A review of the state-of-the-art in wind-energy reliability analysis

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Abstract

Reliability analysis can help to identify, classify, and investigate several issues and concepts that arise in wind-energy systems. In this review, we focus on six important aspects according to available literature. First, we focus true reliability model of wind turbines, where different repair models lead to different mathematical models or stochastic processes, some of which are described by point processes, homogeneous Poisson process (HPP), and non-homogenous Poisson process (NHPP). Next, we discuss the meaning of the Bathtub curve. Then, we review the role of health-management systems, which are an integral component of wind systems, and which ensure high turbine availability and reliability. The resulting health state is a reflection of the wind systems capability, which can be very useful to wind farm (WF) managers for optimizing the scheduling of maintenance-related activities. Then, we present some reliability testing protocols. A primary objective of reliability analysis is to gain feedback for improving designs. We describe a general design for obtaining the reliability estimation of structural components, and we explain the scale for severity classifications. Finally, we conduct a detailed literature survey to investigate and summarize the research done in wind-reliability analyses.

1. Introduction

An important observation of studies on wind-energy reliability is that they lag behind studies into reliability in many other industries. The goal of this work is to provide an introduction on the reliability of wind-energy systems at the wind-energy conversion system level (WECS), and we review the related research efforts.

The overall purpose of a reliability analysis is to i) Completely describe a failure and its impact on components, subsystems, and systems levels, and to correct and prevent unacceptable impacts; ii) Build a rigid, safe, and reliable system; iii) Provide information in order to develop systems, subsystem architecture, and validation design.

This literature review suggests that significant research efforts have focused on improving the reliability of wind-energy systems. These efforts can be categorized into two levels: the wind-farm (WF) level and the wind-energy conversion system (WECS) level. The combination of these two levels is expected to be the building block for future wind-energy systems. A WECS is composed of many subsystems that span the topics of electrical and electronic engineering, software engineering, and mechanical engineering. Some articles that consider WECS in general include [1–5]. Moreover, some modeling of WECS has been reported in [6–8]. The dynamic characteristics and analysis of WECS components have been reviewed in [9–12]. Hence, it will be useful to design and improve the efficiency of WECS [13]. There have also been studies that aim to improve power electronic systems in terms of their reliability [14–19].

The rest of this paper is organized as follows. In Section 2, we present a model of wind-turbine reliability. Next, we discuss the life curve in Section 3. In Section 4, we summarize reliability testing methodologies in WECS. Then, in the next section, we review design methods that mitigate against failures in WECS. In Section 6, we present a proposed reliability design of a WECS that includes designs for electrical, mechanical, and power electronic subsystems. We explain the severity classification in WECS in Section 7, followed by conclusions in Section 8 (Tables 2–4).

2. Modeling wind-turbine reliability

Several investments are required to develop a more suitable and durable WECS because of its economic importance. Reliability theory categorizes the systems into repairable and non-repairable systems. Earlier studies and results in the area of repairable wind-turbine
systems consider that after each repair, a system is like a new one if the repair job was perfect, or is in used condition if a minimal repair job was performed. These two assumptions have found very limited use in practical wind-turbine applications because practically, most repair jobs result in a state that is neither like new or used.

Recently, researchers have begun to focus more on these types of repairable systems, where repair actions do not return a system to a like-new condition, but rather returns the state of a failed system to a level that is somewhere between new and the status prior to failure. Most important wind-turbine models are based on either the homogeneous Poisson process (HPP) or power law process (PLP). There are different mathematical models such as point processes, Poisson processes, homogeneous Poisson process (HPP), and non-homogeneous Poisson process (NHPP) [6,8].

