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A novel folding blade of wind turbine rotor for effective power control

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ABSTRACT

A concept of novel folding blade of horizontal axis wind turbine is proposed in current study. The folding blade comprises a stall regulated root blade section and a folding tip blade section with the fold axis inclined relative to blade span. By folding blade, lift force generated on the tip blade section changes and the moment arm also shortens, which leads to variations of power output. The blade folding actuation mechanism with servo motor and worm-gear reducer was designed. Wind turbine rotor control scheme and servo system with double feedback loops for blade fold angle control were proposed. In this study, a small folding blade model was tested in a wind tunnel to analyze its performance. The blade model performance was estimated in terms of rotation torque coefficient and thrust coefficient. Wind tunnel experiments were also conducted for pitch control using the same blade model in order to make a direct comparison. The power control, start up and aerodynamic brake performance of the folding blade were analyzed. According to the wind tunnel experiment results, fold angle magnitude significantly affected blade aerodynamic performance and the thrust characteristic together with the rotation torque characteristic of folding blade were revealed. The experiment results demonstrated that the folding blade was valid to control power output and had advantages in reducing thrust with maximum reduction of 51.1% compared to pitch control. Optimum fold angles of 55° and 90° were also found for start up and aerodynamic brake, respectively.

1. Introduction

With the development of industry, energy demand is increasing around the world; renewable and clean energy including wind energy, solar energy and geothermal energy nowadays has been recognized as important energy source in many countries and districts for meeting the energy needs. Wind energy, being a prominent renewable energy, has been developing rapidly in the past decades as it is widespread and is a kind of clean energy without greenhouse gases emissions [1–5]. China is active in utilizing wind energy and leads the wind energy market. According to the Global Wind Energy Council (GWEC) annual report [6,7], a total installed capacity of wind power was 318.18 GW in 2013, and compared to 282.88 GW in 2012, the increase was 12.48%. A total installed capacity in China reached 91.41 GW in 2013 followed by USA, Germany, Span and India with a total installed capacity of 61.09 GW, 34.25 GW, 22.96 GW and 20.15 GW, respectively.

As is known, horizontal axis wind turbine (HAWT) is a type of wind turbine most widely equipped worldwide. Most modern Megawatt HAWT is pitch regulated with blade pitch system to control power output [2,8–12]. In general, a pitch regulated wind turbine starts up at wind speed below cut-in speed and stops power output for self-protection at wind speed reaches cut-out; wind turbine power output achieves the rated value when the wind reaches the rated speed and then blade pitch control works to limit power output growth in the further increase of wind speed [13–15]. Attention has been paid to pitch regulated wind turbine due to its crucial role in HAWT and encouraging results on achieving optimum power regulation are reported [2,8,16–23].

The size of HAWT blade is increasing for the sake of enhancing rated power and reducing the cost of per kW electricity generated. Alstom Haliade 150–6 MW offshore wind turbine is among the largest HAWT in the world and its rotor diameter reaches 150.8 m with the rated power of 6 MW, which means the length of a single blade is more than 70 m [24–26]. The increasing magnitude of rotor makes transportation, manufacture and installation of a blade difficult. Besides, pitch control system appears inefficient in rapid response to wind speed variation due to the huge inertia of blade [27,28]. In the past years, generator rotor current control (RCC) technology was applied to wind turbines to overcome inability of pitch control under fast varying wind conditions [29–33].

Power control can be achieved even if tip blade section is pitched, and moreover, reduction of aerodynamic load fluctuation

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is gained by simply pitching tip blade section [13,34–36]. This enlightens a new research topic on large HAWT blade design. In this aspect, Shimizu [37–40] conducted comprehensive studies about performance of tip vane on rotor blade, including power augmentation, flow turbulence around tip vane and pressure distribution along blade. Lanzafame and Messina [41] subdivided a blade into two sections, each with a different pitch angle and absence of twist along blade, and found that power output gained compared to standard full span non-twisted blade. Partial pitch blade with root blade section designed as stall regulated and tip blade section designed as pitch regulated was also reported. Examples of partial pitch wind turbine include MOD-2 2.5 MW wind turbine developed by Boeing Engineering and Construction Co. in the early 1980s and Danish Nibe A wind turbine [13,42–44]. In the patent aspect, US patent US 2012/0288371 A1 [45] proposed a partial pitch wind turbine and an associated control method to reduce loads on blade root and provide a smoother power curve; German patent DE 917540 [46] disclosed a partial pitch wind turbine rotor for generating power at nominal value in certain wind speed range. Fig. 1 shows the schematic diagram of partial pitch wind turbine. In current study, a novel folding blade design was proposed and a small folding blade model was tested in wind tunnel to analysis its performance in power control, start up and aerodynamic brake. Experiments were also conducted with pitch control using the same blade model in order to make a direct comparison. In addition, the blade folding actuation mechanism was designed. The control scheme of wind turbine rotor and the servo system with double feedback loops for tip blade fold angle control were proposed.

