Renewable and Sustainable Energy Reviews 52 (2015) 976–990

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

A survey of health monitoring systems for wind turbines

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ARTICLE INFO

Article history:
Received 11 January 2015
Received in revised form
18 May 2015
Accepted 26 July 2015
Available online 25 August 2015

Keywords:
Wind energy
Health monitoring
Sensing systems

ABSTRACT

Wind energy has played an increasingly vital role in renewable power generation, driving the need for more cost-effective wind energy solutions. Health monitoring of turbines could provide a variety of economic and other benefits to aid in wind growth. A number of commercial and research health monitoring systems have been implemented for wind turbines. This paper surveys these systems, providing an analysis of the current state of turbine health monitoring and the challenges associated with monitoring each of the major turbine components. This paper also contextualizes the survey with the various potential benefits of health monitoring for turbines.

Contents

Abbreviation: AE, acoustic emissions; AWEA, American Wind Energy Association; CBM, condition-based maintenance; CFRP, carbon fiber reinforced polymer; CM, condition monitoring; CWIF, Caithness Windfarm Information Forum; DAU, data acquisition unit; EWEA, European Wind Energy Association; FBG, fiber Bragg grating; FEM, finite element model; FFT, fast Fourier transform; FRP, fiber reinforced polymer; FTIR, Fourier transform infrared spectroscopy; GFRP, glass fiber reinforced polymer; HAWT, horizontal axis wind turbine; HM, health monitoring; LIDAR, light detection and ranging; MCSA, motor current signature analysis; MEMS, microelectromechanical system; MFC, macro-fiber composite; NDE/T, nondestructive evaluation and testing; NREL, National Renewable Energy Laboratory; NSET, nonlinear state estimation technique; OMA, operational modal analysis; OWI-Lab, Offshore Wind Infrastructure Lab; O&M, operations and maintenance; RES, Renewable Energy Systems; RF, radio frequency; RFID, radio-frequency identification; RM, reactive maintenance; RPS, renewable portfolio standard; SCADA, supervisory control and data acquisition; SHM, structural health monitoring; SM, scheduled maintenance; SNL, Sandia National Laboratories; VBDD, vibration-based damage detection; WSN, wireless sensor network

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[1] This work is funded under the U.S. National Science Foundation Grant no. 1069283, which supports the activities of the Integrative Graduate Education and Research Traineeship (IGERT) in Wind Energy Science, Engineering and Policy (WESEP) at Iowa State University.
[2] Work was performed at the Center for Nondestructive Evaluation, Iowa State University, an NSF IU CRC.

http://dx.doi.org/10.1016/j.rser.2015.07.110
1364-0321/

1. Introduction

The wind energy industry has grown quickly since the early 2000s. Global wind capacity reached close to 370 GW by the end of 2014, with China alone installing over 23 GW in 2014 [1]. Wind penetration has increased as well: in 2014, the U.S. state of Iowa generated over 28% of its electricity from wind power [2], and in 2013, wind supplied up to 68.5% of Spain's demand coverage [3]. Additionally, the European Wind Energy Association (EWEA) is tracking plans for over 98 GW of offshore capacity [4], and offshore wind is expected to continue to grow.

Some of wind energy's growth is due to increased public awareness of impending climate issues; another factor is the decreasing cost and increasing output of wind energy systems. Yet another driver of growth has been government policy, such as the adoption of renewable portfolio standards (RPSs) by a majority of U.S. states, requiring utilities to obtain a portion of the electricity they supply from renewable sources. The American Wind Energy Association (AWEA) expects utilities to choose wind to fulfill over 40% of all RPS requirements put in place as of 2013 [5]. With these factors contributing to increased demand, more cost-effective solutions for wind energy are sought to meet this demand and make wind even more attractive.

An emerging approach to reducing wind energy costs is to make wind turbines smarter. Sensing systems deployed on each turbine can collect data that could be used for a variety of purposes. A number of such systems for wind turbines already exist and provide benefits such as online health monitoring (HM) and load mitigation. Many other uses for such systems can be imagined, such as providing data to turbine control processes to maximize wind farm efficiency. Because of this, HM and other data collection systems are expected to play an important role in wind energy's future.