- A point process is a stochastic process describing the occurrence of events in time. When studying the wind-turbine reliability, the events are failures and the index is a set of times or a set of variables expressing the life of objects. The times between failures are not independent and identically distributed (IID).
- A Poisson process is a point process that satisfies the following:
  - Set the observation beginning period at \( t = 0 \), the number of failures is \( N(0) = 0 \).
  - The number of periods is independent,
\[
\forall a < b \leq c < d \Rightarrow N(a, b] \text{and} N(c, d]
\]
  - The intensity function if exists,
\[
\exists \lambda(t) ; \lambda(t) = \lim_{\Delta t \to 0} \frac{P[N(t, t + \Delta t) = 1]}{\Delta t}
\]

- The possibility of simultaneous failures
\[
\forall t \geq 0 ; \lim_{\Delta t \to 0} \frac{P[N(t, t + \Delta t) \geq 2]}{\Delta t} = 0
\]

For a Poisson process, the number of failures in an interval \((a, b)\) is a random variable, where
\[
\lambda(a, b] = E[N(a, b)] = \int_a^b \lambda(u)du
\]

distribution mean
\[
P(N(t) = n) = \frac{1}{n!} \int_0^t \lambda(u)du \exp(-\int_0^t \lambda(u)du)
\]

- Homogenous Poisson process (HPP) [20]
  - A Poisson process is considered an HPP with constant intensity function \( \lambda(t) = \lambda \)
  - A point process is considered an HPP with intensity if and only if the time between failures (TBPs) are IID exponential random variables with an exponential distribution having probability density function (pdf) \( f(t) = \lambda \exp(-\lambda t) \).
  1. Group a certain number of turbines in a certain period (month/quarter), and treat them as an independent variable population.
  2. Consider the TBPs as IID exponentially random variables.
  3. The probability \(P(t)\) of having \( n \) failures through time \( t \) is given as
\[
P(N(t) = n) = \frac{1}{n!} \int_0^t \lambda(u)du \exp(-\int_0^t \lambda(u)du)
\]

where \( \lambda = \frac{1}{\theta} \), with \( \theta \) being the mean TBF (MTBF).

- A non-homogenous Poisson process is a Poisson process that has non-constant intensity functions.
- Power law process
  1. The PLP model is used as a trajectory to measure the reliability improvement of a system.
  2. The PLP model can be used to predict the effectiveness of further design developments.
  3. Necessary to apply fit test.
  4. The PLP is a special case of a Poisson process with the failure intensity function \( \lambda(t) = \rho \beta^t \lambda^t \), where \( \beta \) is obtained by numerically solving the nonlinear equation
\[
\sum_{i=1}^{t} \left( \frac{t^i \ln t_i - t_i^i \ln t_i}{t_i^i - t_i^{i-1}} - \ln t_i \right) = 0
\]

We focus on the failure intensity function of wind turbines \( \lambda \) rather than other wind-turbine parameters such as the availability, capacity factor, wind conditions, and the consequences of faults. Thus, the failure intensity function \( \lambda \) depends primarily on the WECS construction, and is intrinsically predictable. It has been shown that wind-turbine gearboxes appear to achieve reliability values that are comparable to gearboxes outside the wind industry [22]. However, wind-turbine generators and converters both achieve reliabilities that are considerably below those of other industries. To better understand the wind-turbine reliability, we use the following terminology [22] Table 1:

