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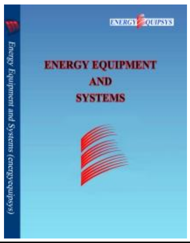

Aerodynamic optimization of a 5 Megawatt wind turbine blade

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ABSTRACT

Wind power has been widely considered in recent years as an available and a clean renewable energy source. The cost of wind energy production is currently the main issue, and increasing the size of wind turbines can reduce wind energy production costs. Hence, megawatt wind turbines are being rapidly developed in recent years. In this paper, an aerodynamic analysis of the NREL 5MW turbine is carried out using the modified blade element momentum theory (BEM). The genetic algorithm (GA) as an optimization method and the Bezier curve as a geometry parameterization technique are used to optimize the original design. The modified BEM results are compared with the NREL published results for verification. Cost of energy (COE) is considered an objective function, which is one of the most important and common choices of objective function for a megawatt wind turbine. Besides, the optimization variables involve chord and twist distributions variation along the blade span. The optimal blade shape is investigated for the minimum cost of energy with considered constant rotor diameter and airfoil profiles. Then the objective function is improved and a new optimum geometry is compared with the original geometry. Although the Annual Energy Production and rated power are reduced by 2% and 3% respectively, the net cost of wind energy production is decreased by 15%, showing the importance of such optimization studies.

Keywords: Aerodynamic Optimization, Megawatt Wind Turbine, Blade Element Momentum Theory (BEM), Genetic Algorithm (GA), Bezier Curve, Cost Of Energy (COE).

1. Introduction

Energy is the base of economic and social progress, and preserving natural resources is one of the most important challenges in the current century. Fossil fuel use has been shown to have correlation with different environmental problems such as global warming and air pollution. Additionally, those fossil fuels face depletion in the next few decades. These problems drive scientists to devise other ways of power production not only to meet increasing energy demands but also to prevent environmental damage caused by the burning of fossil fuels. Wind energy is a clean, renewable, and a fairly cheap source of energy. Many countries have turned to the use of wind energy for the economic and environmental reasons. Therefore, the importance of designing new turbines with low cost and high aerodynamic efficiency in the past few decades pushes us to increase the size of wind turbine blade diameter.

A wind turbine is a complex system that includes several components that have to

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work together in perfect harmony, and its design requires the integration of many engineering fields such as aerodynamics, structures, controls, and electrical engineering [1]. Aerodynamics has an important role in the designing process and criteria. Annual energy production, along with aerodynamic forces, has a direct effect on the structure of the turbine and its price for a megawatt wind turbine compared to the smaller ones [2]. The aerodynamic design optimization involves the selection of the chord and twist distribution along the blade length to reach the maximum efficiency. Therefore, the cost of energy is the most important issue in the optimization of a megawatt wind turbines blade.

Furthermore, we need an analysis tool to predict wind turbine performance and use it in the optimization process. This analysis tool needs to be accurate and consider all the involved physical phenomena, while being fast so as to be used in the optimization process. There are different aerodynamic methods developed for wind turbines such as the blade element momentum (BEM) and CFD [3, 4] methods. Among different numerical methods, the Blade Element Momentum theory has low computing cost and acceptable accuracy, and is more practical compared to the Computational Fluid Dynamic, which has greater accuracy but is it has high computing cost, especially in the case of the very large and lengthy blades of a megawatt wind turbine. Many studies have been done using the BEM method for the evaluation of wind turbine rotor performance [5-9].

The choice of the optimization algorithm is an important task in optimization that depends on the nature of the problem and design variables. This matter is central to wind turbine performance optimization because the final results depend on the accuracy and local minima sensitivity of the used algorithm. In the case of wind turbine blade geometry optimization, there are several design variables. However, some of the variables are continuous, such as chord and twist distribution, and some are discrete, such as the airfoil family and the number of blades. Moreover, some of them mutually affect each other such as chord and twist, and also within the definition of the objective functions like cost of energy. Therefore, an appropriate and powerful optimization algorithm is needed for blade geometry optimization. The genetic algorithm has been successfully implemented to aerodynamic optimization problems for horizontal-axis wind turbines because of the robustness of the GA in the case of a multimodal design space and its advantage in exploring any type of domains and because it is less sensitive to the initial domain.

