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A site-specific design of a fixed-pitch fixed-speed wind turbine blade for energy optimization using surrogate models

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ABSTRACT

This work seeks to add a new approach to optimize a wind turbine blade's performance by implementing a surrogate model using the Kriging function with the chord, twist and the use of 3 different airfoils as design variables for the maximization of the Annual Energy Production. A combination of Genetic Algorithms and the SQP method for Local Search are used to exploit the model. A baseline design of the blade starts with a replica of the Phase VI blade utilized in a NASA-Ames experiment and a MatLab script utilizes the Blade Element Momentum Theory (BEM) for the aerodynamic analysis. Results show a 23% improvement in energy production by using this method.

1. Introduction

With the depletion of fossil fuels, a change to renewable sources of energy is inevitable and wind energy is one of the viable alternatives that have been developed in the last few decades. The U.S. Department of Energy [1] reported that by the end of 2012 its wind power capacity surpassed 60 GW of which 13.2 GW had been added in 2012 alone representing an installation growth of 90% with respect to 2011 and an investment of 25 billion dollars. Furthermore, the U.S. Department of Energy [2] stated a goal of reaching a 20% of the total electricity production generated by wind resources by the year 2030.

The most popular devices to generate energy from wind is the two and three-bladed Horizontal Axis Wind Turbine (HAWT) due to its efficiency, reliability, and acoustics [3]. A variety of HAWTs have the ability to pitch their blades using a pitching mechanism in order to expose the blades to more favorable angles of incidence against the wind direction; this type of wind turbine is known as a Variable Pitch (VP) wind turbine. Another topology of HAWT is concerned with their rotor velocity: the Variable speed (VS) turbine has a rotor which rotates at different velocities, whereas the Fixed Speed (FP) wind turbine utilizes rotors that have a constant RPM regardless of wind speeds. In particular, a wind turbine which has no pitching mechanism and whose rotor speed is constant would be called a Fixed-Pitched Fixed-Speed (FPFS) wind turbine, which is the focus of this study.

The use of FPFS turbines has gained popularity in small and medium wind turbines due to its advantage of direct grid connection due to the fact that they use induction generators [4]. Additionally, it has been shown that for high values of the Weibull's shape parameter of the wind profile, the FPFS turbines have competitive Annual Energy Productions (AEP), to about 88% of its variable-speed version [5]. Also, compared to the FPVS turbines which utilize permanent magnet synchronous generators requiring more complex electronics, the FPFS variety have the advantage of being robust, reliable and of lower cost compared to the variable speed wind turbines [5].

Wind turbine blade optimization has been a persisting endeavor in both the academic and industrial setting for a few decades. Initial wind turbine optimization attempts implemented models which had the chord and twist profiles of the blade as design variables while keeping its airfoils constant; either their objective is to maximize the energy production [6–8], maximize the power

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Nomenclature

A	area spanned by wind turbine rotor
AEP	Annual Energy Production
C_d	coefficient of drag
C_l	coefficient of Lift
Cp	coefficient of power
$FPFS$	Fixed Pitch Fixed Speed
FS	Fixed Speed
Re	Reynolds number
U	wind speed
U_{rel}	relative wind speed to the blade
U_{TAN}	tangent speed of the airfoil to the wind
VS	variable speed
α	angle of attack
α_d	design angle of attack
η	transmission efficiency
μ	air viscosity
ρ	air density
Ω	angular velocity

coefficient of the rotor [9–11], minimize the cost of energy [12,13] or a given combination of them [14]. Other studies have focused in the optimization of airfoil profiles of wind turbine blades for energy maximization of VS rotors, such as the RISO airfoils by Fuglsang [15], where a family of airfoils were designed to maximize the coefficient of torque and lift, along with a minimization of airfoil roughness. In other studies, a modification of the leading edge for roughness sensitivity was applied to airfoil optimization for maximum efficiency [16,17]. Additional research has also focused on designing an airfoil which possesses a high C_l/C_d and a high C_l for a given α, which results in high torque values in variable speed wind turbines [18]. Other studies have added structural constrains to the design of the blade [19], and others have considered the minimization of noise produced by the airfoil in the wind turbine [20]. The literature shows no previous research where a design of a blade incorporates variable airfoils, chord and twist profiles for a FPFS wind turbine, which is the intended goal of this study.

