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# Analysis and Assessment of Onshore and Offshore Wind Turbines Failures

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**ABSTRACT**

The rapidly increasing energy demand and the inevitable negative effects on the environment caused by fossil-fuelled energy production have made renewable energy technologies increasingly important and preferred among the widely used energy sources during the last decades. Wind energy is one of the leading renewable energy technologies. Wind energy is a carbon-free, environmentally friendly and competitive technology. A step forward in production of wind energy is offshore and onshore wind turbines, with their numerous advantages. Today, the increasing energy needs make onshore and offshore wind turbine applications an increasingly widespread renewable energy source. However, with this change, challenges arise during the operation phases as being associated with the strength of the wind turbines. Potential failures must be known in advance so that they can be dealt with strongly and effectively in the design phase. Damages and failures have a negative effect on the continuation of the operation and cause material and economic impacts. In this paper, the findings from a collection of failure data are presented. The database is available on request. The novelty of this paper is to assess and analyse the damages to wind turbines onshore and offshore in order to reduce the risk of potential failures, damages and collapse of wind turbines. According to the results of these studies and analyses, the database of failures experienced is considered to represent the general failure rate in the industry. This paper brings solutions and suggestions for future studies by pointing out risks and the failure situations that wind turbines are exposed to. It can help innovative solutions with the presentation of a detailed view of risk and failure situations.

## 1. INTRODUCTION

This paper analyses and assess damages to wind turbines, onshore and offshore with the objective to reduce the risk of wind turbine failures and collapse by learning from these failures. Thus, damages and failures that may occur in wind turbines are identified, and the importance of strengthening wind turbines as well as maintenance requirements will be discussed.

Today, single wind turbines are typically producing 6 MW and the power output is increasing from new turbines. In addition to the power produced, the blades' length is also increasing. While the blades were around 20 m long in the 1980s, they typically have reached 100 m in the 2000s. As of the 1990s, the installation of offshore wind turbines started. The increase in wind energy units installed after 2000, the decrease in productive locations for onshore wind energy generation, and the high maintenance and repair costs of hard-to-reach locations onshore have accelerated the installation of offshore wind turbines. Offshore wind farms can be found in Europe and in many parts of the world. In Figure 1, the blade lengths and power distributions of wind turbines are shown as function of years [1].

The interest in offshore wind farms, which started to be installed in Europe, is increasing day by day, and it is possible to come across these projects in many different regions of the world. In recent years, even the world's leading wind power plant manufacturers have aimed to create more farms using their own designs [2]. In 2009, the first prototype floating wind turbine, "Hywind" was installed in Norwegian waters. This floating wind turbine, located 10 km from land and in 200 m deep, produced 2.3 MW of power. This concept also allows the establishment of wind farms in deeper waters [2].

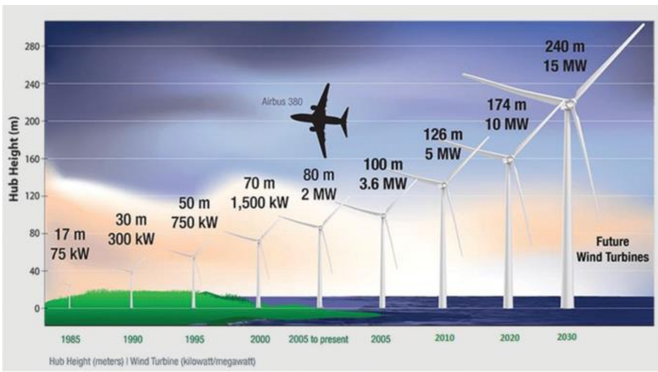


**Figure 1.** Hub height of wind turbines and distribution of power by years, source [3]

Global wind power has roughly quadrupled over the past 10 years, making it one of the most cost-competitive and resilient energy sources worldwide, according to the 2021 Global Wind Report [4]. While this is the case, with the increasing investments and energy demand, risk situations such as failures, collapses and fires during the operation of wind turbines have been observed widely. A wind turbine must operate safely for operators working on maintenance, for the safety of third parties and for itself to avoid financial loss. All risks and hazards must be minimised in order for the wind turbine to work in an orderly and efficient manner. It is possible to obtain a long-lasting and sustainable wind turbine life by minimising these risks. Blades, generators, structural damages and gearboxes come to the fore as the most common failure components of wind turbines [5]. These failures cause extra maintenance costs and preventive approaches during the design phase. In this research, a total of eight failure types that occur during the operation of wind turbines and cover most of the failure types are discussed.

