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Performance assessment of wind turbine gearboxes using in-service data: Current approaches and future trends

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ABSTRACT

The evolution of the wind industry in the last decade has not only seen growth in the installed capacity of turbines and innovation within the industry, but has also seen an increase in research activities in this domain. Gearbox field performance, characterised by reliability, availability and maintainability (RAM), has been a major driver in the research domain due to challenges the industry has faced in gearbox design and operations and maintenance. This paper presents a systematic literature review of the current approaches of performance assessment, such as reliability and maintainability analysis of wind turbine gearboxes with a focus on the use of in-service data. The state-of-the-art in literature are discussed and classified according to key research themes, whilst identifying possible gaps due to lack of literature in specific areas. Also, the future trends in gearbox field performance assessment research are explored. In an attempt to close the gaps in one of the areas not covered in literature, an approach for the estimation of gearbox maintainability was presented. Furthermore, a case study on how preventive maintenance of gearbox bearings which can be applied in practice was carried out to demonstrate the importance of the techniques discussed in this article towards meeting industry's needs.

Contents

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1. Introduction

1.1. Background

Wind turbine (WT) gearboxes, compared to other sub-assemblies, are known to have high downtime per failure [1–4] as shown in Fig. 1. This is largely due to the complexity of their repair and maintenance procedures, particularly in offshore applications [5]. Also, WT gearboxes historically suffered from early failures [6] caused by underestimation of design and operating loads [7]. In reaction to this, WT manufacturers have tended to add large contingencies to sales prices so as to cover warranty issues that may arise from early gearbox failures [7] and the resulting downtime, making gearboxes one of the most expensive WT sub-assemblies [5,7]. This high sales price, combined with those attributed to failure and downtime of gearboxes during operation, contribute to a higher cost of energy, hence affecting the economic viability of wind farms (WFs) especially in offshore applications.

In light of this industrial challenge, the research community has actively been involved in investigating, modelling, assessing and predicting WT gearbox operation, performance and failures, with the aim of improving its RAM and hence reducing the cost of energy. Moreover, notable academia – industry research partnerships, specific to WT and WT gearboxes, emerged during the last decade [9–12], confirming the relevance and importance of research in the WT industry.

Considering all the outputs, in research terms, of WT gearbox RAM in the past decade or so, it will be of value to reflect on the key literature in this area through a systematic review process. However, recent search for antecedent review of literature specific to WT gearbox RAM yielded no results. Even though there have been reviews in other related areas such as WT condition monitoring [13–16], failure modes analysis [17] and WT reliability analysis [18], there is no review at present covering WT gearbox RAM. This served as an initial motivation to the authors in preparing this article.

1.2. Aim of article

This article aims to explore literature in the area of WT gearbox RAM, focusing on the use of in-service (field) data for measuring, monitoring, analysing and predicting RAM of WT gearboxes. This will be done through a systematic literature review, which is also taxonomic and captious so as to identify the state-of-the-art and gaps in current literature. Furthermore, a look into the future direction of RAM research would be taken by identifying both the future trends in literature and possible new areas which would tackle industry's needs. The scope of this literature has been limited to WT gearboxes due to the challenges and issues industry currently face with them – as mentioned in the previous sub-section. However, some of the key learning points from gearbox performance assessment can also be applied to other main components such as generators.

1.3. Reliability availability and maintainability

Before further discussion, it would be useful to define the terms "reliability", "availability" and "maintainability", so as to ensure that all readers are aware of their meaning and use in the context of this article. This is also aimed at establishing a disambiguation between these three terms and other terms such as condition monitoring (CM), failure modes analysis, prognostics, etc., which are also mentioned in this article. There are many variations to the definition of reliability, availability and maintainability, but the authors have chosen the definitions as presented by [19–21] for the purpose of this article. Readers can also refer to [22,23] for more information about RAM.

Ansell and Phillips [19] defined reliability of a system (component) as: *"the probability that the system operates (performs a function under stated conditions) for a stated period of time"*. The two important points to note from this definition are that reliability can be expressed as a probability and that it is a function of time. Carter [20] defined availability as: *"the probability that an item, at any instant in time, will be available"*. Apart from this definition, there are other useful definitions and representations of availability, as mentioned earlier. Furthermore the authors have chosen to adopt Knezevic's definition of maintainability [21] for this article: "*Maintainability is the inherent characteristic of an item/system related to its ability to be maintained in functionable state when the required maintenance task or tasks are performed as specified*". Maintainability can also be expressed as a probability, just as reliability and availability, where it is measured as the probability of achieving the objective (e.g. repair, restoration, condition-based maintenance, etc.) within a stated time period [20]. Hence maintainability can be seen as a measure of maintenance.

For disambiguation, maintenance is defined as *"the act of ensuring that physical assets continue to fulfill their intended functions"* [22]. This implies that activities such as CM, prognostics and fault diagnostics, are maintenance tasks which when performed under a condition-based maintenance strategy, ensure that a physical asset remains functional (available) and reliable. The relationship between reliability, availability and maintainability, described explicitly in [21], is illustrated in Fig. 2.

1.4. Wind turbine in-service data

The life cycle of a WT (including the gearbox) involves a series of stages similar to those described by the generic product life cycle model [26], as shown in Fig. 3. The life cycle stage of interest in this article is the "Utilisation and support stage" also referred to as the "in-service stage". This is the period, after commissioning, during which the WT is expected to be operational, generating