Many studies have been done on aerodynamic optimization of the wind turbine blade, especially by integrating the BEM method and GA algorithm. Yassin et al. [10] optimized the airfoil chord lengths and twist angles of a 5MW wind turbine, and a wind turbine designed for site-specific wind conditions to increase the turbine's annual energy production (AEP) under these site conditions. This optimization is done using the Genetic Algorithm and the BEM method. Ceyhan [11, 12] considered the maximum power output as the objective function and developed an aerodynamic design and optimization tool for wind turbines, using the BEM theory and GA. Liu et al. [13] used an extended compact genetic algorithm to optimize a 1.3MW stall-regulated wind turbine blade for maximum power capture. Design variables were chord and twist distributions, and the aerodynamics were modelled on the basis of a custom BEM code.

Most of the research has been on optimization of twist and chord distribution by taking the power and AEP as the objective function. In the current research, the cost model is considered additionally and the optimum cost of energy has been obtained for the NREL 5MW wind turbine, because of its importance for the massive megawatt-class wind turbines. Besides, the optimization constraints also considered how to ensure a minimum change in the tip shape because its effect on noise and tip vortex loss requires greater consideration than only aerodynamic analysis. It should be noted that different types of airfoil along the blade is used in these turbines. The methodology is implemented within an integrated GA method and a modified BEM developed MATLAB computer code for this complex wind turbine blade.

Nomenclature

A	Weibull scale parameter
AEP	Annual Energy Production
a	Axial Induction Factor
a'	Tangential Induction Factor
B	Number of blades
b_{rotor}	Fixed part of the rotor's cost

$bn_{i,n}$	Bernstein polynomial
Bz	Bezier curve
c	Chord (m)
C_{rotor}	Cost of the rotor
C_d	Drag Coefficient
C_l	Lift Coefficient
C_p	Power Coefficient
C_T	Thrust Coefficient
COE	Cost of Energy
D	Drag force (KN)
$f(x)$	Objective function
$f(U)$	Probability density of a wind
F	Prandtl's loss coefficients
k	Weibull shape factor
$K_{i,n}$	Bionomial coefficients
L	Lift force (KN)
m_i	Mass of a section of the blade (kg)
M_{tot}	Total mass of the blade (kg)
$P(U)$	Power output (KW)
Q	Torque (KN-m)
r	Radial distance from root (m)
R	Blade radius (m)
S_i	Bezier control points
T	Thrust (KN)
U	Wind speed (m/s)
w_i	Weight parameter
W	Relative wind velocity

Greek Symbols

α	Angle of Attack (deg)
θ	Twist (deg)
$\emptyset$	Inflow Angle (deg)
σ_r	Local Solidity
ψ	Non-dimensional blade length
Ω	Rotational Velocity (rad/s)

2.Methodology

This section presents the BEM theory as the computational method for aerodynamic analysis of wind turbine blades, subsequently describing the optimization method and its details.

2.1 Blade Element Momentum theory

In the BEM method, the wind turbine blades are divided into a number of independent elements. Therefore, the two-dimensional force balance is applied by considering torque and thrust as shown in Fig.1b and, then, the momentum balance for an annular element is applied. Finally, a set of equations is derived for each blade section. More details are contained in references [14–16]. Generally, the analysis is performed for torque, power output, efficiency, and thrust force. The results of the analysis, which depend on the accuracy of the flow induction factor calculations, are obtained by the following iterative calculation process.

1. Initial guess for a and a′
2. Calculation of the inflow angle (Eq. 1) (Fig.1a)

$$\emptyset = tan^{-1}\left(\frac{1-a}{(1+a')\frac{r\Omega}{U_\infty}}\right) \quad (1)$$