## 2. TYPES OF FAILURES

### 2.1 Blade failure

The blades are responsible for using the mechanical energy of the wind and are exposed to wind loads during operation. In addition, they may be exposed to abrasion or higher loads, due to environmental conditions such as rain, snow and extreme storm, etc. It can be said that the starting point of the failure in the blades is the transport stage. While the wind turbine blade, which is out from production, is transported to the operation area, minor or major damages may occur in certain parts of the blade. These damages may increase with the assembly and may fail quickly due to the loads it is exposed to during use [6]. Another reason is the blade size. Making the blade larger to use, more of the mechanical energy in the wind also could cause rotor imbalances, corrosion and greater loads on the blade. Blade failures result in blade dropping, breakage, bending or extreme wear [7].

### 2.2 Generator failure

Generators are the parts used to convert the energy obtained into electrical energy. There are many types of generators used. The most commonly used generator type is the double-fed asynchronous generator. There are wind turbines that have become unusable due to generator failures. Failures in generators can be divided into mechanical and electrical failures. Mechanical failures are mostly caused by misalignment or bearing failures. Electrical faults are caused by stator and rotor winding faults and slip ring faults [6].

### 2.3 Yaw system failure

The yaw system is the system used to position the blades according to the desired angle. In yaw systems, shaft cracks, gear failures, bearing failures, and damage to these parts are encountered. These damages occur in case of bad weather conditions and exposure to heavy loads [8]. Failure in the yaw system can lead to larger failures, for example, damage to incorrectly positioned blades or excessive load on the blades.

### 2.4 Gearbox failure

The gearbox is a system consisting of gear wheels that bring the rotational speed of the low-speed shaft to a suitable level for electricity generation. In wind turbines, fixed and variable gear ratios can be used between the turbine rotor and the electric generator. The use of variable gear ratios can result in more stable electricity and provide higher aerodynamic efficiency. In gearboxes that are under heavy operating conditions for a long time, shaft mis- alignment, bearing damage, gear damage, shaft damage and other types of failure occur [6].

### 2.5 Temperature and environmental failure

Wind turbines are installed in a variety of different geographical areas, from a hot and dry climate to a humid and cold climate. In addition, the installed wind turbine is exposed to different climatic conditions and seasonal changes throughout the year. These seasonal and climatic changes have an impact on wind turbines. For example, the gearbox lubrication effect may decrease in cold temperature, and the lubrication must be chosen according to conditions in the region where the wind turbine will be installed. With the change of seasons, the wind turbine is subject to different conditions. The manufacturer must take into account the climatic conditions of the region where the wind turbine will be installed. Different com- ponents are used to cool the engine section of a wind turbine in summer and to heat it in winter. These parts can be fans, blowers and heaters. In summer, blowers that circulate the outside air inside are used to cool the gearbox and generator located in the nacelle part. In the winter, if the temperature inside the nacelle is not sufficient, the heaters will produce warm air in order to keep the interior at the desired temperature. Nonetheless, if the wind turbine is shut down for a long time, the gearbox lubricate may decrease to ambient temperature and cause damage. Temperature change is not only important for selection of lubrication. At the same time, bad weather conditions can affect the maintenance work, resulting in longer periods between maintenance and downtime. Another effect is on anemometers. The anemometer measures the wind speed and maintains turbine control. Extremely cold weather or freezing rain may stop the anemometer from working and the wind speed may be zero, in which case the control orders given will be wrong, resulting in possible damage. For offshore and coastal installations, the effect of sea salt on various components must be taken into consideration, whereas the onshore wind farms are immune from these effects [9].