### Table 1

<table>
<thead>
<tr>
<th>Values of ( \beta )</th>
<th>Failure intensity</th>
<th>Reason</th>
<th>Model type</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta &lt; 1 )</td>
<td>Decreasing with time</td>
<td>Design improvements/alteration on field</td>
<td>NHPP</td>
</tr>
<tr>
<td>( \beta = 1 )</td>
<td>Constant with time</td>
<td>No major modifications-Wear and tear not apparent yet</td>
<td>HPP</td>
</tr>
<tr>
<td>( \beta &gt; 1 )</td>
<td>Increasing with time</td>
<td>Normal deterioration of materials/accumulated stress</td>
<td>NHPP</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>Component number</th>
<th>Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Electrical system</td>
</tr>
<tr>
<td>2</td>
<td>Electronic control</td>
</tr>
<tr>
<td>3</td>
<td>Sensors</td>
</tr>
<tr>
<td>4</td>
<td>Hydraulic system</td>
</tr>
<tr>
<td>5</td>
<td>Yaw system</td>
</tr>
<tr>
<td>6</td>
<td>Rotor blades</td>
</tr>
<tr>
<td>7</td>
<td>Mechanical breaks</td>
</tr>
<tr>
<td>8</td>
<td>Mechanical Break</td>
</tr>
<tr>
<td>9</td>
<td>Gearbox</td>
</tr>
<tr>
<td>10</td>
<td>Generator</td>
</tr>
<tr>
<td>11</td>
<td>Supporting structure/housing</td>
</tr>
<tr>
<td>12</td>
<td>Drive train</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>Component</th>
<th>MTBF (years)</th>
<th>Failure frequency(1/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.9</td>
<td>0.53</td>
</tr>
<tr>
<td>2</td>
<td>2.5</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
<td>4.2</td>
<td>0.24</td>
</tr>
<tr>
<td>4</td>
<td>4.4</td>
<td>0.23</td>
</tr>
<tr>
<td>5</td>
<td>5.6</td>
<td>0.18</td>
</tr>
<tr>
<td>6</td>
<td>5.9</td>
<td>0.17</td>
</tr>
<tr>
<td>7</td>
<td>7.8</td>
<td>0.13</td>
</tr>
<tr>
<td>8</td>
<td>9.4</td>
<td>0.11</td>
</tr>
<tr>
<td>9</td>
<td>10.3</td>
<td>0.097</td>
</tr>
<tr>
<td>10</td>
<td>11.2</td>
<td>0.09</td>
</tr>
<tr>
<td>11</td>
<td>11.5</td>
<td>0.087</td>
</tr>
<tr>
<td>12</td>
<td>19.5</td>
<td>0.051</td>
</tr>
</tbody>
</table>
**Table 4**
Wind-turbine component reliabilities for turbines with capacity greater than 1 MW [23].

<table>
<thead>
<tr>
<th>Component</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTBF (years)</td>
<td>0.59</td>
<td>0.8</td>
<td>1.3</td>
<td>1.4</td>
<td>1.7</td>
<td>1.8</td>
<td>2.4</td>
<td>2.9</td>
<td>3.3</td>
<td>3.5</td>
<td>3.6</td>
<td>6.2</td>
</tr>
<tr>
<td>Failure frequency (1/year)</td>
<td>1.7</td>
<td>1.2</td>
<td>0.75</td>
<td>0.71</td>
<td>0.56</td>
<td>0.53</td>
<td>0.4</td>
<td>0.33</td>
<td>0.3</td>
<td>0.28</td>
<td>0.27</td>
<td>0.16</td>
</tr>
</tbody>
</table>

- **System**: this indicates an entire wind turbine and connection infrastructures.
- **Subsystem**: this is a generic term that indicates parts of the wind turbine that deals with the same form of energy. For example, the entire drive train consisting of the rotor hub, shaft, bearing, gearbox, couplings, and generator is considered as a subsystem.
- **Subassembly**: this indicates devices that perform more specific functions for which the failure data are recorded separately. For example, the gearbox is a subassembly.
- **Component**: this indicates small devices that are typically unrepairable, and which constitute the subassemblies. For example, the gearbox/generator coupling is a component.

Here, we present the subassemblies with the highest failure rates in descending order, the electrical system, rotor (i.e., blades and hub), converter (i.e., electrical control, electronics, and inverter), generator, hydraulics, and gearbox [22]. We found that the power-direct-drive electronic converters and geared WECS exhibit higher failure intensities throughout their operation than converters in other industries. It is worth noting that direct-drive wind turbines do not necessarily have better reliability than geared ones [24]. We also found that during the starting phase, direct-drive and geared generators have higher failure frequencies than generators in other industries, and smaller WECSs have higher reliability values than larger ones.