3. Calculation of the local angle of attack (Eq. 2) (Fig.1[a])

$$\alpha = \emptyset - \theta \quad (2)$$

4. Computation of the tip and hub loss

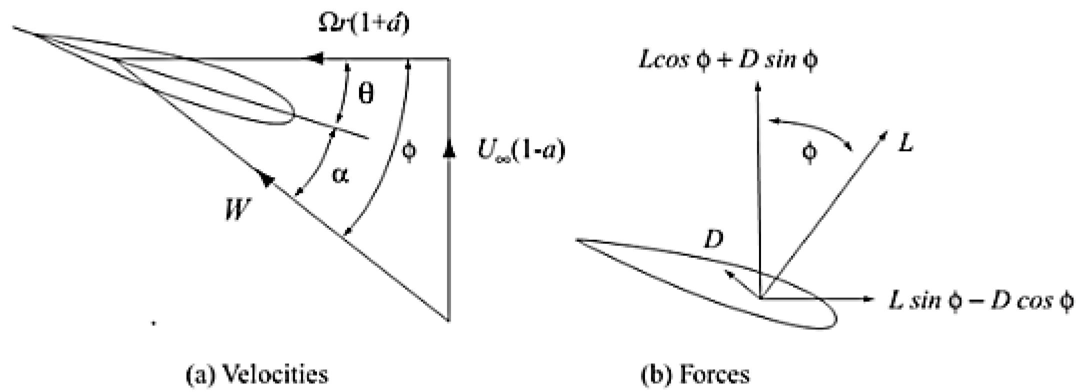

Fig.1. Blade Element Velocity and Forces [14]

coefficients that Prandtl [16] derived to correct the assumption of an infinite number of blades (Eq. 3, 4 and 5).

$$F_{tip} = \frac{2}{\pi} cos^{-1} \left\{ exp \left[\frac{\left(-\frac{B}{2}\right)\left[1-\left(\frac{r}{R}\right)\right]}{\left(\frac{r}{R}\right) sin\emptyset} \right] \right\} \quad (3)$$

$$F_{hub} = \frac{2}{\pi} cos^{-1} \left\{ exp \left[\frac{\left(-\frac{B}{2}\right)\left[\left(\frac{r}{R_{hub}}\right)-1\right]}{\left(\frac{r}{R_{hub}}\right) sin\emptyset} \right] \right\} \quad (4)$$

$$F = F_{tip} . F_{hub} \quad (5)$$

5. Reading lifts and drag coefficient for each section from related airfoil data file.
6. Calculation of the thrust coefficient (Eq. 6)

$$C_T = \frac{\sigma_r (1-a)^2 (C_l \cos\emptyset + C_d \sin\emptyset)}{\sin^2\emptyset} \quad (6)$$

where σ_r is defined as the fraction of the annular area in the control volume that is covered by the blades.

$$\sigma_r = \frac{B}{2\pi} \frac{c}{r} \quad (7)$$

7. Calculation of the axial induction factor (Eq. 8 and 9)

$$a = \frac{1}{\frac{4F sin^2\emptyset}{\sigma_r (C_l \cos\emptyset + C_d \sin\emptyset)} + 1}, \quad C_T < 0.96 \quad (8)$$

$$a = \left(\frac{1}{F}\right)\left[0.143 + \sqrt{0.0203 - 0.6427(0.889 - C_T)}\right], \quad C_T > 0.96 \quad (9)$$

8. Calculation of the tangential induction factor (Eq. 10)

$$a' = \frac{1}{\frac{4F sin\emptyset \cos\emptyset}{\sigma_r (C_l \sin\emptyset - C_d \cos\emptyset)} - 1} \quad (10)$$

9. If the error of a and a′ are more than the considered tolerance, go to Step 2, else go to the next step
10. Computation of the local and overall thrust force (Eq. 11)

$$\delta T = \frac{1}{2} \rho W^2 \mathrm{B} \, (C_l \cos\emptyset + C_d \sin\emptyset) c \, \delta r \quad (11)$$

11. Computation of the local and overall torque (Eq.12)

$$\delta Q = \frac{1}{2} \rho W^2 \mathrm{B} \, r (C_l \sin\emptyset - C_d \cos\emptyset) c \, \delta r \quad (12)$$