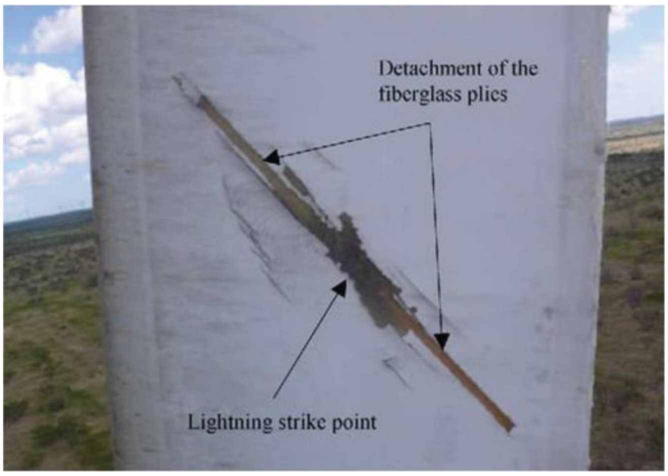


**Figure 2.** Damage from lightning to a turbine blade [10]

### 2.6 Lightning

Lightning is the discharge of millions of volts of static electricity between the clouds and the ground in a very short time with intense light, thunder and a great destructive power. As the size of the wind turbines increases and the blade length increases, the blades become much more open to lightning and attract lightning just like a lightning rod. The impact of this destructive power on any metal or non-metal part on the wind turbine can cause irreversible damage to the wind turbine. Especially the damage it causes on the blades can prevent the wind turbine from working [9]. An example of blade damage due to lightning strike is shown in Figure 2.

### 2.7 Ice forming failure

Ice formation can be observed on the blades of wind turbines that are freezing cold and operating at temperatures close to the freezing point. Different amounts of ice may be formed due to undercooled rain or humidity in the air. The ice layer formed on the blade edges changes the blade profile and causes the drag and lift coefficients to change. The power capture capacity of the blade decreases, causing less energy to be generated. Depending on the weight of the ice, it may even disrupt the balance of the blades. At the same time, in much freezing rain and cold, the entire air foil can freeze, resulting in high losses. Another issue is the falling of ice pieces from a height. It can damage the surrounding structures, living things or settlements [9].

### 2.8 Structural failure

Another type of failure is structural failures. These failures are causing results such as col- lapse, fracture or blade fracture. There are two main causes: extreme winds and the failure of the ground where the wind turbine is located.

Extreme winds, potentially combined with icing caused by undercooled rain, can be very dangerous to the structural integrity of wind turbines. Especially in regions where natural disasters such as typhoons and hurricanes occur, damage to wind turbines is inevitable in some cases, and blade fracture and simple failures are considered acceptable. However, the wind turbines should be designed to account for large forces from the wind. When the wind speed is more than 25 m/s wind speed, the operation mode of the turbine is changed to the 'standstill' or 'idling' state. In these cases, the blades return to the feather position and the turbine is free to yaw. This allows the nacelle to turn in the direction of the wind. In this case, it is ensured that both the blades and the tower are exposed to the minimum wind loads. How- ever, in case of any power loss, mechanical failure, electrical imbalance or instability (likely to be seen in extreme typhoons and hurricanes), the operating mode is 'fault parked' or 'emergency stopped'. In these operating states, the blades return to the feather position, but the yaw system is locked. As a result, the turbine has to maintain the wind coming from any direction without changing its position. In such cases, exposure to high forces as well as weakness in the ground could cause wind turbines to collapse or get damaged easily. Due to the design, reductions in shell wall thickness and low bending stiffness may appear in certain parts of the wind turbine making them susceptible to damage [11].

## 3. METHODS

In this paper, specific wind turbine failures are identified by evaluating data available from the internet, open literature or other sources, and categorising the failures and damages of wind turbines in the light of the data obtained. Malfunctions, risks and failures that occur in wind turbines are collected and their causes are stated. It should also be noted that in some of the situations that resulted in fire, as listed in the dataset, the cause of the fire was not specified as the reason was not stated by the data sources or the authorities. However, these cases cover some fire data, not all fire data as stated. For example, statements such as 'the wind turbine engine caught fire', 'the nacelle caught fire even though there was no storm', 'the engine cover started to burn even though there was no lightning or storm' and 'the reason is unknown' were found in the source base. In these cases, if there was no lightning or storm, the failure type is specified as generator failure in this study. The date of completion of the failures database was May 4, 2022. Additionally, although the sample identified is large and suitable for careful assessment, it should be noted that it is likely that there are other failures that are not identified and recorded.

### 3.1 Data collection and data review

The dataset analysed in this study is a compilation of 458 news reports from 2010 to 2022. The data source was created using the results obtained from the Google search engine using the search terms 'wind turbine failures', 'wind turbine accidents', 'wind turbine collapse', etc., and the dataset summarises the results of many papers and literature studies reviewed throughout the study. In many of the resulting news articles, irrelevant, repetitive and unverifiable news were eliminated. Only news reports that provided a certain level of details were included, and a most reliable data were created. All the data obtained are listed in detail in the dataset.

