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Aerodynamic Design Optimization of Axis Wind Turbine Using Genetic Algorithm

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Abstract

This paper proposes a new approach for aerodynamic design optimization of wind turbines is developed by using Genetic Algorithm. Objective function is maximum power production subject to given wind speed, a rotational speed, a number of blades and a blade radius. We use the data from the literature which are designed or used in wind turbine applications. The airfoils with common geometrical characteristics are grouped as airfoil families in the dataset. We consider optimization variables as a fixed number of sectional airfoil profiles, chord lengths, and twist angles along the blade span. By using this approach the power production is improved by 50 to 70 percent.

INTRODUCTION

Today, Most of the countries are converting their energy sources from fossil fuels to wind energy. US is planning to produce 20 percent of its electricity from wind power by the year 2030. This statistical information shows that wind energy trend will continue to grow up in the future [1].

A wind turbine is a device that converts kinetic energy from the wind into mechanical energy. The mechanical energy is used to produce electricity. Developed for over a millennium, today's wind turbines are manufactured in a range of vertical and horizontal axis types. Vertical-axis wind turbines (VAWT) have the main rotor shaft arranged vertically. Key advantages of this arrangement are that the turbine does not need to be pointed into the wind to be effective. This is an advantage on sites where the wind direction is highly variable. The key disadvantages include the low rotational speed with the consequential higher torque and hence higher cost of the drive train, the inherently lower power coefficient, the 360 degree rotation of the aerofoil within the wind flow during each cycle and hence the highly dynamic loading on the blade, the pulsating torque generated by some rotor designs on the drive train, and the difficulty of modeling the wind flow accurately and hence the challenges of analyzing and designing the rotor prior to fabricating a prototype[2]. Vertical-axis wind turbines (VAWT) have the main rotor shaft arranged vertically. Key advantages of this arrangement are that the turbine does not need to be pointed into the wind to be effective. This is an advantage on sites where the wind direction is highly variable. The key disadvantages include the low rotational speed with the consequential higher torque and hence higher cost of the drive train, the inherently lower power coefficient, the 360 degree rotation of the aerofoil within the wind flow during each cycle and hence the highly dynamic loading on the blade, the pulsating torque generated by some rotor designs on the drive train, and the difficulty of modeling the wind flow accurately and hence the challenges of analyzing and designing the rotor prior to fabricating a prototype[2].

Therefore, modern wind turbines are propeller type HAWT. In this paper, design and optimization of modern horizontal axis wind turbines are studied. Additional information about different wind turbine concepts can be found from reference [3].

In parts of modern wind turbines, wind turbine rotor is the main part of the wind turbine. Generally, it consists of two or three blades which are connected to the hub. Rotor and hub are connected to nacelle. Nacelle covers the internal parts: drive train, generator and control unit. Drive train part contains shafts, gearbox, mechanical brake; namely the rotating parts of wind turbine excluding the rotor. Generator and control unit are also connected to it.

Wind turbine design is a multidisciplinary design process and therefore, naturally, it is an optimization problem. In Figure 1, process of design is shown schematically. Optimization of aerodynamics is the starting point of wind turbine design. Wind turbines are designed for maximum power production. In order to design a wind turbine, an analysis tool is needed for performance predictions of designed wind turbines. Almost all wind turbine design tools use Blade Element Momentum (BEM) theory for aerodynamic analysis [6]. The main reason of this is BEM theory is very fast and gives good results for steady state conditions. Although, the uncertainties of BEM method are coming from the analysis of high wind speeds, unsteady conditions and load predictions on extreme wind conditions, it is still the only tool for design [7-8].

In this paper, wind turbine aerodynamic design optimization is implemented. First, an aerodynamic analysis approach is developed by using BEM theory. Then, wind tunnel test data of several airfoils are collected and an airfoil database is generated. This data based includes airfoil families and they are used

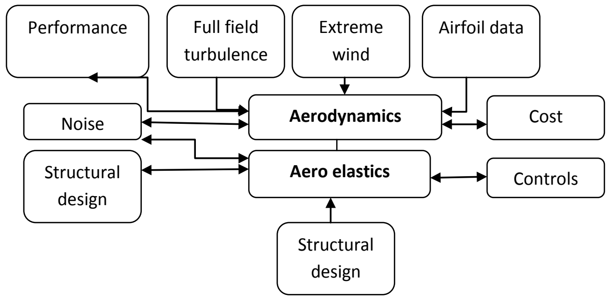

Fig.1. Wind turbine design process based on the information in [5].