The procedure to determine the WECS reliability design can be performed on both the overall system level as well as on sub-system levels. The overall system-level reliability analysis aims to integrate the whole system reliability model using common reliability analysis methods and procedures, as discussed in the previous section. The sub-system level reliability analysis builds an individual reliability model for each subsystem in order to

1. Study the interaction of the sub-system models within the whole system;
2. Promote a design procedure created by a skilled and experienced design for sub-systems;
3. Optimize the locations of sensors and observer devices in order to characterize sub-system failures.

**3. Life curve**

Many mathematical concepts apply to reliability engineering, particularly from the areas of probability and statistics. Similarly, many mathematical distributions can be used for various purposes, including the Gaussian (normal) distribution, the log-normal distribution, the Rayleigh distribution, the exponential distribution, and the Weibull distribution. The Weibull distribution is considered one of the most applicable ones for reliability engineering when evaluating the reliability and failure characteristics of a machine. The typical life curve of a piece of machinery [25] is illustrated in Fig. 1. The bathtub curve effectively demonstrates a machines three basic failure-rate characteristics:

1. The infancy period is characterized by a decreasing failure rate that starts with a relatively high initial value.
2. In the useful life period, there is an ideally constant failure rate. This is due to extrinsic failures that appear spontaneously, and are independent of the operation time; therefore, they can also occur in the infancy period and in the wear-out period. They result from overstress such as high voltage or high current conditions in electronic devices.
3. The wear-out period is the final period in the service life. Because of intrinsic causes such as deterioration and fatigue in electronic components, intrinsic failures are the primary types of failure.

The failure rate of wind turbines is [8]:

$$
\lambda(t) = \frac{\theta}{\theta^t} \left( \frac{1}{\theta} \right)^{t-1}
$$

(8)

where \( \beta \) is a dimensionless shape parameter that determines the shape of the intensity function. \( \theta \) is a scale parameter that has the dimension of time. There are three phases of shape parameter \( \beta \):

3.1. Early failure \( \beta < 1 \)

The failure intensity in (8) decreases with time. Hence, the PLP describes the improvements in the reliability. The main causes of early failures are as follows [26]:

- Poor manufacturing techniques including processing, handling, and assembly practices;
- Poor quality control;
- Poor workmanship;
- Insufficient warming up or debugging;
- Substandard parts or materials;
- Replacing failed components with non-screened ones;
- Part failure during storage or transportation because of improper PHST practices;
- Improper installation;
- Improper start up.

3.2. Constant failure rate \( \beta = 1 \)

With the intensity function of the PLP equal to \( \rho \), the process represents the bottom of the bathtub curve, which is called the intrinsic failure phase. During the intrinsic failure phase, the constant failure rate \( \lambda \) is described as the average failure rate. The failure rate in (9) becomes a constant, and the process becomes an HPP. \( \theta \) becomes the MTBF of the turbine, and the maximum-likelihood estimate (MLE) of \( \theta \) is [8]:

$$
\theta = \frac{1}{\lambda}
$$

(9)
\[ \theta = \frac{1}{\lambda} = \frac{\sum_{i=1}^{I} T_i}{\sum_{i=1}^{I} n_i} \]  

\( i \): Duration of interval (monthly or quarterly).  
\( I \): Number of intervals for which data were collected.  
\( n_{i,k} \): Number of failures per interval \( i \) per subassembly \( k \).  

The major causes of chance failures are as follows [26]:

- Stress strength interference during operation;  
- Occurrence of random loads being larger than expected;  
- Occurrence of random strengths being lower than expected;  
- Insufficient safety margins;  
- Human errors during usage;  
- Unexplained causes.  

### 3.3. Deterioration \( \beta > 1 \)

The intensity function increases with time, and PLP describes the reliability deterioration or wear out. Practically, it has not yet been encountered in wind turbines, and this may be owing to their relatively young age. Furthermore, if the reliability of a wind turbine reduces dramatically, it will be taken out of service before the deterioration phase can be detected. The major wear-out failure causes are as follows:

- Aging;  
- Wear;  
- Strength degradation;  
- Fatigue;  
- Creep;  
- Corrosion;  
- Mechanical, electrical, and chemical deterioration;  
- Replacement of failed parts by partially aged ones;  
- Short design life.

