Energy xxx (2014) 1–8

Contents lists available at ScienceDirect

Energy

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

Aerodynamics performance of continuously variable speed horizontal axis wind turbine with optimal blades

Ahmad Sedaghat [a, *], M. El Haj Assad [b], Mohamed Gaith [b]

[a] Department of Mechanical Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran
[b] School of Engineering, Australian College of Kuwait, P.O. Box 1411, Safat 13015, Kuwait

ARTICLE INFO

Article history:
Received 28 December 2013
Received in revised form
13 September 2014
Accepted 18 September 2014
Available online xxx

Keywords:
Aerodynamics
HAWT (horizontal axis wind turbines)
Compact solutions
Blade element
Method of moment
Wind power generation

ABSTRACT

For conventional HAWT (horizontal axis wind turbines), the rotor speed is maintained constant while the blade tip speed changes continuously. This reduces considerably the power performance of the wind turbine particularly at high wind speeds where the tip speed ratio is small. With growth of variable speed generators, a compact BEM (blade element momentum) analysis is derived to design optimal blades for continuously variable speed HAWTs. First, a generalized quadratic equation on the angular induction factor is introduced which is related to local axial induction factor, blade local speed ratio, and drag to lift ratio. Second, the optimal blade geometry is obtained for which the maximum power coefficient is calculated at different design tip speed ratios and drag to lift ratios by assuming variable operational speed. Third, it is demonstrated that the power performance of the variable speed wind turbine is significantly higher than the conventional constant speed wind turbines. In addition, the present BEM modeling may be useful to reduce the computational effort of iterative numerical methods used in determining off-design power performance of conventional wind turbines with constant speed.

1. Introduction

There are many works that have been dedicated to the subject of wind energy and wind turbine designs. Eggleston and Stoddard [1] have gathered a comprehensive review of aerodynamic theories devoted to the wind turbine designs. Manwell et al. [2] has given insights to the classical Glauert type optimum design of wind turbines and proposed algorithms to numerically design the shape of blades of wind turbines. Technological and historical advancements of the industrial large wind turbines are extensively reviewed by Nelson [3] and Hau [4]. Further progress in aerodynamic design of wind turbine blades by also considering wind turbine blades in yaw motion were examined by Burton et al. [5].

Lampinen et al. [6] have applied the axial fan theory to horizontal-axis wind turbine. They developed a method to evaluate parameters of a horizontal-axis wind turbine using the available data of an axial fan with similar airfoil profile. Their numerical solution for the pitch angle and the chord of the blade were agreed well with the measured data of the commercial HAWT (horizontal axis wind turbines) blade. Kishinami et al. [7] have studied theoretical and experimental aerodynamic characteristics of a horizontal axis wind turbine. They have examined a combined momentum, energy and blade element theory and experiment a subscale model. Their results indicate that both BEM theory and experiments using different three types of blades match properly for variable or fixed pitch control. They also highlight that the optimized design parameters play significant role in the overall performance of the wind turbine. Hoogedoorn et al. [8] have computationally studied aeroelastic behavior of a flexible blade. Their 2D computation was extensively investigated the effects of a range of design parameters including wind speed, pitch angle, and airfoil specification. They concluded that flexibility can improve lift and lift to drag ratio which the latter one has substantial potential to improve the wind turbine performance. In another work by Mohamed [9], the impacts of solidity were investigated in performance of small VAWT (vertical axis wind turbines). The major drawbacks of VAWT were referred to self-starting capability and low efficiency. Mohamed [9] has examined solidity effects using CFD (computational fluid dynamics) and experiments. His findings suggest that flexibility may improve the aerodynamic performance of VAWTs at wider range of operating speed ratio comparing with previous studies by Casteli et al. [10] and Mohamed [11]. These works [8–11] also suggest that there are common effect of enhancing lift to drag ratio on both HAWTs and VAWTs. Other

* Corresponding author.
E-mail address: sedaghat@cc.iut.ac.ir (A. Sedaghat).

http://dx.doi.org/10.1016/j.energy.2014.09.048
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Please cite this article in press as: Sedaghat A, et al., Aerodynamics performance of continuously variable speed horizontal axis wind turbine with optimal blades, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.09.048

advance topics related to transverse vibration of wind turbine rotor connected with elastic foundation [12] and health monitoring of crakes in reinforced composite blades [13] should also be considered for their refined effects in the cited aerodynamic forces.

In all of the classical texts however, the optimum rotor blades were designed based on assumptions that simplify aerodynamic of the blades by ignoring drag force at some points of the analysis. The blade modeling starts with the simplest case of one dimensional flow in a stream tube using linear momentum equations. Then, the effects of wake rotation are incorporated using the angular momentum equation. Next, the blade element method is integrated to utilize the sectional lift and drag of wind turbine blade and finally some amendments are made to encompass the effects of tip and root losses. For the general case of BEM (blade element momentum) theory, the aforementioned modeling has usually assumed zero drag to calculate the axial and angular inductions factors. This then leads to implicit relations to determine the axial and angular induction factors through some numerical recursive iterative schemes for constant speed wind turbines.