as families or single airfoils during the optimization process. In another step, Genetic Algorithm optimization method is combined with wind turbine design and optimization process. Using combination of genetic algorithm and BEM analysis with some minor modifications for constraint, it can be optimized the design of wind turbine. Wind turbine blade is divided into number of sections along the blade. In the optimization process, airfoils are taken from the aerodynamic database; design is optimized to give the best power output for given number of blades, blade radius, wind speed and rotational speed. By using this approach the power production is improved by 50 to 70 percent.

MATERIAL AND METHODS

Blade Element Theory

The simple momentum theory provides an initial idea regarding the performance of a propeller but not sufficient information for the detailed design. Detailed information can be obtained through analysis of the forces acting on a blade element like it is a wing section. The forces acting on a small section of the blade are determined and then integrated over the propeller radius in order to predict the thrust, torque and power characteristics of the propeller.

A differential blade element of chord c and width dr, located at a radius r from the propeller axis, is shown in Figure 2. The element is shown acting under the influence of the rotational velocity, ωr, forward velocity of the airplane, V, and the induced velocity, w. Vector sum of these velocities produce

$$\boldsymbol{V_e = \omega r + V + w} \qquad (1)$$

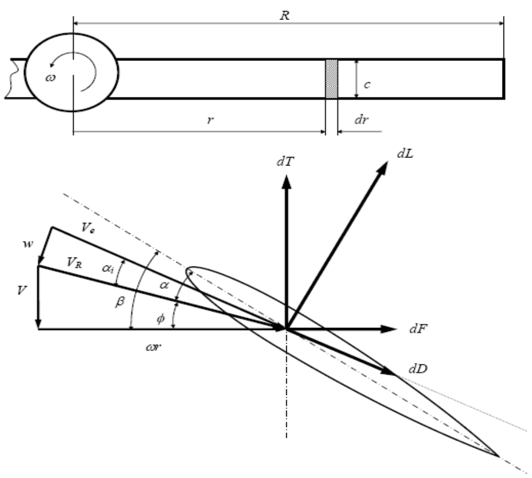

Fig.2. Propeller blade element with velocity and force diagram.

The section has a geometric pitch angle of its zero lift line of β. If it is assumed that V and ωr are known, then calculation of the induced velocity w is desired to find α_i, and consequently the section angle of attack α. Knowing α, and the section type, C_l and C_d can be calculated, then the differential lift and drag of the section will follow. However, w depends on dL which in turn depends on w. Thus the problem is closely related to the finite wing problem but is more complicated because of the helicoidal geometry of the propeller [9].

Wind turbine performance analysis with BEM theory includes the prediction of induction factors, angle of attacks and thrust for each blade element separately. To do this, induction factors are needed to be calculated first which is an iterative process. Similar procedure of Moriarty and Hansen [10] is used for this purpose. To initialize the axial induction factor, it is assumed (for more information it refers to Moriarty and Hansen [10]);

$sin\emptyset \approx \emptyset \qquad \emptyset\ is\ small$

$F = 1; C_d = 0; a_0 = 0$

$C_l = 2\pi\alpha$

Where indexes are defined as defined in [10]. Then, axial induction is found as;

$$\alpha = \frac{1}{4}\left[2 + \pi\lambda_r\sigma' + \sqrt{4 - 4\pi\lambda_r\sigma' + \pi\lambda_r^2\sigma'(8\beta + \pi\sigma')}\right] \qquad (2)$$

Initial value for axial induction factor is taken zero initially. This would not change the result. Initially predicted axial induction factor can decrease the number of steps for iterative induction factors prediction. Then, by using induction factors calculated, the inflow angle is calculated.

$$tan\phi = \frac{U_\infty(1-a)}{\Omega r(1-a')} \qquad (3)$$

β information comes with the wind turbine geometry information. Thus, the only unknown angle is the angle of attack which is calculated from

$$\alpha = \phi - \beta \qquad (4)$$

It can calculate the thrust coefficient and tip loss factor in another form.

