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Parametric study on off-design aerodynamic performance of a horizontal axis wind turbine blade and proposed pitch control

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ABSTRACT

In this paper, a 200 kW horizontal axis wind turbine (HAWT) blade is designed using an efficient iterative algorithm based on the blade element momentum theory (BEM) on aerodynamic of wind turbines. The effects of off-design variations of wind speed are investigated on the blade performance parameters according to constant rotational speed of the rotor. The performance parameters considered are power coefficient, axial and angular induction factors, lift and drag coefficients on the blade, angle of attack and angle of relative wind. At higher or lower wind speeds than the designed rated speed, the power coefficient is reduced due to considerable changes in the angle of attacks. Therefore, proper pitch control angles were calculated to extract maximum possible power at various off-design speeds. The results showed a considerable improvement in power coefficient for the pitch controlled blade as compared with the baseline design in whole operating range. The present approach can be equally employed for determining pitch angles to design pitch control system of medium and large-scale wind turbines.

1. Introduction

The limited amount of fossil fuels as well as the increment of energy expenditure, make fossil fuels a non-sustainable source of energy. Large efforts have been made for exploration of new techniques of replacing fossil resources by renewable ones. Wind energy is one of the greatest energy sources that can be used to meet our future demands. Nowadays, wind turbines have a key role in the field of energy production and it seems essential to provide some guidelines for wind turbine designing process. Investigation of wind turbine design parameters when subjected to different wind speeds is critical for understanding of aerodynamics characteristics at off-design conditions.

Recently, lots of research on aerodynamic design of wind turbine blade have been done [1–4]. As an effective tool, the blade element momentum (BEM) theory has been frequently used to develop mathematical laws for design and optimization purposes of horizontal axis wind turbine (HAWT) blades [5–9].

Vaz et al. [8] developed an improved BEM approach based on Glauert's classic model for performance prediction of HWATs. The employed mathematical model takes into consideration the real phenomena such as tip loss, cascade and turbulent wake effects. Dai et al. [10] performed a numerical aerodynamic load analysis for a large scale wind turbine based on combination of modified BEM and dynamic stall model. These results showed a great coincidence between the presented dynamic stall model and 2D aerodynamic performance data. Lee et al. [11] have investigated the effects of design parameters such as the combination of the pitch angles, rotating speeds and rotors radii on aerodynamic performance of a counter-rotating wind turbine. They also proposed a modified BEM method to analyze the interaction between the rotors for such turbines. Sedaghat et al. [12] designed a 300 kW horizontal axis wind turbine blade using the BEM theory. Design parameters such as axial and angular induction factors, angle of relative wind and lift coefficient were obtained to extract maximum accessible power coefficient at rated wind speed and optimum tip speed ratio. Sharifi et al. [13] proposed a new innovative algorithm to predict the pitch angle distribution along a wind turbine blade. The BEM theory was utilized to obtain maximum power coefficient at a particular wind speed. Although, the cost of blade manufacturing increases by utilizing new complex pitch angle distribution, the output power of the wind turbine is augmented significantly. Using the BEM theory, Liu et al. [14] optimized the chord and twist angle of a fixed-pitch fixed-speed HAWT blade at the rated wind speed and particular tip speed ratio. According to this method, the chord and twist angle distribution along the blade were linearized on a heuristic basis with fixed

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Nomenclature

A	area of wind turbine rotor (m^2)
a	axial induction factor
a'	angular induction factor
B	number of blades of a rotor
c	airfoil chord (m)
C_l	lift coefficient of an airfoil
C_d	drag coefficient of an airfoil
C_p	local power coefficient
$C_{p,max}$	maximum power coefficient
$C_{p,t}$	total power coefficient
C_n	normal force coefficient
C_T	thrust coefficient
C_t	tangential force coefficient
F	local tip loss factor
N	number of blades elements
P	mechanical power (W)
R	radius of wind turbine rotor (m)
Re	Reynolds number
r	blade radius at rotor plane (m)
U_∞	free stream velocity of wind (m/s)
U_{rel}	airfoil relative wind velocity (m/s)

Greek symbols

$\Delta\theta$	Pitch control angle (°)
Ω	angular velocity (s^{-1})
α	angle of attack (degree)
η	efficiency
θ_p	pitch angle (°)
λ	tip – speed ratio of rotor = $R\Omega/U$
λ_r	local speed ratio = $r\Omega/U$
ρ	air density (kg/m^3)
σ	rotor solidity
φ	angle of relative wind (°)

values at the blade tip and the optimal solution was determined to maximize annual energy production for the rated wind speed.