This analysis is based on public information about failures and risks news. Without full access and detail to all wind turbine failures and accidents, it is impossible to say that the data used in this study or similar studies are representative of all wind turbines. It will not be possible to convince all wind turbine manufacturers to share all their data on accidents, let alone convince one manufacturer. The data in this study are reliable as the database was created with precision and meticulousness regarding data collection and examination, but it should not be forgotten that there are additional failures that are not recorded.

Most of the sources of the data obtained are in English. In terms of analysis quality, data quality and study reliability, the data have been validated, with special emphasis on the translation of technical terms in addition to high translation quality in case of data identified in other languages. All of these data, representing failures during 2010–2022, were related to the operation of offshore and onshore wind turbines. Therefore, failure and risk factors during construction or transportation are not included in the data. Details such as location, date, type of failure, cause of failure, type of wind turbine and more features have been carefully manually generated by reading each news reports in detail and understanding the content and researching online the information to complement any missing information. Data sources have been listed in a database in order to ensure originality and scientific reproducibility.

### 3.2 Data attributes

The attributes in the structured dataset are the following:

- Turbine No: Turbine number defined for each failure
- Year, month and day: Year, month and day of failure reporting
- Wind turbine location: The specific location of the turbine and name
- Location: State, province and county in which the failure occurred
- Country: Country where the failure occurred
- Failure location: Section showing which part of the wind turbine fails
- Failure type: Section showing the type of fault
- Failure cause: Section that explains the reason for the failure
- Failure effect: Showing damage and result of the wind turbine failure
- Type: Offshore or onshore wind turbine classification

## 4. RESULTS

### 4.1 Failure rates

Data analytics refers to the analysis of data collected in order to extract patterns, identify the desired information and create knowledge in line with the determined purpose. This section summarises the data collected and generated during the research, such as failure rates, country distributions, risk factors, with table and graphic analyses. The first analysis in this research was the analysis of the collected data showing the rate distribution of the failure types of the datasets. The chart in Figure 3 shows the failure rates.

The first analysis focused on the distribution of failure rates as shown in the above list. Yaw system failures were not found in the collected data, this detail is evaluated as a comment in the next section. Failure rates are also shown in Table 1 for easier assessment of the graphic results.

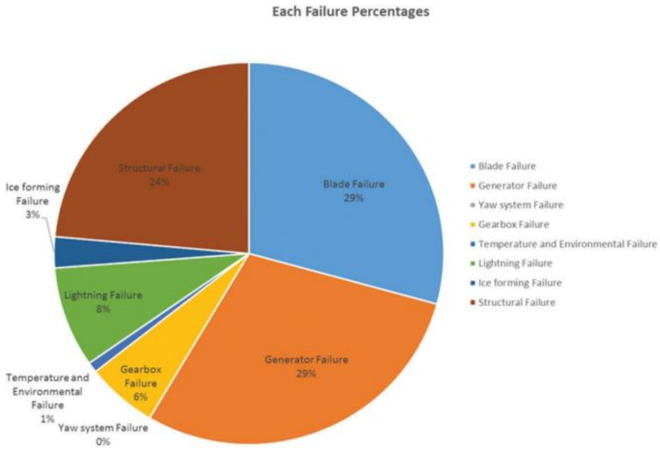


**Figure 3.** Wind turbine failure rates

**Table 1.** Failure rate percentages

| Failure type | Failure percentage (%) |
|---|---|
| Blade failure | 29 |
| Generator failure | 29 |
| Structural failure | 24 |
| Lightning failure | 8 |
| Gearbox failure | 8 |
| Ice forming failure | 3 |
| Temperature and environmental failure | 1 |

**Table 2.** Analysis of causes of failure

| Failure type | Percentage due to this failure type | Failure cause | Percentage of failure cause |
|---|---|---|---|
| Blade failures | 29 | Storm | 76 |
| | | Material fatigue | 9 |
| | | Cable fault | 2 |
| | | Sensor fault | 2 |
| | | Bolt fault | 11 |
| Generator failures | 29 | Electrical fault | 28 |
| | | Energy fluctuations | 5 |
| | | Storm | 22 |
| | | Short circuit | 28 |
| | | Human failure | 6 |
| | | Mechanical fault | 11 |
| Structural failures | 24 | Foundation fault | 7 |
| | | Storm | 63 |
| | | Mechanical fault | 15 |
| | | Human fault | 1 |
| | | Collison | 4 |
| | | Equipment fault | 7 |
| Lightning failures | 8 | Lightning | 100 |
| Gearbox failures | 6 | Storm | 5 |
| | | Break part fault | 20 |
| | | Material fatigue | 20 |
| | | Bearing fault | 15 |
| | | Oil leak | 40 |
| Ice forming failure | 3 | Ice formation | 100 |
| Temperature and environmental failure | 1 | Other types of failure | 100 |

### 4.2 Causes of failures

The percentage shares of the causes of blade failures, which have a high rate of overall failure, are shown in Table 2. As a result of these failures and risks, results such as blade break, falling, damage to the blade, bending of the blade were encountered.

