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Review of computational and experimental approaches to analysis of aerodynamic performance in horizontal-axis wind turbines (HAWTs)

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A B S T R A C T

Horizontal-axis wind turbines (HAWTs) are the primary devices used in the wind energy sector. Systems used to evaluate the design of turbine blades and generators are key to improve the performance of HAWTs. Analysis of aerodynamic performance in turbine blades focuses on wind speed, rotational speed, and tip speed ratios (TSRs). This paper reviews computational as well as experimental methods used to measure the aerodynamic performance of HAWT blades. Among the numerical methods, we examine classical blade element momentum (BEM) theory and the modified BEM as well as computational fluid dynamics (CFD) and the BEM-CFD mixed approach. We also discuss the current computational methods for investigating turbine wake flows. Among the experimental methods, we examine field testing and wind tunnel experiment including aerodynamic torque measurement and blockage effects. A comparison of numerical and experimental approaches can help to improve accuracy in the prediction of wind turbine performance and facilitate the design of HAWT blades.

Contents

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1. Introduction

Wind turbine systems are among the most important renewable energy resource in the world. Optimal design of the turbine blade and integration with the generation system are crucial to improve the aerodynamic performance of wind turbines under steady-state flow conditions. There are two types of wind turbine system, differentiated by the outward appearance of the blades: horizontal-axis wind turbines (HAWT) and vertical-axis wind turbines (VAWT). Generally, more of the wind energy can be captured from HAWT blades than from VAWT blades due to the fact that the entire area swept by HAWT blades always faces into the wind during operations. Large-scale HAWTs are installed either as wind farms or in off-shore areas. Small-scale HAWTs are commonly seen in residential areas, occasionally integrated with solar energy systems [1–3] (referred to as wind and solar hybrid power generation systems).

HAWTs are classified according to the diameter of the blade as follows: micro-scale (μSWT, diameter $\leq$ 0.1 m), small-scale (SSWT, 0.1 m $<$ diameter $\leq$ 1 m), mid-scale (MSWT, 1 m $<$ diameter $\leq$ 5 m), and large-scale (LSWT, diameter $>$ 5 m) [4].

LSWTs with an output capacity of approximately 500 kW are based on mature technology and are expected to grow rapidly in coming decades. LSWTs generally operate at a various speed using a gear box system between the turbine blade and electric generator [5–7], wherein the blades operate close to stall conditions under high wind speeds. MSWTs, SSWTs, and μSWTs are relatively simple and produce relatively little power; therefore, they are of limited economic importance. New materials for wind turbine blades include carbon, carbon-hybrid and S-glass and the costs depend on the material and manufacturing processes [8,9]. The blades of the devices in these categories are generally variable-speed with a fixed angle of attack. The wind turbines require the use of additional electronic controls and uniform wind flow. Changes in the angle and speed of wind tend to produce variations in the torque provided by the blades.

In order to avoid the stall conditions, The aerodynamic performance of the HAWT blade can be adjusted by power regulating systems, which are classified into two types: stall-regulated and pitch-regulated (Fig. 1). HAWT systems can be operated at a constant speed or a variable speed according to their types of generator. In a constant-speed HAWT, the blade operates with a fixed speed when the wind speed is superior to the rated wind speed. The stall of the blade occurs with the increase of wind speeds in the stall-regulated system. Though the HAWT system can be built with a low-cost (without pitch control system), it has the many stall issues at high wind speeds. To improve the aerodynamic performance at high wind speeds, the pitch-regulated system or so-called pitch control system is applied to adjust the power to the rated power output when stall happens.

For the variable-speed operation, the rotational speeds of turbine blade vary with the wind speeds. The aerodynamic performance of the blade with the stall-regulated system is operated at the optimal tip speed ratio (TSR) by the control approaches such as maximum power point tracking (MPPT). Similarly, in order to keep the power value within the rated power output, the pitch control system is also used to regulate the power when stall happens.

HAWTs include a number of subsystems, including those of the rotor, drive train, pitch control system, generator, and electronic control system (Fig. 2). In LSWTs, a pitch control system adjusts the pitch angle (stall region) under high wind speed conditions. MSWTs and SSWTs use electronic control systems within the direct-drive generator to maximize efficiency. All types of wind turbine use rotors, which comprise the blades and a hub for the conversion of kinetic energy from the wind into mechanical

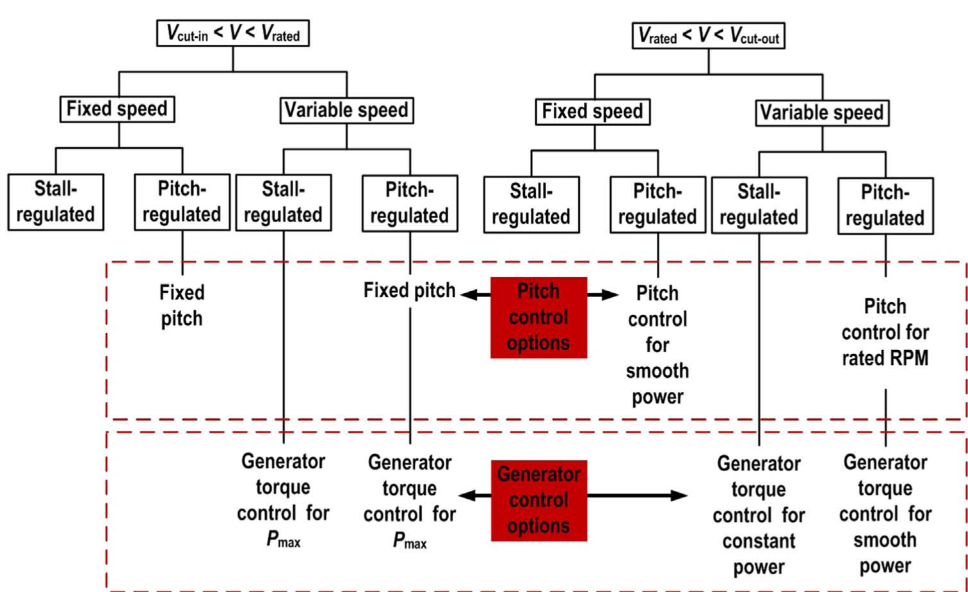

Fig. 1. Classification of power regulating systems of HAWT.