The failure rate is the number of failures per turbine per year, and is calculated by [8]

\[ \lambda = \frac{\sum_{i=1}^{k} n_{i,k}}{N_t \times 8760} \]  

where

\( N_t \) is the failure rate, and is the number of failures per turbine per year.  
\( n_{i,k} \) is the number of failures in subassembly \( k \) during interval \( i \).  
\( T_i \) is the number of turbines in the population at interval \( i \).  

### 4. Reliability testing methodologies

Nowadays, long life cycles of component have resulted in cost reduction and miniaturization of components. Moreover, accurate, inexpensive, sufficient, and less time-consuming reliability test methods are needed. Several methods have been established to help wind-field engineers and operators to determine and predict reliability issues in a more rapid and efficient way (Table 5):

### 5. How to design against failure?

The only satisfactory approach to solving failure problems is to prevent them by ensuring proper designs. The aim of this section is to present some ideas that help to solve the primary design problems in order to prevent failures. There are several strategic approaches to design against failures [27]:

- Condition monitoring (CM) is a real-time measurement of a components condition. If it drifts from the healthy condition, an appropriate action will be taken [28]. This technique monitors the operating characteristics of components, and is considered one of the most cost-effective means of improving reliability and customer service in power equipment [28]. CM is applied to components that are closely related to the deterioration failures in the wear-out period of the components. It enables us to decrease the number of extrinsic component failures. The main feature is that changes in the monitored characteristic can be used to schedule maintenance before failure occurs. CM techniques are utilized in several applications such as vibration analysis, oil analysis, thermography, strain measurements, acoustic monitoring, electrical effects, process parameters, visual inspection, performance monitoring, and self-diagnostic sensors.

The main problem associated with CM techniques is the requirement for a large number of sensors among WF, which makes this technique complex and expensive to implement. CM is considered very important to power-electronic systems [28]:

- For unpredictable failures such as catastrophic accidents or unscheduled maintenance, the use of CM in power electronics becomes more essential.
- Comprehensive knowledge about the failure in wind turbines.
- Improvement in sensors and signal processing leads to effective power-electronic converter CM systems.

Applying the concept of CM to power-electronics modules is a challenging issue, and it has been addressed in a survey paper [28]. Structure health monitoring (SHM) techniques are still unclear, and dealing with vibration monitoring on wind-turbine towers has not yet been overcome [29]. Some of the components of wind turbines that need to be monitored are faults due to imbalance, wear, fatigue, and impending cracks in rotor blades, bearings, shafts, gearboxs, generators, yaw, and the pitch-angle mechanism [29].

- Diagnosis and prognosis aims to identify the root cause of a fault that has occurred [28]. Diagnosis encompasses detecting, isolating, classifying, and analyzing faults [30]. Prognosis assesses the current health level of a component, and predicts the health of the component at some point in the future [28]. In addition, prognosis enables the prediction of the remaining useful life for the components until it reaches the wear-out period.

- Ensuring redundancy and fault tolerance are efficient methods of improving the reliability and availability of a system. The affected component will be isolated and the redundant component takes over the operation in the case of failure. A redundant strategy tries to maintain operations when a failure takes place. Although the component exists in a period of a higher failure probability because of the deterioration mode, the exact time for the failure point cannot be predicted. If its operating quality decreases rapidly, the decrease is proportional to the severity of the failure. By having at least one independent redundant converter, we guarantee the system operation in the case of a converter failure [31,32]. The use of redundant converters will increase the systems’ cost, volume, and weight. The proposed cost-rate minimization model aims to simultaneously determine the optimal allocation of redundant converters and the optimal number of converters that are allowed to fail before dispatching maintenance staff to the offshore platform.