where W is the relative wind velocity in a particular blade section

$$W = \sqrt{U_\infty{}^2 (1-a)^2 + r^2 \Omega^2 (1+a')^2} \quad (13)$$

Flow induction factors a and a' are assumed to be zero as an initial guess at Step 1, and the calculated results obtained from Steps 2 to 8 are checked to see whether they converge or not. If so, it proceeds to Step 11; otherwise, goes back to Step 2, and flow induction factors are calculated again with updated initial values. Performance analysis must be applied independently to all elements as calculation points in the blade's spanwise direction. Local torque and thrust force at each element are computed by using local aerodynamic properties, lift and drag coefficients, and the total torque and thrust force is obtained by integrating local values along the blade spanwise direction. The collection of reliable aerodynamic data at each calculation point is, therefore, necessary to improve the accuracy of performance analysis. Since the airfoil shape of each section of the blade change along the span, weighted interpolation is used for calculating the aerodynamic properties in Step 5 for section witch lacking the exact geometry. About Steps 6 and 7, it should be noted that, if the axial flow induction factor of the blade is predicted to be over 0.5, the momentum theory would not be valid any more. Under such conditions, the calculated value of the thrust coefficient and the experimental results tend to be very different as can be seen in Fig.2. To rectify this, the value of the axial induction factor must be corrected by empirical correlation such as Eq. 9 if $a > a_T$ at a local element suggested by Glauert [15, 16, 17].

2.2 Optimization

An optimization problem contains a set of design variables, an objective function, a set of constraints and an appropriate optimization algorithm. The most important issue in performing optimizations is to locate all the important parameters and a suitable objective function. In this section we try to formulate the aerodynamic optimization of the wind turbine blade. In the following subsections, the definition of different objective functions for a wind turbine, especially the cost of

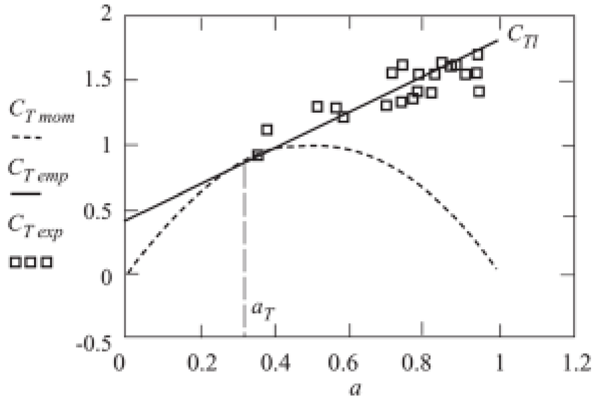

Fig.2. Comparison of Theoretical and Measured Values of CT [14]

energy, is described. Afterwards, the cost model, the Bezier parameterization technique and Bezier control points as the design variables and genetic algorithm used in the current optimization model are presented.

2.2.1 Objective function

Some common objective functions for aerodynamic optimization of a wind turbine blade are the maximization of the power coefficient (C_p) and annual energy production (AEP). But the megawatt class wind turbines have a great size and length, also the mass of their blades is much greater than that of common smaller turbines. Therefore, in order to reach more functional and operational optimization results, the cost of energy (COE) is intended as the objective function to optimize the NREL 5 MW turbine. The best way is to minimize the cost of energy, based on the AEP, and the manufacturing cost of the turbine. Therefore, estimating the cost of the wind turbine is the key point to reach the goal. So the cost model used in this study is described in the following section.

2.2.2 Cost Model

The economic performance of the wind turbine and its investigation is an important issue, especially for megawatt wind turbines. Estimating the cost of a wind turbine is an important and difficult matter, but is also very important in a successful optimization. As operation and maintenance costs can be assumed to be a small percentage of the total cost, a reduction of the total cost, therefore, becomes an inevitable task of wind turbine designing. Further, the rotor of a well-designed wind turbine with a low energy cost should be aerodynamically efficient and plays the most important role in the entire design and optimization process. Thus, in this study, the objective function is defined as:

$$f(x) = COE = \frac{C_{rotor}}{AEP} \quad (14)$$

where COE is the cost of energy of a wind turbine rotor and C_{rotor} is the total cost for manufacturing, transporting, and setting up a wind turbine rotor. The blade cost is divided into fixed and variable components. Xudong et al. [18] classifies the transportation, installation and operation expenses among the components of wind blade fixed costs. These are relatively small compared to the blade production costs, consisting mainly of material costs, designing expenses, and direct labour costs. The latter are related to the variable component of the overall blade cost. In the economic function, the relative rotor cost *Crotor* is:

$$C_{rotor} = b_{rotor} + (1 - b_{rotor})\, w_{rotor} \quad (15)$$

In the present study, the fixed part of the cost for a wind turbine rotor b_{rotor} is chosen to be 0.1. Therefore, the total cost of a rotor. And, w_{rotor} is the weight parameter of the rotor. The variable rotor cost component is derived with the relative material usage and attributed to the relative difference in mass multiplied by the elemental chord between the initial blade geometry and intermediate shape considered within the optimization procedure.

