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A review of diagnostics and prognostics of low-speed machinery towards wind turbine farm-level health management

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ABSTRACT

Large wind farms are gaining prominence due to increasing dependence on renewable energy. In order to operate these wind farms reliably and efficiently, advanced maintenance strategies such as condition based maintenance are necessary. However, wind turbines pose unique challenges in terms of irregular load patterns, intermittent operation and harsh weather conditions, which have deterring effects on life of rotating machinery. This paper reviews the state-of-the-art in the area of diagnostics and prognostics pertaining to two critical failure prone components of wind turbines, namely, low-speed bearings and planetary gearboxes. The survey evaluates those methods that are applicable to wind turbine farm-level health management and compares these methods on criteria such as reliability, accuracy and implementation aspects. It concludes with a brief discussion of the challenges and future trends in health assessment for wind farms.

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1. Introduction

Renewable energy sources are gaining importance due to depleting fossil fuel reserves and their adverse environmental impact. The European Union (EU) aims to shift 20% of its energy reliability to renewable energy resources by 2020 and the European Wind Energy Association estimates about 14% of this to be fulfilled by wind energy [1]. Higher wind energy production translates to larger wind farms and higher capacity turbines. As the wind farms grow larger, it is becoming a necessity to adopt advanced maintenance strategies in order to ensure high availability and profitable operation.

Substantial research in the area of improving maintenance strategies for wind farms in order to optimize maintenance cost and improve reliability has been conducted through collaborative efforts of the industry and academia. Energy research Center of Netherlands (ECN)'s CONMOW [2], ReliaWind [3] and Supergen [4] are some of the notable efforts undertaken by European research consortia for wind turbine (WT) condition monitoring. Some of the significant surveys on operation and maintenance data of wind farms have appeared in Ribrant et al. [5] on Swedish wind farms, Hahn et al. [6] on German wind farms and ReliaWind [3] on turbines across EU, wherein the most frequent failures and their corresponding downtimes were identified. It has been identified through ReliaWind that the WT drivetrain gearbox, pitch and yaw systems contribute to about 35% of the faults and 35% of the down time [3].

It is now well accepted that condition monitoring (CM) is important in predicting failures in remotely located WTs both by the wind farm operators and insurance companies [7]. There are a variety of commercial CM systems that are offered by original equipment manufacturers (OEM's), turbine operators and third parties. A recent research claims that there are as many as 36 different products on the market [8] which are primarily based on techniques like vibration sensing, oil debris analysis and temperature monitoring. Condition monitoring plays an important role in advanced maintenance strategies such as condition based maintenance (CBM) and reliability centered maintenance (RCM). These maintenance strategies are established areas in aerospace, energy and other industry sectors and are forming the basis for defining a maintenance strategy in wind energy sector with necessary modifications. It is important to notice that unlike most of the other sectors, equipment in wind farms have to withstand a highly corrosive environment (in offshore installations), bad weather conditions like storms and varying loads in relatively low-speed operating profiles.

Although CM systems exist, National Renewable Energy Laboratory (NREL) [9] reports that even as recently as 2010, most of the wind farms follow scheduled and reactive maintenance strategies. It has been identified that about 59% of the wind turbine failures are gearbox related and of these, about 70% are attributed to bearing faults [9,10]. Multi-stage gearboxes, with at least one planetary stage are present in most wind turbine configurations in the drivetrain, pitch and yaw systems. Rolling element bearings are ubiquitous, and are significant contributors to failures in motors, gearboxes and in most rotating machinery. Gearboxes and bearings have been classical candidates for condition monitoring and a variety of condition monitoring techniques exist in the literature. Given the unique challenges of wind energy, a careful scrutiny of the state-of-the-art is necessary for selection of most suitable condition monitoring strategy. With right choice of CM technique, many failures may be averted at incipient stage, resulting in significant savings on maintenance costs and down times. This proposition motivated the survey of diagnostics and prognostics of two highly failure prone and critical components of the wind turbines, namely, planetary gearboxes and bearings. Thus, the main contribution of this paper is to assess the state-of-the-art in diagnostics and prognostics against their applicability to wind turbines and wind farm-level implementation.

The remainder of this paper is organized as follows. The role of monitoring, diagnostics and prognostics in advanced maintenance strategies is discussed in Section 2. The state-of-the-art in health monitoring and condition assessment of bearings and gearboxes is surveyed in Sections 3 and 4 respectively. The status of prognosis and remaining useful life assessment are detailed in Section 5. Section 6 presents a discussion comparing the methods described against key features such as accuracy, reliability and implementation aspects. Finally, the conclusions are outlined in Section 7.

2. Maintenance methodologies

In order to understand the current status of maintenance, it is necessary to revisit the development of maintenance strategies chronologically. It may not be overstating to say that most significant developments in the field of maintenance existing today owe their origins to aerospace industry and have evolved over time due to stringent safety and tight monetary constraints. These maintenance strategies, owing to the nature of aviation industry, are conceived with objectives of scalability and fleet-level implementation and hence are suitable candidates for wind farm-level implementation. Until the later part of 20th century, the maintenance consisted primarily of two types: (1) *reactive maintenance* where repair or replacement is performed upon failure and (2) *calendar based maintenance*, wherein the repair or replacement is performed periodically or based on number of usage hours. It is believed that systems mostly follow a bathtub curve and eventually fail after a certain number of hours and maintenance is planned prior to this failure as per bathtub curves.

2.1. Reliability centered maintenance

A discovery by Nowlan et al. [11] that about 89% of the aircraft equipment does not follow the bath-tub curve in aging patterns made them question the idea of a calendar maintenance overhaul of the aircraft. At this point of time, the reliability centered maintenance is first defined with a simple objective: *preserve system function*. The idea is to determine all those factors that could stop the system from fulfilling its functional objective and eradicate them. An elaborate detail of RCM and its implementation aspects may be found in SAE standards documents SAE JA-1012 [12], NAVAIR 00-25-403 [13,14].

RCM breaks the system down into components and then identifies the key *failure modes* that could result in functional failure. Once the failure modes are identified at subsystem and component levels, appropriate maintenance tasks are chosen per component and subsystem, based on their impact on safety and

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