- The choice of components is more complicated, and is driven by a variety of factors. A proper decision will provide excellent support and flexible solutions to meet the system needs, take advantage of lower costs, increase flexibility, and ensure high quality. The choice of components appears to be a daunting task with many different models and features available.

- The wind-farm topology and architecture are characterized by a specific number of WECs simultaneously connected to the power system. The WECS interconnection within a wind farm is based on
AC or DC topologies. A suitable topology and voltage level of the offshore network should be chosen for optimal efficiency, reliability, ease of maintenance, and cost effectiveness. The total power produced by the WF is the sum of the power produced by each individual unit. The distance to shore and the distance between individual units are the main factors that are considered when designing the WF topology.

- Root-cause analysis components include thermal aging, thermal-mechanical cycling fatigue mechanisms in the conduction and insulation materials of electromechanical components, and thermal-mechanical fatigue stress, as shown in Fig. 2. Root causes presented in [33], viz. stress-strength interference during operation, the occurrence of random loads that are higher than expected, the occurrence of random strengths that are lower than expected, insufficient safety margins, and human error during use. The reliability problems of the failure root causes in stress distribution sources can be reduced by ensuring a better understanding through improved fault analysis, early detection through reliability methods, improved redundancy during design, and better quality control.

It has been found that the most important factor that affects the component reliability is the degree to which the manufacturer is able to fabricate defect-free components [33]. The in-depth knowledge of the operation, maintenance practices, and references to equipment design and engineering practices make it possible to develop an overall understanding of the root-cause analysis.

- Operating environment conditions such as temperature, humidity, and turbulence stress directly influence the reliability assessment, as shown in Fig. 3.

### Table 5

Wind-turbine component reliability values.

<table>
<thead>
<tr>
<th>Method</th>
<th>Features</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>HALT</td>
<td>Reveals weak points and failures provides information about product operation valid in a harsh offshore environment saves time and money works under accelerated stress conditions best suitable for application during early engineering development</td>
<td>No industrial standards available no specifications in design documents no testing procedure to follow varies from component to component and from application to application.</td>
</tr>
<tr>
<td>ALT</td>
<td>Works in short period of time suitable for finding dominant failure mechanism performed on individual assembly level rather than subassembly level or system level best suited for application before production release</td>
<td>Needs more test time, samples, and cost no industrial standards available no specifications in design documents no testing procedure to follow varies from component to component and from application to application.</td>
</tr>
<tr>
<td>Environmental</td>
<td>Guarantees top performance in climatic conditions verifies that a component is capable of operating under the test conditions for a certain period of time</td>
<td>It cannot be used to quantify reliability parameters such as MTB no industrial standards available no specifications in design documents no testing procedure to follow varies from component to component and from application to application.</td>
</tr>
</tbody>
</table>

6. Reliability design

Each component in a wind plant will eventually fail, assuming that it has been in service for a long time. Fig. 4 shows that five component groups, namely electrical systems, control systems, hydraulic systems, sensors, and rotor blades, are responsible for 67% of failures over a 15-year period [35]. Components reaching their lifetime has been related to many factors viz. electrical equipment failure such as incorrect installation, inaccurate connection between systems, subsystems, and components, as well as faults and erroneous grounding systems.

Electrical, electronic, and mechanical components require monitoring, control, reporting, routine maintenance, and testing to manage their failure rates and increase their reliability. The failure rates of electrical and electronic subassemblies are higher than those of mechanical subassemblies, but their downtimes are lower than those of mechanical ones as shown in Fig. 5 and 6. This is because electrical and electronic ones are more easily replaced. Thus, to ensure a reliable design of power-electronic systems, there is a need to achieve higher MTBF values for power-electronic components. In addition, low-frequency electrical noise is recognized as a very sensitive measure of the quality and reliability of electrical and electronic components [36].