4.2.1 Generator failure

When the known causes of the generator failure data obtained are examined, the percentage of failure causes is as seen in Table 2. Short circuit and electrical faults are seen to contribute with 28%. Electrical faults include faults made in the electrical panel, voltage conditioning fault and converter fault. It is also seen that the failure rate in the generator due to storms is 22%, mechanical faults represent 11%, human faults are 6% and energy fluctuations are 5%. The vast majority of generator failures result in fire.

4.2.2 Structural failure

When the percentiles of the known causes of structural failures are examined, wind turbines were damaged due to storm with 63% in the first place, mechanical failures such as misalignments and stabilisation faults are 15%, high maintenance costs, faults such as missing mechanical parts are equipment failures 8%, 4% is collision and 1% is human fault. The vast majority of structural failures result in the collapse of wind turbines.

In Table 2, percentiles of the causes of gearbox failures, which constitute 6% of general failures, are shown.

4.2.3 Gearbox failure

The main problem of gearbox failure causes is oil leakage with 40%. It was seen that the braking system and material fatigue represents 20%, the faults in the bearing 15%, and the failure and risk situations as a result of the storm 5%.

### 4.3 Distribution by countries

Another analysis focused on the distribution of failures by country, as shown in Figure 4. The majority of the failures in the dataset occur in the countries United States, Germany, United Kingdom and Canada.

Because the research is conducted and reported in English and the search terms used were in English, probably some failures in non-English and non-Scandinavian-speaking countries are missing in the full dataset. However, it is expected that the distribution of failures will be the same in case these data were also included.

Considering the distribution of faults by country, United States is in the first place with 31%, in the second place is Germany with 24%, in the third place is United Kingdom with 16%, in the fourth place is Canada with 7% and in the fifth place is Denmark with 3%. More detailed information can be found in the dataset. According to the collected and ana- lysed data, the distribution ratio of the failure types according to the countries is given in Figure 5.

In Table 3, the distributions by country are examined in detail. Blade failures, generator and structural failures seem to be leading as a result of examining the distributions in countries with high number of data, such as United States, Germany and the United Kingdom.