$$C_T = \frac{\sigma'(1-a)^2(C_l COS\phi + C_d Sin\phi)}{sin^2\phi} \qquad (5)$$

for the tip loss calculation,

$$F = \frac{2}{\pi}COS^{-1}\left(\exp\left(-\frac{B}{2}\frac{R-r}{rsin\phi}\right)\right) \qquad (6)$$

Once the thrust coefficient and tip loss factor is calculated, the axial induction is calculated. If CT > 0:96F, then the blade is highly loaded and modified Glauert correction is applied.

$$\alpha = \frac{18F - 20 - 3\sqrt{C_T(50-36F) + 12F(3F-4)}}{30F - 50} \qquad (7)$$

Otherwise, the blade is lightly loaded and standard BEM theory is used. Tangential induction factor cab be calculated directly from BEM theory. Once the induction factors are calculated, thrust and torque of each blade element are found by equation 8 and 9.

$$dT = B\frac{1}{2}\rho V_{tot}^2 C_N c dr \qquad (8)$$

$$dQ = B\frac{1}{2}\rho V_{tot}^2 C_{Tan} c dr \qquad (9)$$

The overall turbine thrust and torque parameters are calculated by integrating the Equation 8 and Equation 9 along the turbine span. Power is also calculated from following equation:

$$\delta P = \delta Q \Omega \tag{10}$$

Lift and drag coefficients are given as input during the iteration process. For each blade element, airfoil information is required with chord and twist values. Drag and lift coefficients have to be given according different to angle of attack values. The iteration and power calculation procedure explained here is coded by using Matlab programming language. By considering the given geometrical variables, BEM analysis can predict the performance of wind turbines. This analysis is also used for calculating wind turbine power production during the optimization loop. BEM analysis is validated with the experimental data obtained from literature which is explained in the next section.

Set Up Airfoil Database

In this study, different airfoils and airfoil families are included into the optimization process. An airfoil database is set up for this purpose. This airfoil database consists of many airfoils or airfoil families designed for wind turbines or used in wind turbine applications [11-16]. In the database, lift and drag coefficients for a range of angle of attack values and for different Reynolds numbers fare used. There are two groups in the database. First group consists of airfoils belongs to an airfoil family. There are single airfoils not belong to any airfoil family but still kept in the database for single airfoil applications along a wind turbine blade. Airfoil families are shown in Table 1.

Implementation Of Genetic Algorithm

Wind turbine optimization includes aerodynamics, structures, electrical systems and production and maintenance costs as main disciplines. Therefore, optimization starts with aerodynamics. By optimization of wind turbine geometrical properties for maximum power output can be obtained more power with similar blade geometry. In this research genetic Algorithm optimization that is a very efficient method for parametrical studies, is combined with BEM analysis to develop for wind turbine optimization purposes. Methods and implementation are explained in this section.

Table 1. Airfoil families used in airfoil database

Name of Family	Number of Airfoils in the Family	Thickness Range	Re Number Range
NACA	2	17 to 23	1.0E7 to 8.0E9
NACA	3	17 to 35	2.0E6 to 7.0E9
NACA	2	17 to 26	6.0E6 to 7.0E8
NACA	3	17 to 24	4.0E7 to 9.0E5
Risoe A1	4	19 to 28	6.6E7
FX-61	2	14 to 18	5.6E8
DU	3	23 to 24	1.0E9
FFA-W3	2	25 to 33	4.6E9
FX-60	4	12to 18	4.0E7 to 8.0E4
FX S	2	16 to 20	6.6E7
FX-66	3	17 to 21	2.0E6 to 7.0E7

Genetic Algorithm Overview: Genetic algorithms are one of the best ways to solve a problem for which little is known. They are a very general algorithm and so will work well in any search space. All you need to know is what you need the solution to be able to do well, and a genetic algorithm will be able to create a high quality solution. Genetic algorithms use the principles of selection and evolution to produce several solutions to a given problem [17].

Genetic algorithms tend to thrive in an environment in which there is a very large set of candidate solutions and in which the search space is uneven and has many hills and valleys. True, genetic algorithms will do well in any environment, but they will be greatly outclassed by more situation specific algorithms in the simpler search spaces. Therefore you must keep in mind that genetic algorithms are not always the best choice. Sometimes they can take quite a while to run and are therefore not always feasible for real time use. They are, however, one of the most powerful methods with which to (relatively) quickly create high quality solutions to a problem. Now, before we start, I'm going to provide you with some key terms so that this article makes sense [17].