6.1. Electrical reliability design

Of all of the failure types, electrical ones are the most difficult to identify before failures occur. Appropriate maintenance and other predictive techniques are considered as key to increasing machine life, and can result in major improvements in terms of zero maintenance and reduced cost. For electrical components, we should consider both the physical model and measurement uncertainties. The main root cause of electrical failures tends to be voltage irregularities and electrical stress due to operational temperature fluctuations.

Transformer failures are considered one of the main reasons for long downtime. For such a failure, their replacements are very expensive, difficult, and time consuming, especially during harsh weather. Thus, in some case, it is preferred that their use be discontinued. However, it is recommended that we use a high-frequency step up voltage, three-phase transformer that operates at high frequency, thus reducing its volume and weight; it can easily fit into the nacelle of the wind turbine [38]. Apart from that, high-frequency transformers provide good isolation between the grid and the generator.

From a reliability point of view, it is preferred to handle fault without mechanical vibration sensors, which are very attractive for CM systems to collect data about healthy situation. However, it is difficult to install them. On the other hand, electrical analysis using sensors is considered more reliable and less expensive, and faults can be detected more rapidly. Consequently, observers should obtain the required information using only measured voltages and currents at the terminals. CM techniques involve mainly vibration analysis, oil analysis, thermography, strain measurements, acoustic monitoring, electrical

![Fig. 2. Failure root-cause distribution [34].](image-url)
effects, process parameters, visual inspection, performance monitoring, and self-diagnostic sensors [39].

Because of the long distance between WF components, the reliability of the whole system is significantly affected by the reliability of the cables. The cable life can be divided into stages, namely manufacture, storage, installation, servicing, and recovery. To maintain cables during service, clear troubleshooting and repair procedures have to be established involving reactive repair and replacement and proactive replacement. It is important to ensure that the cables use quality compounds and consistently meet the specification and qualification requirements. Otherwise, failures could occur while the cable is being handled, installed, and operated within specifications. The effective and reliable operation of infrastructure cables and redundancies will enable the availability of power during a failure. There is therefore a need for a reliable method to terminate a cable such that it can achieve long-life service in a marine environment, where mechanical and environmental conditions are unfriendly. It is worth noting that the repair strategies play an important role in identifying a cable’s overall availability [40].

Electrical winding failures are considered one of the main failures that take place in wind-energy systems, as shown in Fig. 7 [10]: i) Rotor banding; ii) Conductive wedges; iii) Cooling-system failures; iv) Rotor lead damage; v) Under-designed materials and systems; vi) Catastrophic failure due to surges; vii) Contamination issues.

6.2. Power-electronics reliability design

The goal of the wind-energy industry is to achieve extremely high reliability with zero maintenance. Nowadays, the availability of modern onshore WECSs is around 95–99% [41]. The reliability is especially important for offshore WECS as the size and number of installed units increase. The repair cost and the value of the lost energy when failure
occurs can be high and sometimes disastrous for WF owners. The
development of power electronics for modern wind turbines has led to
a dramatic evolution in the wind industry. The main function of power-
electronics converters is to handle the energy flow between systems.
For example, a power converter provides a flexible and very efficient
interconnection between entities on a smart grid, conversion, energy-
storage systems, transmission, distribution, and loads. All of these
entities must assign the highest priority to grid security and safety. The
most important aspect of connecting a wind-energy system to the
electric grid requires a power-electronics converter that allows variable
speed operation, reduces mechanical stress, and increases reliability.

Power electronics is able to change the basic characteristics of wind
systems from an energy source to an active electrical power source
[42]. The reliability design of power-electronics converters in wind
systems must consider the minimum power-loss requirements for
converters, the maximum operation reliability, and the minimum
capital cost of the system [43]. The most important causes of failure
of semiconductor devices are voltage stress, cosmic rays, and thermal
cycling [44]. Some problems that have been encountered with con-
verters in wind systems such as [45] are i) Converters have a
considerable failure rate, hence loss of power production. ii) At low
power levels, converters have low efficiency. iii) Because of pulse-width
modulation (PWM), converters cause harmonic voltages on the grid.
On the other hand, increasing the availability of power-electronics
converters typically involves [46]: i) Improvement in the reliability of a
component; ii) Application of CM to the system; iii) Application of CM

Table 6
Severity of failure modes.