In fact, as time goes on, HM of wind turbines becomes more important and more attractive. Turbines have rapidly grown in physical size, and correspondingly, in power generation. This means that each turbine is becoming a greater source of revenue, and mitigating downtime is becoming more critical. Additionally, larger components are generally more expensive to maintain and replace. More and more wind farms are being sited offshore, where remote monitoring is particularly useful. And finally, wind energy is becoming a larger part of the world's electrical generation portfolio, so wind turbines are going to be relied upon for consistent operation more and more. Therefore, increased interest in systems for smart wind turbines is expected. This paper is intended to provide a contextualized, practical introduction to these systems.

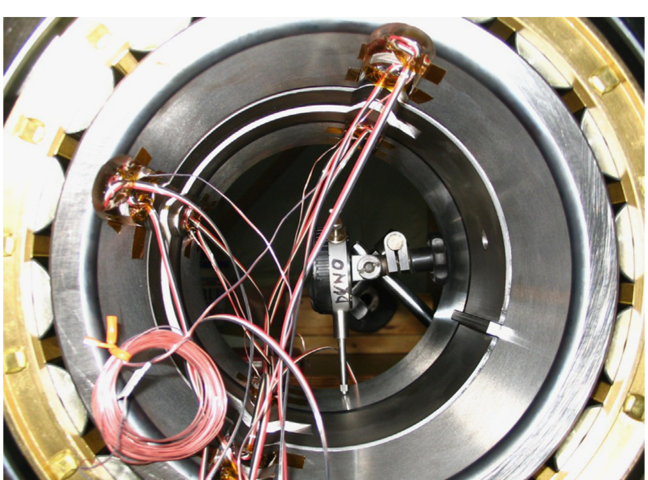

Fig. 1. Instrumentation of a gearbox bearing. Photo by Jeroen van Dam, NREL 19680.

Existing surveys of HM for wind turbines tend to focus on monitoring techniques [6–11], such as sensing technologies, with minimal attention given to the systems perspective. Existing lists of systems [12,13], while useful, are not intended to provide much context about monitoring, and also do not cover academic and research systems. Finally, existing surveys tend to either focus on particular turbine components, or provide little context about for which component a technology is suited. The goal of this paper is to provide a comprehensive, component-by-component survey of existing HM systems for wind turbines. Contrasting with existing surveys, the primary focus is at the system level. Specific sensing technologies and data processing techniques are discussed to the extent required to contextualize the systems and discuss future directions, but for more details on sensing technologies and analysis techniques, readers are encouraged to refer to other sources. This paper is also intended to provide context and high-level background on HM and the challenges faced by industry and researchers applying HM to wind turbines.

The remainder of this paper is organized as follows. The next section provides background information on HM. Section 3 presents a discussion of the motivations for monitoring wind turbines and an overview of the challenges and current state. Sections 4–7 examine challenges, existing systems, and the future for HM of turbine nacelles, foundations, towers, and blades, respectively. Finally, the discussion is concluded in Section 8.

2. Health monitoring

This section presents background information about HM in general. As discussed in Section 3, the potential uses of a turbine's sensing system are not limited to traditional HM. However, the bulk of existing systems are designed for HM-related purposes, so HM is discussed here to provide context.

The definitions of HM and related topics are not consistent in the literature. In this paper, HM refers to the process of using a sensing system to detect damage to an object, with damage being defined as a change in the object's properties that adversely affects current or future performance [14]. This paper defines condition monitoring (CM) as HM applied to machinery, and structural health monitoring (SHM) as HM applied to structures. This paper distinguishes HM from nondestructive evaluation and testing (NDE/T) by further defining HM as online, continuous monitoring using a permanent or semi-permanent sensing system installation. By this definition, an HM system could use NDE/T technologies for