the hazard function, new products have high possibility of failing [10]. This would help explain the poor performance of the site considered and examination of later data will allow this factor to be assessed. In addition, only the major incidents are reported in source [6]. However, the failures in this paper include all types of failures occurred in the WTGs. There are 256 failures whose downtime is less than 24 hours in this paper. The 51 failures which take 16.6% of total number of failures need more than 24 hours to restore.

It is found in the study that the blades are the components that demand the longest downtime per failure. The reason for this is that they are big and cumbersome to replace or repair, and replacement involves special devices such as cranes, etc. Since blades rarely fail, one reason for the long downtime could be that spare parts need to be ordered which could prolong the time to repair.

Comparing the results of this paper with those presented in [3], the majority of failures which relate to electrical and electronic components mostly occur in megawatt wind turbines. Other surveys [5][6][7] focused on different WTGs which have different capacities, therefore their results are difficult to compare. However, it is possible to conclude that the most frequent failures occur in electrical components in the results of [5], [6] and [7]. Statistics indicate that 80% of the total failures occurred in the electrical and electronic components. It is crucial to improve operation and maintenance for avoiding electrical and electronic failures. The quality of electronic components should be taken into account when ordering components, in order to reduce the number of electronic failures.

5. Conclusions

The number of failures and downtimes for each component, equipment and subsystem of WTGs were surveyed in this paper. An effort is made in the present paper to prove that there is a difference between the statistical results of specific WTGs and general types of WTGs. Important conclusions drawn from the present analysis are as follows.

- The wind farm studied is in its first operational year and three WTGs failures have occurred among per month.
- Encoders in the pitch system of WTGs have failed 28 times in the six months studied. This makes the pitch system one of the most critical parts in a WTG.
- Electric motor may fail fewer but each causes a downtime of 42.86 hours per failure.
- The cable failures caused the longest downtime, over 2,000 hours, when compared with other failures. It is estimated from the study that 87% of cable failures are caused by third party damage. Improving wind farm management and security may reduce cable theft and the wind farm generation will increase, e.g. by 0.35% in the studied six months.
- It is estimated that 22.2% of pitch system failures were as a result of loose components.

- It is estimated that 83.3% of slip ring failures which account for 10% of the total number of pitch system failures are caused by pollution. These failures could be prevented by improving the scheduled maintenance.
- It is estimated that 19.2% of total failures were caused by loose components. Although this may not cause a significant loss of generation (0.08% of output) due to the short repair time, this may cause frequent restart of WTGs and this, in turn, may result in additional electrical and mechanical stress failures.
- Statistics indicates a loss of 2,414.367 MWh during the studied six months. If the failures had been eliminated completely, the wind farm generation could have increased by 1.38% and the capacity factor of six month operation would have increased by 0.28%.
- Compared with failures of small WTGs, failures of megawatt WTGs are mainly linked to electrical and electronic components. Statistics indicates that 80% of the total failures occurred on the electrical and electronic components.

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