$$w_{rotor} = \sum_{i=1}^{N} \frac{m_i\, C_{i,opt}}{M_{tot}\, C_{i,orig}} \quad (16)$$

where m_i is the mass of the i-th cross-section of the blade; $c_{i,opt}$ is the averaged chord of the i-th cross section of the optimized blade; $c_{i,orig}$ is the averaged chord of the i-th cross-section of the original blade; M_{tot} is the total mass of the blade.

In order to calculate the AEP, it is essential to combine the probable wind density (the Weibull distribution) with the power curve which achieved from the BEM method. The probable density function can be written in the following form:

$$f(U_i < U < U_{i+1}) = \exp\left(-\left(\frac{U_i}{A}\right)^k\right) - \exp\left(-\left(\frac{U_{i+1}}{A}\right)^k\right) \quad (17)$$

where A is the scale parameter, k is the shape factor and U is the wind speed. In the current study, the shape factor is k = 2.19 and the scale parameter is A= 8.29 as mentioned in reference [19].

If a wind turbine operates about 8,700 h per year, its AEP can be evaluated as

$$AEP = \sum_{i=1}^{N-1} \frac{1}{2}\left(P(U_{i+1}) + P(U_i)\right).f(U_i < U_o < U_{i+1}).8760 \quad (18)$$

where $P(U_i)$ is the power at the wind speed of U_i .

2.2.3 Design variables

Another important point for solving an optimization problem is to choose a set of suitable design variables especially in the case of a wind turbine blade optimization. In other words, the used geometry parameterization method should show the blade geometry specifications accurately and completely with a small number of possible variables. The Bezier curve, used in this paper, is an appropriate method to determine wind turbine blade geometry. This is because of its performance in parameterization geometry with high accuracy and adaptability to curve peak points and changes in the concave curve. Additionally, by changing the Bezier coefficients, the shape of the curve changes smoothly, making this method suitable for the optimization of wind turbine blade geometry. The Bezier curve is defined in following equation.

$$Bz(\psi) = \sum_{i=0}^{n} S_i \; bn_{\,i,n}(\psi), \quad 0 \le \psi \le 1 \quad (19)$$

where n is the polynomial curve order, S_i, is the i-th Bezier control point and $bn_{i,n}$ is the i-th sentence of the n-th order Bernstein polynomial that is described in the following equation:

$$bn_{\,i,n}(\psi) = \sum_{i=0}^{n} K_{i,n} \; (1-\psi)^{n-i}\psi^i \quad (20)$$

where the $K_{i,n}$ is the bionomial coefficients

$$K_{i,n} \equiv \binom{n}{i} \equiv \frac{n!}{i!\,(n-i)!} \quad (21)$$

2.2.4 Constraint

In this optimization, the minimum and maximum limits of the Bezier control point values are considered as constraints. The maximum allowable range of change in the initial coefficients was set 10 per cent of the initial values. Moreover, the optimization constraints considered ways to keep the blade tip shape as unchanged as possible because of its important effect on the noise and tip vortex loss, demanding greater consideration beyond the aerodynamic analysis. This makes the results more reliable and operational.

2.2.5 Optimization Method

Genetic algorithm is one of the most popular evolutionary algorithms because of its robustness and reliability and low sensitivity to local minima. The genetic algorithm optimization method imitates Darwin's principle of the survival of the fittest in a population of candidate solutions or individuals evolving over generations. Similar to a DNA chain, each individual is coded in one string and uses reproduction, crossover, and mutation operation to direct the search over generations. Individuals with a greater fitness have stronger probability to reproduce in forming a new generation compared with those with lesser fitness value according to the specified objective function for the optimization process. Maximum iteration and the initial population values used for this paper are set respectively to 200 and 50. The initial value of the Bezier control points as the design variables is fed to the BEM code from the optimization programme, the cost of energy is evaluated as an output of the BEM code. The GA algorithm modifies the design variables and runs the BEM code again until optimization conditions are fulfilled.