In this work, the same BEM analysis is extended so as drag force is not discarded throughout our approach. A compact mathematical solution is obtained to model an optimum blade for horizontal axis wind turbines. For a generic modeling of an optimum blade using the proposed method, all important aerodynamic parameters are incorporated such as local drag and lift forces over airfoil sections, axial and angular induction factors, and tip losses in all stages of the mathematical modeling. A new quadratic formulation is introduced for the angular induction factor which incorporated all important design parameters including drag to lift ratio, axial induction factor, and the local speed ratio. This new formulation may also facilitate most BEM iterative methods for calculating off-design rotor performance.

The topics addressed in this paper include a review of aerodynamic modeling of horizontal axis wind turbines in Section 2 which highlight the momentum, the blade elements, and tip losses modeling. In Section 3, the formulation of blade element momentum theory is given in general form. The proposed compact mathematical solution is given in Section 4 in a more detailed manner with inclusion of drag force in all stages of analysis. The aerodynamic performance parameters are given in Section 5 in a unique manner to distinguish between the local and the total power and to understand a dual point optimization. Section 6 gives a comprehensive results and discussion of results for the optimum rotor with variable speed and the Section 7 concludes this article.

2. Aerodynamic design of wind turbines

Currently for determining the blade performance parameters in general case, the wind tunnel measurements of drag and lift forces over airfoil sections for a specific blade are combined with the momentum theories encompass under the name of BEM theory. This leads to implicit relations to be solved through some numerical schemes iteratively for obtaining off-design aerodynamic performance of wind turbine blades [2]. Sedaghat and Mirhosseini [14] have developed a computer program based on the BEM theory to numerically design blades of a mid-class 300 kW site specific wind turbines using RISO type airfoils. Mirhosseini and Sedaghat [15] have further extended the computer code to assess simplified blades with linear distributions of chord and/or twist angle across the blade for ease of manufacturing. The basic theory and its extension are discussed in details below.

2.1. The momentum theory

Considering wind turbine rotor as an actuator disk in a one dimensional tube as shown in Fig. 1, the effect of an actuator disk is to induce a step drop in pressure while allowing a continuous speed at the rotor area [2–5]. In the momentum theory, the rotor of wind turbine is taken as an actuator disk which retard the incoming uniform wind speed U_∞ at the rotor area, to a lower uniform speed of $U_\infty(1-a)$ just on the rotor blades. Here, the axial induction factor, a, provides a means of wind retardation in the axial direction (see Fig. 1).

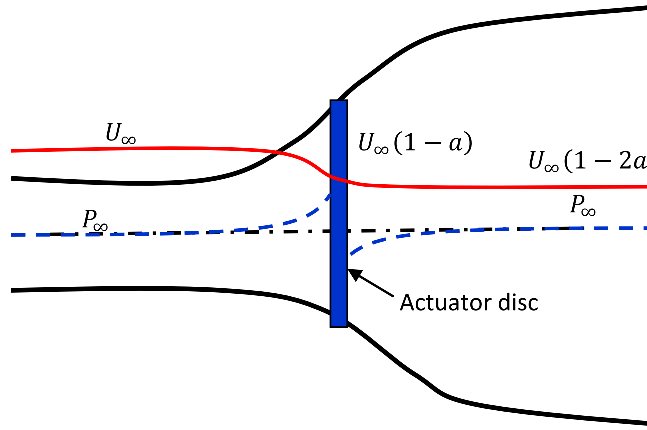

Fig. 1. Actuator disk model of a wind turbine in a stream tube.

By the step pressure change across the actuator disk in the rotor area, the differential thrust force, dT, is acted on an annular element at radius r with thickness of dr in a rotor area of, $dA = 2\pi r dr$. The thrust force may be determined from one dimensional momentum theory as follows.

$$dT = 4a(1-a)\rho U_\infty^2 \pi r dr \quad (1)$$

Here, ρ is the average air density at the height of wind turbine hub. From the Betz limit [2], an ideal wind turbine reduces wind speed to two third of the free stream value; i.e. $a = 1/3$ which also corresponds to the maximum power capture coefficient of $C_{Pmax} = 16/27$, i.e. 0.593. Employing a torsion torque by wind on the wind turbine rotor which generates the wind turbine power, the conservation of moment of momentum must also be satisfied using a wake rotation downstream of the wind turbine. The wake rotation affecting a particle passing through an annular control volume of the actuator disc is shown in Fig. 2.

The induced wake rotation is defined by an angular induction factor, $a' = \omega/2\Omega$, in which ω is the wake rotation and Ω is the angular velocity of the wind turbine rotor. From the moment of

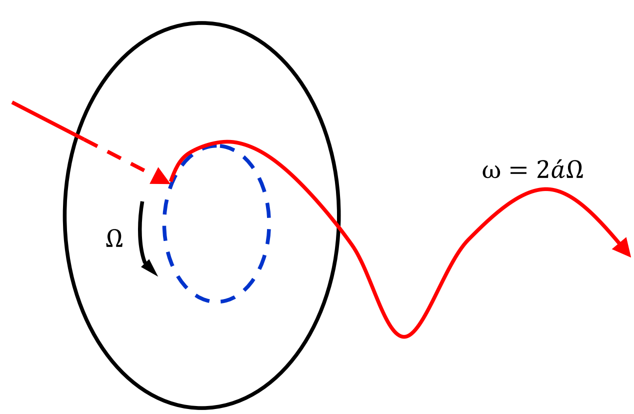

Fig. 2. Effects of wake rotation on a particle passing through the actuator disk.