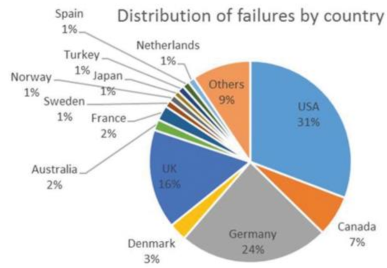


**Figure 4.** Distribution of failures by country

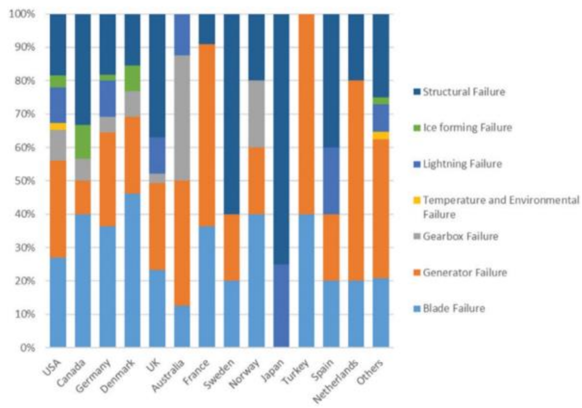


**Figure 5.** Failure types by country

**Table 3.** Percentages of failure types by countries

| Countries (total cases) | Blade failure | Generator failure | Gearbox failure | Temperature and environ- mental failure | Lightning failure | Ice formation failure | Structural failure |
|---|---|---|---|---|---|---|---|
| United States (141) | 27 | 29 | 9 | 2 | 11 | 4 | 18 |
| Canada (30) | 40 | 10 | 7 | 0 | 0 | 10 | 33 |
| Germany (110) | 36 | 28 | 5 | 0 | 11 | 2 | 18 |
| Denmark (13) | 46 | 23 | 8 | 0 | 0 | 8 | 15 |
| United Kingdom (73) | 23 | 26 | 3 | 0 | 11 | 0 | 37 |
| Australia (8) | 13 | 38 | 38 | 0 | 13 | 0 | 0 |
| France (11) | 36 | 55 | 0 | 0 | 0 | 0 | 9 |
| Sweden (5) | 20 | 20 | 0 | 0 | 0 | 0 | 60 |
| Norway (5) | 40 | 20 | 20 | 0 | 0 | 0 | 20 |
| Japan (4) | 0 | 0 | 0 | 0 | 25 | 0 | 75 |
| Turkey (5) | 40 | 60 | 0 | 0 | 0 | 0 | 0 |
| Spain (5) | 20 | 20 | 0 | 0 | 20 | 0 | 40 |
| Netherlands (5) | 20 | 60 | 0 | 0 | 0 | 0 | 20 |
| Others (43) | 21 | 42 | 0 | 2 | 8 | 2 | 25 |

### 4.4 Offshore versus onshore facilities

Another analysis is the failure rates of wind turbine types. There are 29 offshore wind turbines and 429 onshore wind turbines in the dataset with covers 458 cases. Failure rates of offshore and onshore wind turbines are shown in Figure 6.

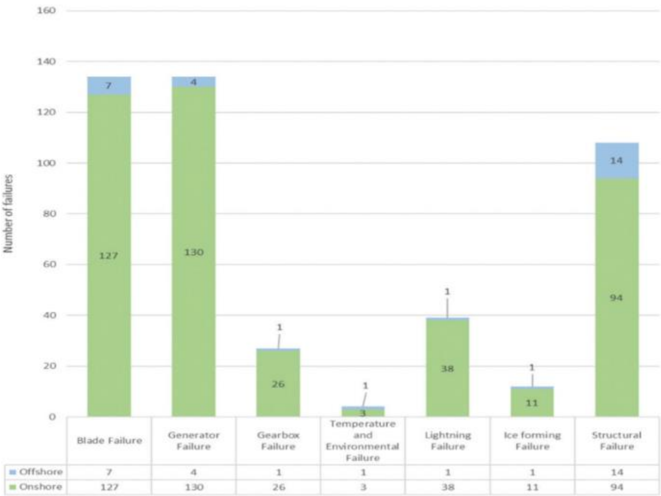


**Figure 6.** Failure rates of offshore and onshore wind turbines

Regarding the onshore wind turbine failure types, generator failures ranked first with 30.3%, followed by blade failures with 29.6%, structural failures with 21.9%, lightning with 9.2%, gearbox failures with 6%, ice forming failure with 2.3% and finally temperature and environmental failures are included with 0.7%.

### 4.5 Consequences of failures

In the light of the data obtained, the causes and consequences of the failure types are shown in Table 4. Failures represent various risks and damages. These summary statistics, based on the recent decade of failures, can be used in many ways, including where to focus on reducing failures and in the calculation of rates for risks.

## 5. DISCUSSION

The analysis of the dataset aims to create sustainability for the operation of wind turbines by focusing on the failure and risk situations of offshore and onshore wind turbines. In this section, our explanations for each type of fault and discussion on the best mitigating measures that can be taken based on the analysis results are presented.

**Table 4.** Causes and consequences of failure types

| Failure type | Failure cause | Failure effect |
|---|---|---|
| Blade failure | Storm<br>Material fatigue<br>Cable fault<br>Sensor fault<br>Bolt fault | Fall down<br>Bend<br>Crack<br>Break<br>Stop operation |
| Generator failure | Electrical fault<br>Storm<br>Energy fluctuation<br>Short circuit<br>Human fault<br>Mechanical fault | Fire<br>Noisy operation<br>Stop operation<br>Oil leak<br>Explosion |
| Gearbox failure | Storm<br>Brake part fault<br>Material fault<br>Bearing fault<br>Oil leak | Idle blades with high rotation speed<br>Stop operation<br>Fire<br>Blade and gearbox fall down<br>Gearbox break |
| Temperature and environ-mental failure | Cold weather<br>Storm<br>Sudden weather changes | Stop operation<br>Oil leak<br>Expansion |
| Lightning failure | - | Fire<br>Stop operation<br>Crack on blades<br>Damage to turbine |
| Ice forming failure | Minus temperature | Ice forming on blades |
| Structural failure | Foundation fault<br>Storm<br>Mechanical fault<br>Human fault<br>Collision<br>Equipment fault | Collapse<br>Stop operation<br>Parts fall down<br>Damage to turbine<br>Tower bend<br>Unstable<br>Remove to turbine<br>Fire |