3.Result and Discussion

3.1.NREL 5MW properties

The geometry of the rotor blade wind turbine described in reference [20]. The NREL 5MW is a conventional upwind three-bladed wind turbine specialized for offshore use. This wind turbine uses the Pitch Regulated Variable Speed (PRVS) control approach. The geometry data of reference is summarized in Table 1. The length of blade is 61.5 m and radius of the hub 1.5m, which means total radius of the wind turbine, is 63 m. The cross sections of the rotor blade are composed of a series of DU (Delft University) and NACA (National Advisory Committee for Aeronautics) 64xxx airfoils from the hub to the tip; and their aerodynamic properties are accessible in [20].

3.2.BEM validation

The output power, torque, and thrust in different operational wind speeds is compared with the reported analysis data in reference [21] to validate the aerodynamic analysis of the NREL 5MW wind turbine with the modified BEM theory code and to show its accuracy. The calculations in reference [21] have been performed with the steady-state parameters of the commercial software Garrad-Hassan Bladed. Rated speed, with which the maximum output power is determined, is one of the important wind speeds and, for this turbine, it is almost equal to 11.4 m/s. In addition, the tip-speed ratio is kept constant and equal to 7.55, giving the turbine the maximum power coefficient at this point. Ultimately, Fig.s 3, 4 and 5 show the comparison between the BEM results and the reported data for different wind speeds, showing accuracy and compatibility.

Table 1. Wind turbine rotor geometry definition from [20]

r (m)	Twst(°)	Chord (m)	Airfoil
2.8667	0	3.542	Cylinder
5.6	0	3.854	Cylinder
8.3333	0	4.167	Cylinder
11.75	13.308	4.557	DU40
15.85	11.48	4.652	DU35
19.95	10.162	4.458	DU35
24.05	9.011	4.249	DU30
28.15	7.795	4.007	DU25
32.25	6.544	3.748	DU25
36.35	5.361	3.502	DU21
40.45	4.188	3.256	DU21
44.55	3.125	3.01	NACA64
48.65	2.319	2.764	NACA64
52.75	1.526	2.518	NACA64
56.1667	0.863	2.313	NACA64
58.9	0.37	2.086	NACA64
61.6333	0.106	1.419	NACA64
62.9000	0.000	0.700	NACA64

