Renewable and Sustainable Energy Reviews xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Prognostic techniques applied to maintenance of wind turbines: a concise and specific review

Gustavo de Novaes Pires Leite[a], Alex Maurício Araújo[a,*], Pedro André Carvalho Rosas[b]

[a] UFPE – Federal University of Pernambuco, Department of Mechanical Engineering, Fluid Laboratory, Brazil
[b] UFPE – Federal University of Pernambuco, Department of Electrical Engineering, Brazil

ARTICLE INFO

Keywords:
Wind farm
Prognosis
Remaining useful life
Condition-based maintenance

ABSTRACT

Wind turbine installation is growing consistently and fast. Wind turbines are getting bigger in size and power, what incurs that a simple unit breakdown causes large energy losses. They operate under varying, complex and dynamic loads due to the environmental conditions, such as wind shear, turbulence, gusts, etc. Condition-based and prognostic and health maintenance is key to assure reliable and efficient performance of wind farms, especially offshore. Fault diagnosis is important, but given the operational complexity of the wind turbines, previous knowledge about the condition of a wind turbine component and fault prognostics are the state of the art of wind farm operation. Although some advance has been made in the diagnostics of faults of wind turbines, very little research has been carried out in the field of fault prognostics of wind turbines. Then, there is an urgent need to develop prognostic techniques for such complex systems operating in real conditions. This article aims to present a comprehensive, specific and concise review of the up to date efforts and advances in the research of prognostic techniques and remaining useful life estimation methods applied to the critical components of wind turbines and analyse its advantages, capabilities and limitations.

1. Introduction

Wind energy is one of the fastest growing sources of energy worldwide. The sector presented a global growth rate of approximately 16% in the last years, reaching a total installed capacity of 435 GW, according to the World Wind Energy Association [1]. This impressive amount of power represents an enormous number of wind turbines installed worldwide.

An actual wind turbine (WT) can present the following impressive characteristics: 150 m hub height, 160 m rotor diameter and 8 MW rated power. They normally run on a 24/7 schedule, are geographically distributed [2] and unexpected breaks can lead to huge financial losses due to its respective size. All these combined conditions and characteristics turn the operation and maintenance (O & M) of a wind farm (WF) a very challenging task, not only from a technical but also from a cost perspective.

Some studies [3] carried out to quantify the total costs of European WFs showed that O & M costs, when compared to the total cost of energy of an operational WF, can vary from 12% for onshore, to 23% for offshore, what certainly encourage WF operators to employ the most advanced and adapted O & M methodology and focus on the most critical components to reduce the failure rate, time to repair and maximizing WF performance.

Critical components are those whose unexpected failures cause unscheduled downtimes which will have a great impact on the availability and productivity of the WF. Gearbox, generator, main bearing, blades and tower are classified as critical components in a WT [4].

Among the critical components, drive train components of WTs are subjected to highly dynamic loads due to the interaction of inertial forces, aerodynamic forces, elastic and structural forces, control forces and mechanical vibration. The fatigue experienced by the components of WTs can be orders of magnitude greater than for other systems or machines [5], what makes WF O & M even more distinct.

Among the drive train components, gearboxes are still a major source of turbine failures, although its technology has been developed for decades. The main systems subjected of concern are the gearbox bearings, the gear wheels and the lubrication. Unpredicted repairs or replacements of bearings, shafts and gear wheels, can be very expensive, requiring sometimes the disassembly of the entire WT rotor and drive train.

Some studies have been carried out with the aim to quantify a

* Correspondence to: UFPE - Federal University of Pernambuco, Department of Mechanical Engineering, Av. da Arquitetura - Cidade Universitária, Recife, PE Zip Code: 50740-550, Brazil.
E-mail addresses: gnpleite@gmail.com (G.d.N.P. Leite), ama@ufpe.br (A.M. Araújo), pedro.a.rosas@gmail.com (P.A.C. Rosas).

http://dx.doi.org/10.1016/j.rser.2017.06.002
Received 5 May 2016; Received in revised form 8 February 2017; Accepted 1 June 2017
1364-0321/

Please cite this article as: de Novaes Pires Leite, G., Renewable and Sustainable Energy Reviews (2017), http://dx.doi.org/10.1016/j.rser.2017.06.002

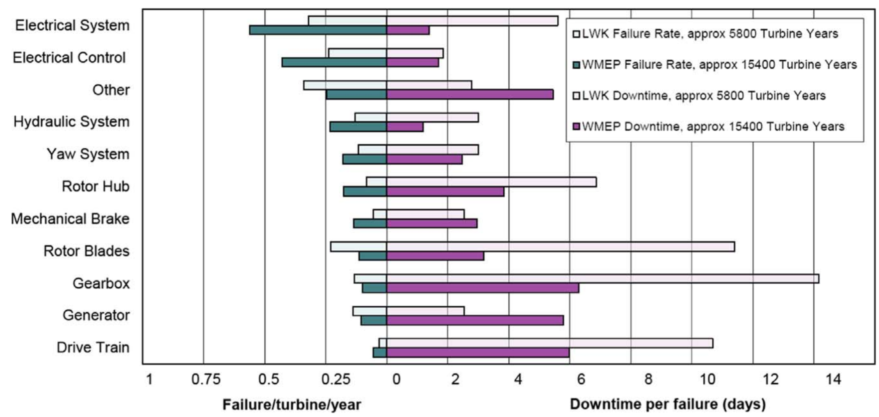

Fig. 1. Failure rate and downtime of onshore European WTs [6].

