Energy 119 (2017) 334–350

Contents lists available at ScienceDirect

Energy

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

Wind tunnel testing and improved blade element momentum method for umbrella-type rotor of horizontal axis wind turbine

Wei Xie, Pan Zeng*, Liping Lei

Key Laboratory for Advanced Materials Processing Technology of MOE, Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 1 September 2016
Received in revised form
30 November 2016
Accepted 13 December 2016

Keywords:
Wind tunnel testing
Blade element momentum theory
Horizontal axis wind turbine
Power coefficient
Thrust coefficient

ABSTRACT

The umbrella-type rotor concept for horizontal axis wind turbine is proposed. The rotor allows blades to fold along the hinge which is fixed at the hub. The blade pitching and rotor coning are coupled as the hinge is inclined. This rotor is designed as a new approach to realize power control in high wind speed. The model-scale umbrella-type rotor with three blades was made and a rotor mechanical power testing platform was set up. Wind tunnel testing was conducted to supply data to estimate the rotor power performance. In the field of wind turbine aerodynamics theory, the blade element momentum model was improved for the umbrella-type rotor aerodynamics calculation. Comparison between wind tunnel testing data and simulation result has been made. Experiment result showed that umbrella-type rotor was effective in adjusting power output by folding blades. The highest power coefficient was 0.259 in current study. Nevertheless it dropped down to 0.06 when the blades were folded at 20°. In wind speed from 5 m/s to 9.54 m/s, a constant power output of 8.87 W was achieved. The calculated rotor power coefficient was found to be in good agreement with the experiment data. The highest average deviation was 11.81%.

1. Introduction

Wind turbine rotor design is a hot topic among researchers around the world. An innovative umbrella-type rotor concept was proposed by the authors [1,2]. This innovative umbrella-type rotor is upwind configured and allows blade to fold upwind at hub according to wind conditions. The blade pitching and rotor coning are coupled due to the inclined folding axis. This rotor design with blade folding movement resembles umbrella configuration. The rotor is designed specially for small to medium size wind turbine and blade fold angle is actively controlled to realize power control in high wind speed. A general description of this rotor concept is on section 2. In present work a model-scale umbrella-type rotor was tested in wind tunnel and blade element momentum method was developed for its aerodynamics calculation.

In aspect of innovative rotor design, Pasupulati et al. [3] firstly presented variable length blade rotor concept. This concept sufficiently utilizes retractable blades to adjust rotor swept area and hence the power productivity. Corresponding researches has been conducted by McCoy and Griffin [4]. A prototype wind turbine with retractable rotor diameter of 81–110 m was studied with field testing and the maximum annual energy output increase of 22.8% was found. In the research conducted by Lanzafame and Messina [5], a rotor concept with segmented blades has been proposed. Each segmented blade section is absent of twist and carries a variable chord. This rotor is featured in the blade shape simplicity and the satisfactory power output performance. Similar to the umbrella-type rotor concept, these two rotor concepts were proposed to control power productivity. However, both of the concepts were passive stall regulated. The umbrella-type rotor is pitch regulated, which is the main difference from these two rotor concepts.

As to the blade pitching and rotor coning coupled rotor, late in last century, bend-twist coupled rotor was invented [6,7]. The blade bending load increases with wind speed and blade pitch angle increases as well due to blade bend-twist coupling. This rotor coning-pitching coupling results from the elaborate layout of reinforced fiber in the blade material and the particular blade structure design. Similar to the umbrella-type rotor, this rotor concept utilizes blade pitch angle change to control power productivity. However, this blade pitch angle change is still passively achieved by the blade bending moment. The coupling between blade pitch angle and rotor cone angle is achieved by the blade structure design and

* Corresponding author.
E-mail address: zengp@mail.tsinghua.edu.cn (P. Zeng).

http://dx.doi.org/10.1016/j.energy.2016.12.051
0360-5442/

Nomenclatures

λ	angle of attack [°]	C_l	airfoil lift coefficient
β	blade local pitch angle [°]	Cp	power coefficient
ε	folding axis incline angle [°]	Ct	thrust coefficient
δ	fold angle [°]	D	rotor diameter [m]
σ	rotor local solidity	f	tip loss correction factor
φ	relative wind direction angle [°]	M	rotor rotation torque [Nm]
Ω	rotor angular speed [rad/s]	n	rotor revolution rate [r/min]
a	axial induction factor	N	number of blade
a'	tangential induction factor	P	power output [W]
A	rotor swept area [m^2]	R	rotor radius [m]
c	blade local chord length [m]	T	wind thrust [N]
C_d	airfoil drag coefficient	TSR	tip speed ratio
		V_0	wind speed [m/s]
		W	relative wind speed [m/s]

material property. For the umbrella-type rotor, the rotor is coned upwind and this coning is realized by folding blade actively. The blade pitching and rotor coning are coupled by the particularly designed folding mechanism rather than special blade materials property.