The vast majority of blade failures are caused by storms. In addition, results such as falling, bending and cracking of blades as a result of material fatigue, wiring and assembly faults, and sensor faults were observed. It should, however, be noted that data about the age of failed blades is not known and aero-elastic considerations have recently become much more important during the design phase of modern wind turbines to avoid blade failures. Aerodynamic and structural modelling should be integrated according to the location of the offshore and onshore wind turbines, and climatic conditions should be among the main fac- tors to be considered in wind turbine design. A delicate balance must be found between durability, aerodynamic properties and noise. Especially in today's wind turbines with large rotor diameters, this issue is of vital importance in order to solve the interaction of fluid and structure and to minimise excessive loads. In addition, the selection of aero-elastic materials should be made under these conditions, and structural health monitoring by using online feedback sensors should be implemented in wind turbine blades that are quite long. In order to avoid these failures and associated risks, regular and routine maintenance work should be carried out, and the time between maintenance should be decreased if necessary.

The main causes of generator failures are electrical faults that include short circuits and energy fluctuation, storms and mechanical failures. The majority of generator failures result in fire, causing the entire turbine to be out of service. Since it is difficult to intervene in a wind turbine that has started to burn, the fire is expected to burn out. This type of fire not only damages the turbine, but it also damages the environment. Therefore, electric stability analysis of all turbines or wind turbines in the wind farm should be done in order to minimise and overcome generator failures. Thus, energy fluctuations, current differences and electrical faults that wind turbines are exposed to can be detected. The spectral analysis method can be used to detect winding faults, which are frequently encountered in generator failures; in this method, the fault sidebands of a signal in the frequency dimension are looked at. In this way, failures can be detected and tracked. A dynamic state space model can be created to detect short-circuit faults in the stator windings. More information on these methods can be found in the literature. In addition, there are methods that use generator output power to detect and prevent mechanical faults in the generator, such as axial misalignment. Vibration and generator current analysis can be performed for bearing failures. This situation should be prevented by simultaneous current monitoring and time-frequency monitoring.

The majority of structural failures are caused by storms. In addition, mechanical faults such as assembly and misalignment and foundation faults are among the causes. As a result of these faults, the wind turbine collapses, turbine parts fall, the turbine tower bends or becomes unstable. In order to prevent structural failures, aerodynamic and structural models should be developed, just like for blade failures. The response of the wind turbine to excessive loads should be determined beforehand. This involves collection of wind-data at site to ensure the turbines are designed to withstand the actual wind velocities and the wind turbulence at the site with a low probability of exceedance (normally the design is to withstand the wind conditions having an annual probability of exceedance of $2\times10^{-2}$. The costs of selecting a reduced probability of failure in the design phase are low and should be considered, in particular as the wind turbines are getting larger and more costly. During the wind turbine construction phase, the tower foundation should be made stable and solid. The wind turbine should be designed in accordance with climatic and environmental conditions, that is, according to the location. With the monitoring of the latest model sensors providing online feedback, the wind turbine should be kept under constant control and routine maintenance should be carried out and the frequency of maintenance periods should be increased if necessary. At the same time, maintenance activities should be considered in order to prevent assembly faults. Assembly faults can be detected by vibration analysis.

The main causes of gearbox failures are oil leakage, braking mechanism faults and mate- rial fatigue. For these reasons, results such as from idle wind turbine blades rotating at high speed and then abruptly stopping the operation, have been encountered. Gearbox diagnostics are difficult. Vibration analysis is performed for fault detection in the gearbox communication chain, but due to the working principle of the gearbox, fault detection with vibration analysis may not always be successful. Therefore, a common amplitude and frequency demodulation analysis method based on the energy separation algorithm has been proposed in the literature [12]. This method can be used to detect wear and damage in the gearbox. In order to detect gearbox failures, apart from routine maintenance, performing these analyses at regular intervals by experts can prevent oil leakage, unhealthy functioning of the braking system and material fatigue.

