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Load monitoring for active control of wind turbines

Aubryn Cooperman *, Marcias Martinez

Faculty of Aerospace Engineering, Delft University of Technology, Building 62, Kluyverweg 1, 2629HS Delft, P.O. Box 5058, 2600 GB Delft, The Netherlands

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A B S T R A C T

This review article examines the range of sensors that have been proposed for monitoring wind turbine blade loads for the purpose of active load control over the past decade. Wind turbine active load control requires sensors that are able to detect loads as they occur, in order to enable a prompt actuation of control devices. Loads may be detected based on structural effects or inferred from aerodynamic measurements. This paper is organized into the following sections: wind turbine control, requirements for load monitoring sensors, sensing technologies and field tests of load control. The types of sensors examined in this article include fiber optic sensors, inertial sensors, pressure measurements and remote optical sensing.

Contents

* Corresponding author. Tel.: +31 15 278 8233.
E-mail address: a.m.cooperman@tudelft.nl (A. Cooperman).

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1. Introduction

Wind turbines are an important source of renewable electricity generation. Worldwide, electricity-generating capacity from wind energy has exceeded 300 GW [1] and it continues to grow, contributing 22% of the new capacity installed in 2011 [2]. As a clean, renewable energy source, wind energy capacity is expected to continue growing.

Wind turbines are not only becoming more numerous but also larger. Increasing the size of individual rotors reduces the total number of turbines needed to produce a given amount of energy. This is particularly important for offshore wind farms where the costs of installing and connecting each foundation are much higher than onshore. Taller turbines also capture more energy from faster wind speeds found higher in the atmosphere. Increased energy capture produces higher aerodynamic loading on the structure, while there is also a need to minimize the structural weight of the blades in order to reduce gravitational loads. Monitoring and controlling these loads will become more important as turbines become larger and are located farther from shore.

Load sources on wind turbines can be described as aerodynamic, operational (caused by control actions), gravitational or inertial (gyroscopic and centrifugal) [3]. The rotor is the source of the most significant loads on the turbine. Reducing loads on the blades also reduces loads throughout the drivetrain and tower [4,5]. Turbines are becoming large enough that rotors span significant changes in wind speed including gusts, low-level jets, wind shear and turbine wakes [6–10]. Many of these affect only a portion of the rotor and require detection and response on a smaller scale than the full blade.

Fig. 1 highlights some of the key locations where sensors may be placed on a wind turbine. The nacelle houses the main electrical components and the controller. Condition monitoring sensors such as vibration sensors and oil contamination monitors may be installed in the nacelle to detect deterioration of the generator and gearbox. An anemometer and wind vane are typically located on top of the nacelle to detect the wind speed and direction. The rotor comprises the blades and rotating hub. Processors, sensor interrogators and LIDAR may be located in the rotating hub. The blade roots are a key location for detecting blade bending moments and also house the pitch drives that orient the blades with respect to the incoming wind. The outboard sections of the blades experience the largest aerodynamic forces, with the largest deflection occurring at the blade tips.

Sensors can be categorized as aerodynamic (inflow) or structural. Inflow sensors provide information about variations in the incoming wind field that produces the loads an active control system seeks to mitigate. They are able to provide measurements before the load occurs, giving the control system and actuators more time to bring the blade into an optimal state [11]. A downside to this approach is the disconnect between the measured quantity and the actual loading experienced by the turbine. Inaccuracy in the model used to correlate inflow measurement and loads can decrease the control system effectiveness and potentially cause instability [12,13]. The accuracy of inflow measurements can be reduced by the evolution of the wind field and variations in the turbine rotational speed between the time of measurement and the time at which the blade interacts with the measured flow. Structural measurements suffer from the opposite problem: loads may be measured accurately but too late to alleviate their effects on the turbine. Structural sensors can detect loads that are not anticipated by a particular model (although optimal sensor positions are facilitated by good modeling of the dynamics).

Structural sensors can also add value by contributing to condition monitoring and structural health monitoring of a turbine. Condition monitoring is expected to be implemented on more turbines in the future, particularly in offshore wind farms where access for maintenance can be difficult. Multipurpose sensors that contribute to structural health or condition monitoring as well as load control systems could provide several benefits. Many of the sensors described in this paper can also be used for condition monitoring [14–16] or structural health monitoring [17–20].

This paper is organized into the following sections: wind turbine control, requirements for load monitoring sensors, sensing technologies and applications to load control.

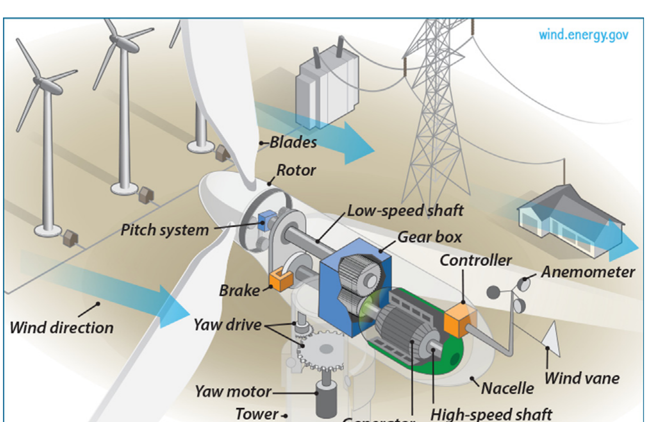

Fig. 1. Wind turbine schematic.
Source: US Department of Energy

2. Wind turbine control

This section gives a brief outline of control systems in modern wind turbines; for more in-depth discussion on the subject see references such as [3,21,22]. Wind turbines require control for several purposes: to ensure safe operation of the turbine, to maximize power production and to minimize extreme and fatigue loading of the structure. Each of these goals is prioritized in different regions of the turbine's operational range as shown in the idealized power curve in Fig. 2. Supervisory control is responsible for start-up and shutdown of the turbine, both under normal conditions in Regions 1 and 4, as well as in abnormal conditions such as a grid fault [22]. Operational control in Region 2 seeks to maximize power output, while in Region 3 the power output is held constant at the rated power in order to limit loads. The change from Region 2 to Region 3 encompasses some of the most significant loads on the turbine, so some controllers define a Region 2.5 in order to smooth the transition. Another transitional region (Region 1.5) is sometimes defined at low wind speeds where the turbine may spin without generating power.

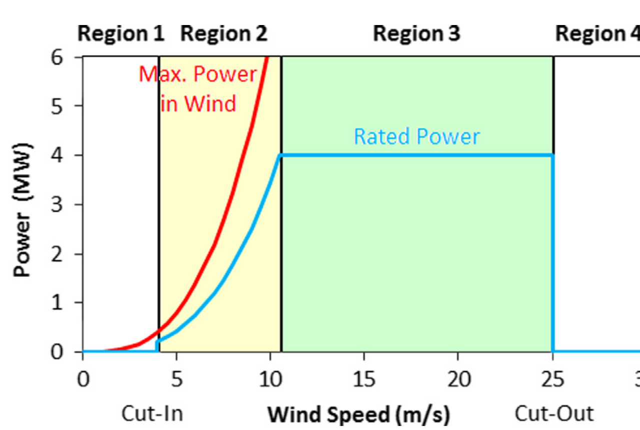

Fig. 2. Wind turbine power curve with control regions. No power is generated below the cut-in wind speed in Region 1. In region 2, the controller maximizes power output up to rated power. Rated power is maintained in region 3 up to the cut-out wind speed. Transitional control between Regions 1 and 2 and Regions 2 and 3 may be defined as Region 1.5 and Region 2.5.