<table>
<thead>
<tr>
<th>Description</th>
<th>Category</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catastrophic</td>
<td>i</td>
<td>A failure mode that causes death, WECS loss, or severe environmental damage.</td>
</tr>
<tr>
<td>Critical</td>
<td>ii</td>
<td>A failure mode that causes severe injury, severe occupational illness, major WECS, or environmental damage.</td>
</tr>
<tr>
<td>Marginal</td>
<td>iii</td>
<td>A failure mode that causes minor injury, occupational illness, minor WECS, and environment damage, or mission degradation.</td>
</tr>
<tr>
<td>Minor</td>
<td>iv</td>
<td>Less than minor injury, occupational illness, or less than minor WECS or environmental damage</td>
</tr>
</tbody>
</table>

Fig. 7. Failures detecting maintenance or test [34].

Fig. 8. Gearbox failures based on 257 damage records released in 2014 [48].
to the components; iv) Application of prognosis to the components; v) Redundancy and fault tolerance.

6.3. Mechanical reliability design

Vibration analysis is the most commonly known technology applied to CM, especially for rotating equipment such as gearboxes. Vibration measurements are performed to determine healthy situations using sensors or observers that are spread across the wind system. Operators can measure the acceleration. An in-depth understanding of the vibrations can be gained by analyzing the data received from sensors. The frequency spectrum is evaluated using spectral analysis algorithms based on the fast Fourier transform (FFT), and can provide users with critical information regarding the health of the vibrations.

Gearboxes are mechanical devices that are capable of transferring torque loads from a primary mover to a rotary output, typically in different relationships of angular velocity and torque. They connect the low-speed shaft to the generator. Therefore, the gear ratio is generally dictated by the requirement of the generator and the angular velocity of the turbine rotor [47]. However, gearbox failure rates are still high, approximately 20% of the wind-system downtime [47], and according to the latest statistics obtained from the database, the majority of wind-turbine gearbox failures (76%) are caused by the bearings, as shown in Fig. 8. Even if the failure of gearboxes is troublesome, they require a crane for handling, replacement, and greasing. Therefore, the cost is increased because of costs associated with crane rental and labor, as well as economic losses that are incurred. The gearbox has to work in random loading conditions. Many factors, such as friction, lead to increased temperature. Further, mechanical stresses cause shaft cracks, tooth breakage, shattering, and in the worst-case scenario, damage to the tower. WECS CM shows that gearbox fault diagnosis is not an easy task, but is important to enhance a wind systems’ reliability.

7. Severity classifications

With respect to the reliability, the impact of security issues found in WECSs has been rated using a four-point scale: minor, marginal, critical, and catastrophic. This severity scale provides a prioritized risk assessment to help understand and schedule upgrades to a WECS. The scale takes into account the potential risk based on a technical analysis of the failure on the system and subsystem levels, as mentioned in Table 6.

8. Conclusions

In this review, we investigated the reliability analysis of wind-energy systems, focusing on wind-turbine modeling. We proposed a way of modeling wind-energy system failures, assuming the use of the bathtub curve. The model should consider other parameters such as the MTTR, operation and maintenance cost, weather conditions, grid effects, and load variation. There is also a need to enhance the understanding of failure mechanism and effects. Because WECSs are complex electromechanical systems, several techniques viz. condition monitoring, fault diagnosis and prognosis techniques, redundancy mechanism, and fault tolerance have been employed to increase the wind system reliability, availability, and lifetime service of offshore wind farms because of the limited accessibility, while reducing the downtime and maintenance cost.

The evaluation of component reliability must consider the operation conditions, maintenance records, and failure records. This work should be extended from a component level to a WF level. Finally, there is a need for increased collaboration between manufacturers, operators, and investors in order to improve wind-energy system reliability.

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