Another coned rotor concept is the segmented ultra-light pre-aligned rotor [8,9]. This rotor concept aims to address mass-scaling issues for extreme large wind turbine rotor with rated power larger than 10 MW. This rotor is downwind configured and is pre-set with a cone angle. The cone angle is determined so that blades are aligned with the loads. Due to this downwind pre-coned rotor configuration, wind loads on blades are much less. Hence, the blade stiffness and the blade mass are reduced. The pre-align angle is designed based on wind speed of 1.25 rated speed. This segmented ultra-light pre-aligned rotor concept addresses issues of blade weight reduction and wind loads alleviation. Different from this rotor with fixed downwind coning configuration, the umbrella-type rotor cone angle is adjustable. The fold angle is changed according to wind speed. One of the main purposes of this rotor coning is to control power productivity. The goal of rotor coning movement is to achieve blade pitch angle change. This is not achievable for the pre-aligned rotor concept. Umbrella-type rotor concept is proposed specially for small to medium size wind turbine and rotor is upwind configured to avoid the tower shadow effect. For pre-aligned rotor, in study conducted by Loth, Steele, and Ichter et al. [8] the aerodynamic forces acting on a 10 MW segmented ultra-light pre-aligned rotor were calculated. The torque-wise force was obtained according to rated power output and rated angular speed. Angle of attack and airfoil lift-to-drag ratio on blade segment were estimated. Wind thrust was estimated based on torque-wise force and lift-to-drag ratio. In current study, the main content is the wind load testing and rotor aerodynamics calculation. The blade element momentum method was improved specially for umbrella-type rotor aerodynamics calculation. The accurate wind loads and power putouts were calculated by this improved method and wind tunnel testing data were used to examine the calculation precision.

For umbrella-type rotor, blade pitch angle change is the main factor that leads to power adjustment. In the field of innovative pitch regulated rotor concept, partial pitch regulated rotor has been proposed. One of the main purposes of this rotor concept is to alleviate blade pitch control duty [10]. Envision Energy Co., Ltd. has recently designed and constructed a 3.6 MW two-bladed offshore wind turbine with such rotor concept [11]. The inner part blade with length of 20 m was fixed to rotor hub and was stall regulated. The outer part blade with length of 42 m was connected to the inner part blade by pitch bearing and was pitch regulated type [12]. This rotor was equipped with pitch bearing to achieve blade pitch control. The pitch bearing was installed inside the inner blade segment at the blade segment junction position. Theoretically, the blade pitch bearing is the same as the one of full span blade pitch regulated rotor. For the innovative umbrella-type rotor concept, the pitch bearing, however, is replaced by the folding mechanism which is mounted on the hub. The folding mechanism rather than the pitch bearing is used to bear the loads from the blade. This folding mechanism structure is elaborately designed so as to refine the loads distribution. Blade pitch angle change is no longer achieved by the pitch bearing, and instead, is achieved during the blade folding process, due to the inclined folding hinge.

In previous studies conducted by the authors, a partial folding blade concept has been proposed [13]. This blade was designed as a new solution to control power productivity specially for large size wind turbines. A worm-gear type blade folding mechanism and control system with both fold angle control subsystem and generator rotor current subsystem were designed. A 660 mm long partial folding blade was erected in wind tunnel and was tested to obtain the aerodynamic load data. A small rotor, with diameter of 0.8 m and outer folding blade section of 0.17 m, was also tested in wind tunnel [14]. The rotor Cp curves were obtained and relationship between fold angle and wind speed to maintain constant power output in high wind speed was obtained as well. In current work, the umbrella-type rotor concept is inspired by this partial folding blade concept. This new rotor concept also aims to control power productivity and reduce wind thrust. Different from the partial folding blade used in large wind turbines, the umbrella-type rotor is designed for small to medium size wind turbine. The blade folding hinge is moved to rotor hub, which results in full span blade folding. Since blade pitch control duty for small rotor is not as much as that of large size rotor, this full span blade folding is acceptable. Due to this folding hinge movement, folding mechanism is integrated on rotor hub as well. This is a practical solution to compact rotor design, since there is limited space to mount folding mechanism inside blade for small wind turbines. As an effort to improve the rotor mechanics property, a folding mechanism utilizing truss structure theory to refine load distribution was designed. The mechanical theory and design drawings of the folding mechanism were presented in previous work by the authors [2]. Wind tunnel testing for a 0.65 m diameter model-scale umbrella-type rotor has been conducted as well [1]. The wind tunnel testing data demonstrated that this rotor concept was valid in adjusting power coefficient and reducing wind thrust. The umbrella-type rotor concept effectiveness has already been demonstrated in these previous works. Current study focuses on theoretical analysis on umbrella-type rotor aerodynamics. This is not considered in the work done