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Wind turbine reliability: A comprehensive review towards effective condition monitoring development

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HIGHLIGHTS

- A review of thirteen wind turbine reliability studies is performed.
- The impact of failure rates and downtime is analysed across the studies.
- The goal is to elucidate the right direction for condition monitoring development.
- Remarkable differences are found between the least and the most reliable assemblies.
- The same critical components are found for both onshore and offshore applications.

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ABSTRACT

The current work presents a review of wind turbine reliability studies. Thirteen reliability studies were identified in the scientific literature, highlighting the lack of public reliability data. We present the differences across the studies, with great effort being made to unify the various studies to obtain comparable results. To this end, we have endeavoured to develop a wind turbine taxonomy that is common across the different studies, formed by thirteen assemblies, and the failure rates and downtimes from each study have been normalised. The results establish differences between the least reliable assemblies, categorised as critical, and the most reliable ones. Small differences emerge between onshore and offshore locations, and between studies on European wind farms and others in the U.S. and China. The influence on the total failures and downtime of the most recent studies is evaluated against older studies. These results will contribute to elucidate the right direction for condition monitoring design and development, and therefore to improve reliability and availability of wind turbines.

1. Introduction

Of all types of renewable energy sources, wind has experienced the greatest growth [1–3] and is one of the most economic sources of electricity [4,5], contributing with more new power generation than any other renewable source in the last year, with a global installed capacity of 539 GW by the end of 2017 [6].

Wind turbine technology continues to evolve [7–9], with sophisticated multi-MW machinery under constant development, both for onshore and offshore applications [10]. Such growth comes along with important challenges to be addressed [11]. Larger wind turbines have proven to develop more failures than small ones [12–14] and offshore wind farms can be inaccessible for several months [15,16]. Furthermore, a significant share of the existing technology has already achieved its 20-year estimated lifetime [17,18]. Under this framework, wind turbine availability and hence reliability must be developed in parallel, so that wind energy continues to be financially viable [19,20].

Operation and Maintenance (O&M) activities are a key aspect with regards to availability [21–23]. In fact, the global market for O&M is expected to grow to 27400 million dollars by 2025 [24]. In this scenario, identification of critical components is vital, so that they can be monitored "as cost-effectively, reliably and efficiently as possible" [25].

1.1. Problem statement: the need for condition monitoring

Typical onshore availability has been found to be over 97% [14,15,26], achieved through appropriate O&M activities. Different numbers are obtained for offshore sites, of about 85% availability

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[27,28], due to inaccessibility issues and the current uncertainty surrounding offshore failure characteristics. Although offshore wind energy is in its early years, it is a rapidly growing field, with promising results [29,30].

O&M activities have been identified as one of the leading costs in the total expenditure of a wind farm project [31]. They represent 25% of their lifetime costs for onshore wind farms, and 35% for offshore plants [32–34]. Access and repair (both major and minor) are the main contributors towards O&M costs [35]. Furthermore, there is "a lack of operating experience in the field of offshore wind energy" [36] which increases the complexity of the current problem. The imperative of reducing O&M costs while improving availability and reliability is therefore patent.

Three maintenance strategies are commonly implemented [32,37]: time-based (TBM, which is preventive), failure-based (FBM, corrective), and condition-based (CBM, predictive). Conventional onshore O&M activities consist of a combination of preventive and corrective maintenance operations [27], but this approach has room for improvement and is unwise offshore. The new trends are moving from TBM and FBM towards CBM [22,31]. In the latter strategy, condition monitoring (CM) determines the optimum point between preventive and corrective maintenance, which reduces unnecessary repair actions and saves unplanned downtime [21,38]. In this framework, condition monitoring has been identified as the key to achieving higher availabilities [15,39] while reducing O&M costs [40,41]. Nevertheless, the secrecy present in the wind energy sector makes it difficult to understand which components are critical for condition monitoring.

1.2. Existing literature reviews

We have conducted a comprehensive search of previously published literature reviews. Only those where various reliability studies had been included, compared and conclusions extracted, were taken into consideration for the present section. These include seven independent reliability studies:

- Technical Research Centre of Finland (*Valtion teknillinen tutkimuskeskus*, VTT) [42].
- Survey in Schleswig Holstein, Germany (*LandWirtschaftsKammer*, LWK) [13].
- Windstats in Denmark (WSDK) and in Germany (WSD) [43].
- Survey by Fraunhofer in Germany (*Wissenschaftliches Mess- und Evaluierungsprogramm*, WMEP) [14].
- Swedish survey (referred to as "SW" by the authors from now on) [12].
- Results from the European Project Reliawind ("RELI" onwards) [44].