2. Description of folding blade

2.1. Theory of folding blade

The blade is the basic component of wind turbine and plays an important role in energy conversion. Power coefficient (C_p) differs along blade span due to airflow variation and estimation of C_p distribution is the key for efficient wind power utilization. C_p can be estimated by several theories. Early in the last century, Betz studied power coefficient of wind turbine by simplifying the rotor as an actuator disc [14,15]. The air that passes through the rotor undergoes a speed change, which leads to energy extraction from air. The power output calculation derived from momentum theory is shown in Eq. (1), and from energy conservation theory, power can be calculated using Eq. (2). Combining Eqs. (1) and (2), the wind speed (V_D) at rotor plane is determined as $0.5(V_1 + V_2)$. The maximum power is $P_{\max} = 0.593 \times (0.5\rho V_1^3 A)$ when $V_2 = V_1/3$.

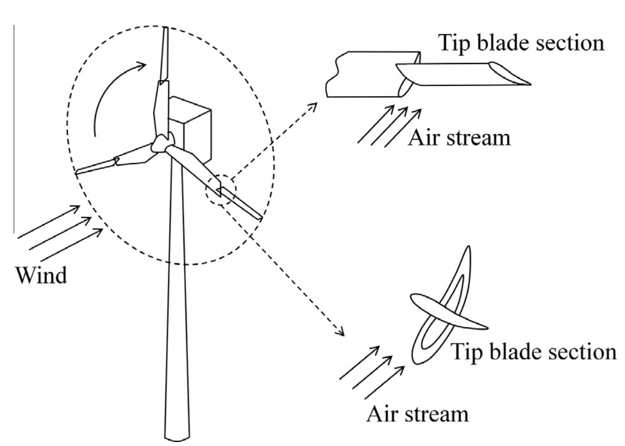

Fig. 1. Schematic diagram of partial pitch wind turbine.

Considering Eq. (3), the highest power coefficient is 0.593 known as the Betz limit.

$$P = \rho A V_D^2 (V_1 - V_2) \tag{1}$$

$$P = 0.5\rho A V_D (V_1^2 - V_2^2) \tag{2}$$

$$C_p = \frac{P}{0.5\rho V_1^3 A} \tag{3}$$

where C_p is the wind turbine power coefficient; P is the wind turbine power output; ρ is the air density; A is the rotor swept area; V_D is the wind speed at rotor plane; V_1 is the rotor upstream wind speed; V_2 is the rotor downstream wind speed.

Another fundamental theory related to power coefficient is the blade element momentum theory (BEM) [13–15]. In this theory, the axial-wise and tangential-wise induced flows are taken into account. Based on blade element forces, the thrust (dT) and driving torque (dM) are expressed in Eqs. (4) and (5), respectively. As a simplification, drag force is ignored in the equations. From momentum theory, dT and dM on annular ring of rotor disc are calculated using Eqs. (6) and (7), respectively. C_p is expressed as $(\omega dM)/(\rho\pi r V_1^3 dr)$. By simplifying Eqs. (4–7) and considering wind speed relationship $\cos(\varphi) = r\lambda(1 + h)/(R(1 + k))$, C_p is simplified as Eq. (8). Similar to non-rotating wake case, k is assumed to be 1/3 and C_p distribution is plotted in Fig. 2. As can be seen, C_p is quite low at blade root, while presents relatively high value around blade tip.

$$dT = 0.5\rho n c w^2 C_L \cos(\varphi) dr \tag{4}$$

$$dM = 0.5\rho n c r w^2 C_L \sin(\varphi) dr \tag{5}$$

$$dT = \rho\pi r V_1^2 (1 - k^2) dr \tag{6}$$

$$dM = \rho\pi r^3 \omega V_1 (1 + k)(h - 1) dr \tag{7}$$

$$C_P = \frac{r^2\lambda^2(1+k)}{R^2}\left(\sqrt{1 + \frac{(1-k^2)R^2}{r^2\lambda^2}} - 1\right) \tag{8}$$

where n is the number of blades; c is the chord length of blade element; w is the relative wind speed; C_L is the blade element lift coefficient; φ is the relative wind direction angle; r is the rotation radius of blade element; R is the rotor radius; k is the axial speed factor; h is the tangential speed factor; ω is the rotor angular speed and λ is the rotor tip speed ratio.

Based on the understanding of blade C_p distribution, rotor swept area is divided into a low efficiency area in the center and

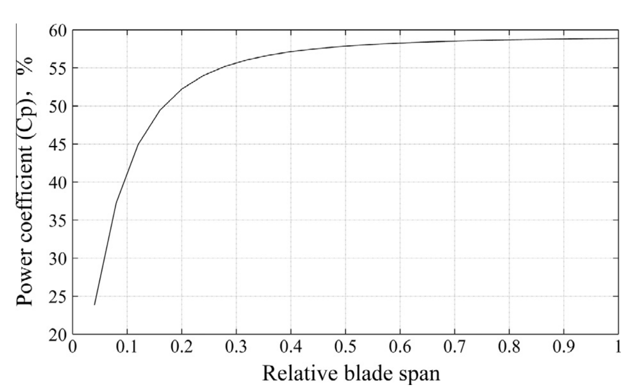

Fig. 2. Blade power coefficient distribution from BEM.