Because of the variability in the wind speed, the power coefficient deviates significantly from its optimum value [15]. In recent years, variable-speed wind turbines attracted many attentions due to their ability to operate at off-design wind speeds. Variations in wind speed causes significant deviations in power coefficient from design conditions [16,17]. To overcome this deficiency, pitch control mechanism is implemented as an effective tool in variable-speed wind turbines [18,19]. In this mechanism, blade pitch angle, which is defined as the angle between the blade chord line and the plane of rotor rotation, is varied in accordance with wind speed. Thereby the maximum amount of energy that available in a specific wind speed is captured and the structural loads at high wind speeds is minimized [20,21].

Measurements of wind speed at hub height are extremely important in the pitch control variable speed wind turbines [22]. As turbine towers go higher, the remote sensing (RS) devices are considered as more accurate and reliable devices to measure wind speeds at the hub heights. These devices are becoming easier, cheaper alternatives to meteorological masts installed cup anemometers, and wind vanes particularly for pitch control purposes.

Kishinami et al. [23] have investigated aerodynamics characteristics of a HWAT experimentally and theoretically. A subscale model was used to validate their numerical code for variable pitch control based on a combination of momentum, energy and blade element theory. They have also found that the design parameters such as angular and induction factors and angle of attack play a crucial role in the overall performance of the wind turbine. Lanzafame and Messina [24] investigated the performance of a wind turbine which continuously operates at maximum power coefficient. For this aim, a numerical code based on the BEM theory was developed at different wind speeds and the annual energy production of wind turbine at constant rotational velocity was compared with the same turbine at variable velocities. Sedaghat et al. [25] have studied aerodynamics performance of continuously variable speed horizontal axis wind turbine with optimal blades. In the case of constant rotor speed, the results showed that the power coefficient of the wind turbine considerably decreases as the wind speed increases. Through an explicit correlation for angular induction factor, a compact BEM analysis was introduced to design optimal blades for continuously variable speed HAWTs.

In the present work, a 200 kW wind turbine blade is designed using two-dimensional airflow model for a rigid blade based on modified BEM theory. The behavior of its design parameters such as axial and angular induction factors, angle of attack, angle of relative wind and power coefficient is studied at off-design wind speeds. Furthermore, the proper angles that must be applied to the pitch control mechanism to enhance the aerodynamic performance of the HAWT is obtained. The present work provide a basis for the design of pitch control mechanism of medium and large-scale wind turbines.

2. Design methodology

The basis of wind turbine blade design was firstly developed by Betz and Glauert in the 1930s. After that, a number of researchers tried to develop new methods for predicting the aerodynamic performance of wind turbine rotors. In all of these methods, the blade element momentum theory, which is a combination of momentum theory and blade element theory, was used to calculate wind turbine performance. The blade element momentum (BEM) model, as the most common wind turbine analysis method, is used in this study.

2.1. Mathematical modeling

The blade element momentum theory can be divided into two parts. In the first part, the turbine rotor is modeled as an actuator disk in a one dimensional stream tube. In this model, the actuator disk is responsible for wind speed reduction as the flow passed over the disk. Using the momentum theory for an annular element, the differential thrust force can be obtained as follows:

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

where the axial induction factor, a, provides a means of wind retardation in the axial direction, (see Fig. 1). By defining the angular induction factor in the same way and applying the angular momentum conservation on the rotor disk, the differential torque exerted on the annulus element can be obtained as:

$$dQ = 4a'(1-a)\rho U_\infty \Omega \pi r^3 dr \quad (2)$$

On the other hand, in the blade element theory, the turbine blade is divided into several elements. It is also assumed that the aerodynamic forces on each element can be approximated using