Regarding temperature and environmental failures and ice accumulation failures, the region where the wind turbines are located is very important. Especially if the seasonal differences in the region where the wind turbines are located are high, it is possible for the wind turbine to be affected by these seasonal differences. It is seen that temperature difference damages turbine parts and the lubrication oil. In order to prevent this situation, it is important to choose the materials and the lubrication suitable for the climatic conditions of the region where the wind turbine is located. The wind turbines operating offshore are affected by salt water and salty sea-spray, and all parts are thus negatively affected. Regular and frequent maintenance is required to prevent this situation. In addition, decrease in the air temperature to minus or close to minus causes ice formation on the blades. In order to prevent this situation, regular maintenance should be done, and operational activities should be stopped, especially in certain seasonal conditions. On the other hand, in dusty regions, a turbine eventually gets dirty. A cleaning of the blades and tower, although relatively expensive, may prolong the useful life as well as the efficiency of operation of a turbine. As a matter of fact, the inside of a turbine nacelle, hub and tower must always be kept clean from oil spills, grease and other materials used by a turbine or for maintenance works. It is the responsibility of an operator to make sure that after maintenance work, everything is back to normal, and no pieces of tools or extra stuff are left behind.

Fire and associated damage occur as a result of lightning strikes to wind turbines. There are two different suggestions for mitigating effects of lightning. The first is to protect the wind turbines from lightning, the second is to reduce the effect of lightning. First, a strong grounding system should be established to protect against lightning. It is possible for wind turbines to attract lightning due to their size. For such cases, lightning rods should be used, and the high energy voltage obtained should be removed from the system by grounding. Thus, energy fluctuations, current changes and other faults are avoided. Maintenance work should be increased, especially after stormy weather. The second method is to use coordinated surge protection units for power supply systems to prevent lightning damage. These lightning surge arrester systems are effective in the coordinated protection of wind turbine components and in reducing the consequences of sudden voltage differences.

Yaw system failures were not found in the dataset. In the obtained data and news sources, the cause of the failure was not specifically stated as yaw system failure. Among the main reasons for this is the indication of such failures as structural failures, technical failures or failures in the engine part. Although this type of failure is rare compared to other types of failures, and the fact that the owners of the companies did not specify the reasons for the failures made it difficult to identify a yaw system failure.

## 6. CONCLUSIONS

As can be seen from the data analysis, the number of offshore wind turbine failures are less than the number of onshore wind turbine failures. Apart from the fact that there are fewer offshore wind turbines and that these turbines represent a newer technology, factors such as the high installation and maintenance costs, the absence of an infrastructure that every country can establish and the inaccessibility of the place where they are located explain this situation.

From this study, it is suggested to draw attention to generator failures. As can be seen from the dataset, generator failures are common, and most generator failures result in fire. While a blade can be obtained at a certain, and perhaps high cost in case of a blade failure, the entire turbine is to be dismantled in case a generator failure is resulting in a fire. It is very common to wait for the fire to burn out on its own while taking the surroundings under control to ensure the fire does not spread to the surroundings.

While obtaining the database, many cases were evaluated, and the appropriate ones were included in this research. While collecting the data, it was found that the background reasons for failures were not specified and these data could not be used for this research. Furthermore, the transportation and construction phases (other than the operation) were not included because failures during these phases are not related to the operation of the wind turbines or the subject of this research. Also, processing the data is difficult and time consuming. There are such limitations when collecting data, but the database includes many failures, and all cases have been obtained as a result of serious investigation.

This research revealed recurring themes and patterns. It provides new insights, and has created clear and unambiguous statements as the results of the performed analysis. This research and dataset can be used by the wind energy industry stakeholders, governments, academics and communities to make data-driven plans and decisions. Different stakeholders can create information flow and innovations by presenting different views and ideas.

It should be noted that, when analysing these data, results such as downtime, cost, total operational hours or age of defective wind turbines were not evaluated. There is a need, and it is necessary to record all datasets and failures in an international database so that it will be a source that can be used by all mentioned stakeholders and for future work.

Although governments, academics, communities and non-governmental organisations, and all other stakeholders have their own reasons for adopting green energy, they should focus on the issue of wind turbine failures to limit failures in the future. The novelty of this research has been to document areas of concern in the design of wind turbines so improvements can be made. This research can thus support different stakeholders by facilitating discussions and interactions, giving ideas on this issue. It can be the inspiration to create a large database and additional insights for future works.

A similar analysis can shed light on offshore versus onshore wind power. Preventive actions can be adopted to reduce the occurrence and negative consequences of these failures. The research can be a reference for researches such as: which measures can be taken in which region and which measures can be taken in which country. In our increasingly digitalised age, it may be possible to minimise risks and failures by using much more digital and robotic monitoring systems.

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