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# 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, homogenous 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

*Abbreviations:* WECS, wind-energy conversion system; WF, wind farm; HPP, homogeneous Poisson process; PLP, power law process; IID, independent and identically distributed; TBF, time between failures; MTBF, mean time between failures; MLE, maximum-likelihood estimates; HALT, highly accelerated life test; ALT, accelerated life test; PHST, Packaging Handling Storage and Transportation

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**Table 1**
Values of $\beta$ for different failure intensity [21].

| Values of $\beta$ | Failure intensity | Reason | Model type |
|---|---|---|---|
| $\beta < 1$ | Decreasing with time | Design improvements/ alteration on field | NHPP |
| $\beta = 1$ | Constant with time $\lambda(t) = \rho$ | No major modifications-Wear and tear not apparent yet | HPP |
| $\beta > 1$ | Increasing with time | Normal deterioration of materials/accumulated stress | NHPP |

**Table 2**
Wind-turbine components are included in the reliability model [23].

| Component number | Component |
|---|---|
| 1 | Electrical system |
| 2 | Electronic control |
| 3 | Sensors |
| 4 | Hydraulic system |
| 5 | Yaw system |
| 6 | Rotor blades |
| 7 | Mechanical breaks |
| 8 | Mechanical Break |
| 9 | Gearbox |
| 10 | Generator |
| 11 | Supporting structure/housing |
| 12 | Drive train |

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 processes 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,

$$\forall\ a < b \le c < d \Longrightarrow N(a, b] and N(c, d] \tag{1}$$

  - The intensity function if exists

$$\exists\ \lambda(t)\colon \lambda(t) = \lim_{\Delta t \to +0} \frac{P[N(t, t + \Delta t) = 1]}{\Delta t} \tag{2}$$

  - The possibility of simultaneous failures

$$\forall\ t\colon \lim_{\Delta t \to +0} \frac{P[N(t, t + \Delta t) \ge 2]}{\Delta t} \tag{3}$$

For a Poisson process, the number of failures in an interval (a,b) is a random variable, where

$$\bigwedge(a, b] = E[N(a, b]] = \int_a^b \lambda(u)du \tag{4}$$

distribution mean

$$P(N(t) = n) = \frac{1}{n!}\left(\int_0^t \lambda(u)du\right)^n \exp\left(-\int_0^t \lambda(u)du\right) \tag{5}$$

- 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 (TBFs) 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 TBFs as IID exponentially random variables.
    3. The probability P(t) of having n failures through time t is given as

$$P(N(t) = n) = \frac{1}{n!}(\lambda t)^n \exp^{\lambda i}, n = 0, 1, 2, \ldots \tag{6}$$

    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 $\lambda(t) = \rho \quad \beta \quad t^{(\beta-1)}$ where $\beta$ is obtained by numerically solving the nonlinear equation

$$\sum_{i=1}^{I} n!\left(\frac{t_i^{\beta}\ln t_i - t_{i-1}^{\beta}\ln t_{i-1}}{t_i^{\beta} - t_{i-1}^{\beta}} - \ln t_i\right) = 0 \tag{7}$$

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 3**
Wind-turbine component reliabilities [23].

| Component | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MTBF (years) | 1.9 | 2.5 | 4.2 | 4.4 | 5.6 | 5.9 | 7.8 | 9.4 | 10.3 | 11.2 | 11.5 | 19.5 |
| Failure frequency(1/year) | 0.53 | 0.4 | 0.24 | 0.23 | 0.18 | 0.17 | 0.13 | 0.11 | 0.097 | 0.09 | 0.087 | 0.051 |