typical distribution of failure for an operational WT, mainly focused on the critical components. Since European WFs are the ones with the most years of operations, their data have been analysed in order to characterise failure rate and downtime of WT components. The Fig. 1 presents a compilation of two studies showing the distribution of failure rate and WT downtime [6]:

i. Study 01: the *Wissenschaftliches Mess- und Evaluierungsprogramm* (WMEP) database was accomplished from 1989 to 2006 and contains failure statistics from 1500 wind turbines.
ii. Study 02: failure statistics published by *Landwirtschaftskammer Schleswig-Holstein* (LWK) from 1993 to 2006. It contains failure data from more than 650 wind turbines.

In both studies, it can be seen that critical components present the largest downtime when compared to other WT subsystems.

Given the consistent increase in the installed capacity worldwide, all the operational challenges and the costs associated with the O & M of WTs, there is a clear academic and commercial interest in increasing reliability and, consequently, having the most economical and efficient operation of WTs. The main aspects involved in improving WT reliability are reducing the downtime, increasing the availability and performance of the WTs [7]. These benefits can be reached with the application of more efficient O & M methodologies, allowing incipient diagnostic and anticipated prognostic of WT components' failures.

Prognosis is a very vast research area which is present in distinct subjects, from medicine and neuroscience to engineering, physics and others. Prognosis is a word related to the action of predicting something, such as an upcoming disease or the remaining useful life (RUL) of a machine component.

The determination of RUL of WT components is a still open field in which many techniques and strategies are being recently evaluated in order to find consistent and reliable results. However, this is a challenging task given the complexity to model the operational regime of WTs and also to predict the RUL and its corresponding uncertainties. Another important point is, sometimes, the lack of communication between researchers and owners of WFs incurring in the inaccessibility of real operational data to researchers of prognosis and the unavailability of ready-to-use, powerful, reliable and mature techniques and systems to WT operators. One of the main reasons for this lack of communication is due to proprietary reasons what, finally, causes a lack of consistent literature studies.

The aim of this work is to present a concise review of the actual effort in the field of prognosis and RUL estimation methods applied specifically to components of operational WTs.

Firstly, the standard O & M maintenance strategies used on WTs are presented, namely corrective and preventive maintenance. As an evolution of the previous O & M practices, condition based maintenance (CBM) is then defined and its main steps are explained in Section 2. In Section 3, the most relevant papers related to prognostic methods applied to WTs are presented, divided by WT component. Then, in Section 4, further works needed in the area of prognostics of WT are suggested and, finally, the conclusions summarise the present work in Section 5.

2. Wind farm O & M practices

In general, the following standard maintenance strategies are employed in a WF O & M campaign [8]:

i. Corrective (breakdown or reactive response) maintenance strategy: the rule of thumb in this strategy is “fixing when it breaks”. No condition monitoring is carried out. Incipient faults could lead to catastrophic failures in WTs, even if they are found in non-critical components.
ii. Preventive (periodic) maintenance or planned intervention maintenance policy: regular inspection and small maintenance actions are executed and components can be changed based on the number of running hours despite its current degradation conditions.

Normally, both strategies require a huge effort from expert technicians and engineers, locally and remotely based, so that unexpected breakdowns are avoided. A considerable spare parts stock is also needed in order to avoid discontinuity in the operation of a WT if a faulty component is unavailable. Giving the size of the units, the geographic distribution of WFs and the complexity of loads, it is evident that the combined approach, corrective-preventive, is not an adequate strategy for reliable O & M of WFs, either for onshore or offshore.

Condition-based maintenance (CBM) is a robust approach to be used for WFs O & M since this is a maintenance strategy, based on the information collected through sensors of a condition monitoring system (CMS) in which the operational condition of a machine is continuously monitored and the machine is only stopped to be fixed when a pre-established alarm level is reached [9]. The philosophy behind this strategy is “fixing only when it is needed”.

In recent years, the implementation of CBM has been used extensively as an alternative to increasing reliability and reduce O & M costs of WFs [10]. However, CBM implementation is challenging and depends on the efficacy of various subsystems (Fig. 2) such as data acquisition, data processing, fault detection, prognostic assessment and maintenance decision of WF components.

CBM has been presented as an interesting alternative to standard O & M strategies for WFs O & M. In the next section diagnosis and prognosis will be more deeply described to confirm its suitability for WFs O & M. An emphasis will be given to the prognosis techniques, which is the objective of this article, showing the relevant aspects of the