A master's thesis from 2006 [45] includes a comparison of the Swedish, Finnish and German studies. A table is used to present the results and the conclusions show similarities among the studies where the drive train is the assembly requiring the longest downtime per failure. The comparison between the WSD, WSDK and LWK studies seems to be the most popular collation, performed by three different authors [43,46,47] in 2007, 2009 and 2010 respectively, which the authors from [43] extended a year later by including the WMEP study in [48]. Next, Ref. [49] presented a comparison between WSD, WSDK and WMEP results. The general findings of all these studies indicate that the electric and electronic components, as well as the wind turbine rotor (blades and hub), are the most critical ones.

The comparative analysis that seems to have the widest scope is presented as a technical report in [50] summarising the outcome of the 67nd International Energy Agency Topical Expert Meeting, held in 2011. It combines the results obtained from WSD, WSDK, WMEP, LWK, VTT and Swedish reliability analyses by comparing the top three assemblies with the highest failure rates and downtimes. Here, the gearbox and drive train are the common factor in the top three assemblies with the longest downtime per failure. Another technical report conducted in 2013 by [51] collected in one highly explicit graph the studies from WSD, WSDK, LWK, VTT and Reliawind Project. It also included (but not in the joint graph) the WMEP and CREW reliability analyses. The present paper compares all studies jointly.

The latest review paper publication belongs to [52], 2013. Here, a comprehensive survey of reliability studies by countries, manufacturers and different technologies is presented. The results from the previously mentioned Swedish, VTT, LWK, WSD and WSDK studies are analysed independently. Moreover, the results of two European Projects named DOWEC and CONMOW, which are the result of simulations and estimations based on previous experiences, are considered. The reliability results from VTT, LWK and Swedish studies are combined in one plot which highlights the gears and blades as the most critical assemblies. Finally in 2014, a new technical report was published by [53] showing the comparison between WMEP, LWK and Swedish studies where the most critical assemblies appear to be the gearbox and drive train.

1.3. Motivation

All the mentioned reliability studies carried out in Europe (Swedish, LWK, VTT, WSD, WSDK, WMEP, Reliawind) and the U.S. (CREW) have been included in this work, and will be presented in detail and referenced in the following sections. Furthermore, the present paper includes six new reliability studies, published in and after 2012, that were not included in previous reviews. These include wind farms located in Europe (one in the Netherlands, one in UK, and two more in different European countries, one onshore and one offshore), the U.S. and China. It should be noted that the current study is the first to take offshore developments into consideration in a wind turbine reliability review.

Analysing reliability studies will help to identify the most critical components of a wind turbine. On the basis that identifying the most critical components maintenance can be optimised, the motivation behind the present work is to contribute towards O&M cost reduction by establishing the basis for effective condition monitoring system's design and development.

In addition to this introduction, the paper is structured as follows: Section 2 provides an overview of current condition monitoring systems and past efforts. Section 3 presents the reliability studies used for the current analysis. It includes a description of each individual study (Section 3.1), the limitations of the research (Section 3.2) and the individual result from each study in normalised plots (Section 3.3). Then, in Section 4, a detailed comparison of the various studies is presented (Section 4.1), including different collations to analyse the influence of the study's origin, location, the date when it was carried out and a few selected assemblies (Sections 4.2,4.3,4.4,4.5). Finally, the conclusions and the main ideas extracted from the current work are summarised in Section 5.

2. Overview of condition monitoring systems

Condition monitoring systems provide accurate information on the status of a component or assembly so that maintenance can be planned accordingly (CBM) [54,55], diagnosis and prognosis is achieved and critical failures and downtime avoided [56,57]. Many reviews for wind turbine condition monitoring and fault diagnosis have been published in the last fifteen years. These typically present the latest techniques and methods [58,59] according to wind turbine subsystems [60,61], differentiating between structural [62], mechanical [63] and electrical parts [64–66], power electronics and control systems [67].

Specific reviews for one particular assembly or sub-assembly can also be found in the literature, such as structural CM reviews [68,69], on the drive train [70,71], gearboxes [72,73] and bearings [74], induction machines [75–78] or power converters [79,80]. Some reviews focus on the diagnostic [81,82] or prognostics [83] methods rather than