The lack of pitching mechanisms in the blade of a FPFS turbine exposes its airfoil to a wide variety of angle of attacks (α), thus airfoil optimization for Variable-Speed (VS) wind turbines differ from that of a fixed-speed (FS) because in a VS wind turbine the control strategy can vary the rotational velocity of the rotor to alter the blades to their optimal angles of incidence. In a FPFS where the rotational speed and the blade pitch are always constant, a change in wind speed implies that there always will be a diverse range of α's from the wind on the blades. This means that an independent optimization of the airfoil's C_l/C_d for one given design angle of attack (α_d) may not be as productive in a FPFS rotor.

In this study, experimental data obtained from the Phase VI wind turbine will be utilized as benchmark and for comparison of results obtained. In 2001, The U.S. Department of Energy's (DOE) National Renewable Energy Laboratory published experimental data [21] for the Phase VI wind turbine performed in the NASA-Ames wind tunnel located in Moffet Field, California. The wind turbine consists of 2-blades with 5.03-m radius with chord and twist variable along the blade and a 3-degree pitch. The airfoil is the S809 and it is the same along the blade; the rotational velocity is 72 RPM [22].

The proposed design to optimize consists of a 2-bladed FPFS rotor with 3 different airfoils described by four Bezier curves; the chord and the twist are also modeled using a Bezier curve. The aerodynamic analysis of the rotor is calculated using Blade Element Momentum theory as in Manwell [23]. Since there are three airfoils, each will be used for one third of the total length of the blade and will be referred as root, mid-section and tip airfoil. The flow analysis of the airfoils is calculated with Drela's XFOIL [31] code to find their coefficients of lift and drag. As BEM theory requires an extrapolation of the coefficients of lift and drag from −180 to 180° the AERODAS method by Spera [24] is utilized to perform the extrapolation.

The motivation of this work is to make an optimization and an assessment regarding the use of a diverse number of airfoils designs, with a variation of the chord and twist profiles for a site-specific wind profile for an AEP maximization of a FPFS wind turbine. The calculation of the AEP uses the wind profile taken from the city of Roswell, NM which has been characterized using a Weibull distribution with a shape parameter of 5.717 and a scale parameter of 7.8371. The data was obtained from the National Climatic Data Center [25], which consists on hourly data of wind speed from January 1st 2010 to December 31st 2010.

This paper is organized as follows. Section 2 presents the objective function to be maximized to find an optimal design. Section 3 explains the Kriging function utilized to build a surrogate model of the function. Section 4 establishes the design variables utilized with their respective constraints. After that, Section 5 explains the methodology followed for the optimization, Section 6 presents results obtained, and finally the last section closes with concluding remarks.

2. Objective function

Yearly wind data is needed for the proper assessment and planning of farms for an accurate projection of power production. Accurate wind data can be gathered from the National Oceanic and Atmospheric Administration (NOAA) in heights of 30, 60, or 90 m depending on the location and intervals. Data sets with intervals as small as 10 min are being consistently recorded. Wind data models can be used to design or test the performance of a given wind turbine concept.

Having obtained the coefficient of power C_p curve with BEM theory, the AEP can be calculated by using the formula as defined by Hau [26]:

$$AEP = 8760 \times \frac{1}{2}\eta\rho A \int_{cut\ in}^{cut\ out} U^3 C_p(U) \times f_w(U) dU \qquad (1)$$

where η is the transmission efficiency of the wind turbine including the mechanical and electrical efficiency which is considered 85% in this study, ρ is the air density 1.062 kg/m^3, $A = 79.485$ m^2 corresponds to the area spanned by the rotor, the cut-in and cut-out speeds are 5 and 25 m/s, and $f_W(U)$is given by:

$$f_w(U) = \left(\frac{k}{c}\right)\left(\frac{U}{c}\right)^{k-1} \exp\left[-\left(\frac{U}{c}\right)^k\right] \qquad (2)$$

which corresponds to a Weibull Probability Density Function (*pdf*) of the wind speed. To determine the Weibull probability density function the calculation of a shape factor k, and a scale factor c is required; both parameters depend on $\overline{U}$ and σ_U where U represents the wind speed data obtained from the specific site to be studied.

3. The surrogate model using the Kriging Function

The AEP model of the rotors will be performed using the Kriging Function which is used to optimize the design. For a set of