- Individual - Any possible solution
- Population - Group of all individuals
- Search Space - All possible solutions to the problem
- Chromosome - Blueprint for an individual
- Trait - Possible aspect of an individual
- Allele - Possible settings for a trait
- Locus - The position of a gene on the chromosome
- Genome - Collection of all chromosomes for an individual

The most common type of genetic algorithm works like this: a population is created with a group of individuals created randomly. The individuals in the population are then evaluated. The evaluation function is provided by the programmer and gives the individuals a score based on how well they perform at the given task. Two individuals are then selected based on their fitness, the higher the fitness, the higher and the chance of being selected. These individuals then "reproduce" to create one or more offspring, after which the offspring are mutated randomly.

This continues until a suitable solution has been found or a certain number of generations have passed, depending on the needs of the programmer [17].

Implementation of GA for Optimization of to Wind Turbine: For the genetic algorithm optimization, a code is written by Matlab. This code is used as core of the wind turbine optimization problem by making some minor modifications for constraint definitions which are also explained in this section.

The optimization code itself needs some inputs. These are related with the efficiency of Genetic Algorithm and they are used as they are proposed by author. Fitness function in the optimization code is replaced with BEM analysis code which is developed for this study. In every generation population produced are analyzed with BEM analysis tool for power output. When a member has a high power production, its optimization variables are kept for next generations for better power production. Wind turbine optimization is performed by optimizing the parameters which are used to define a wind turbine blade in BEM analysis. These are turbine diameter, number of blades, chord, twist distributions and airfoils. For this study, optimization parameters are chosen as chord, twist and airfoil sections for each blade element. However, diameter and number of blades are kept constant. In the optimization, twist and chord values are limited with predefined upper and lower values. Optimization is performed for a chosen operating point which is turbine rpm and wind speed. As a result, genetic algorithm searches for best chord and twist distributions with best airfoils to give highest power output for the given operating condition.

RESULT AND DISCUSSION

Wind turbine optimization starts with the selection of blade elements along the blade span. The more blade elements are used, the more accurate results are obtained from BEM analysis. However, when the number of blade elements is high, time required for optimization process is high, too. For example, if 50 numbers of sections are used in the optimization, accuracy would be increased by 3-4 percent compared to 8 sections, but optimization time would be about 6 times longer than the case when 8 numbers of sections are used in the optimization. Therefore, limited number of blade elements is chosen for the optimization. Radial locations of each blade elements are also kept constant during optimization. For each blade element, 2 parameters are being optimized: chord and twist. As a result, there are 2 x (number of blade elements) parameters coming from the blade elements. In addition to these, airfoil families are also involved in the optimization as a parameter. Totally, 2 x (number of blade elements) +1 (airfoil family) parameters are optimized.

In the optimization, some constraints are introduced to the optimization parameters. These constraints are required in order to prevent wind turbine to become an improper geometry. In BEM method, blade elements are decoupled by assumption. This does not create big problems for basic wind turbine performance analysis applications. However, in the optimization, blade elements have to be related or connected somehow, in order to create more realistic wind turbine geometries.

CONCLUSION

In this study, aerodynamic design and optimization of horizontal axis wind turbines are done by using BEM theory and Genetic Algorithm. BEM analysis is developed for this paper. As a result, the analysis developed for this paper successfully performs for low and moderate wind speeds where BEM theory assumptions are valid.

This research creates an aerodynamic database by collecting several airfoils from the literature which is used in wind turbine applications. All of the airfoils used in the paper have wind tunnel test data and most of the airfoils have data for different Reynolds numbers. Airfoil families are kept in database according to common geometrical characteristics.

Genetic Algorithm optimization method is selected for optimization applications. BEM analysis is used as fitness function in the optimization. Twist and chord distributions of each blade element are optimized for best power output for given blade radius, number of blades, wind speed and rotational speed. In the optimization, optimum airfoil family is also selected from airfoil database during the optimization. We consider optimization variables as a fixed number of sectional airfoil profiles, chord lengths, and twist angles along the blade span. By using this approach the power production is improved by 50 to 70 percent.

To sum up, developed aerodynamic design and optimization approach is performed successfully for both design and optimization of wind turbines. It is possible to design more powerful wind turbines. Also, improvements in power production of any present wind turbine are also possible.

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