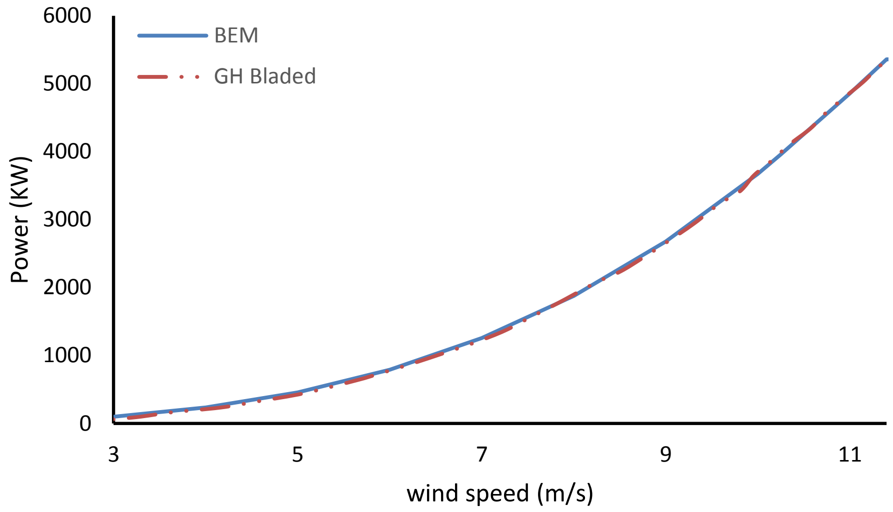

Fig.3. Comparison of the output powers for BEM code validation

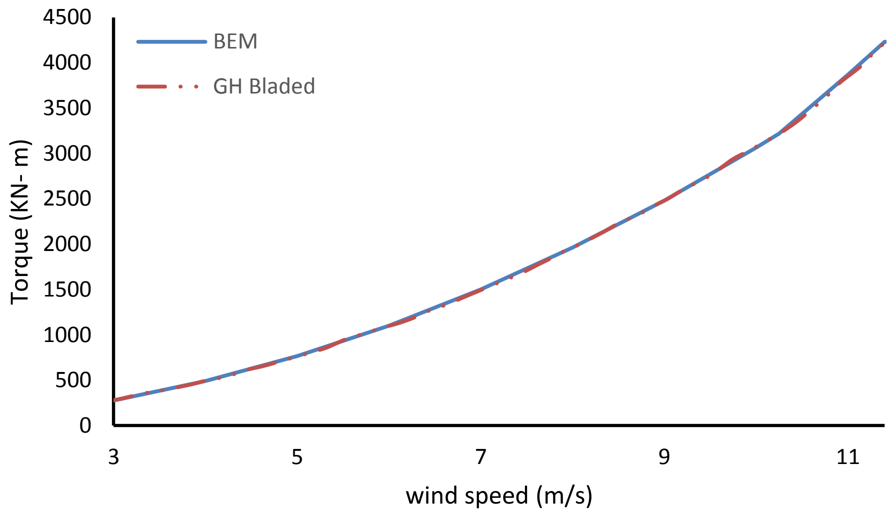

Fig. 4. Comparison of the Torques for BEM code validation

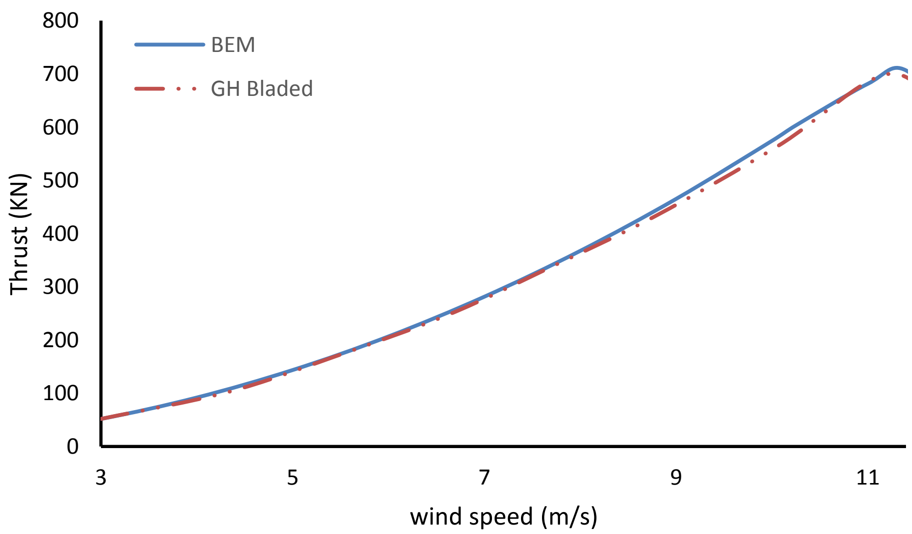

Fig.5. Comparison of the thrust forces for BEM code validation

3.3.Bezier validation

In this study, an 8th order and a 5th order Bezier curve have been used respectively for the chord and twist distribution of the NREL 5MW wind turbine blade. Therefore, the total number of the Bezier control points, as design optimization variables, is 15. It is necessary to mention that the chord and twist curves have been dimensionless by dividing respectively with 4.652 and 13.308, the maximum value of the chord and twist along the span. Figures 6 and 7 show the result of the Bezier parameterized geometry compared to the original one. As can be seen, the Bezier curves have acceptable conformity with the original diagrams and the Bezier control points can describe the blade geometry and represent it well.

3.4.Optimization results

The optimal chord distribution is shown in Figure 8. The cost of energy mostly depends on the blade's weight, which varies according to the chord length in a constant radius. Figure 8 shows that an optimized wind turbine has a smaller chord length in each section, and is evenly distributed along the span in an optimized design. Moreover, Figure 8 shows that, in this optimization, the general form of the blade is not been altered or has not

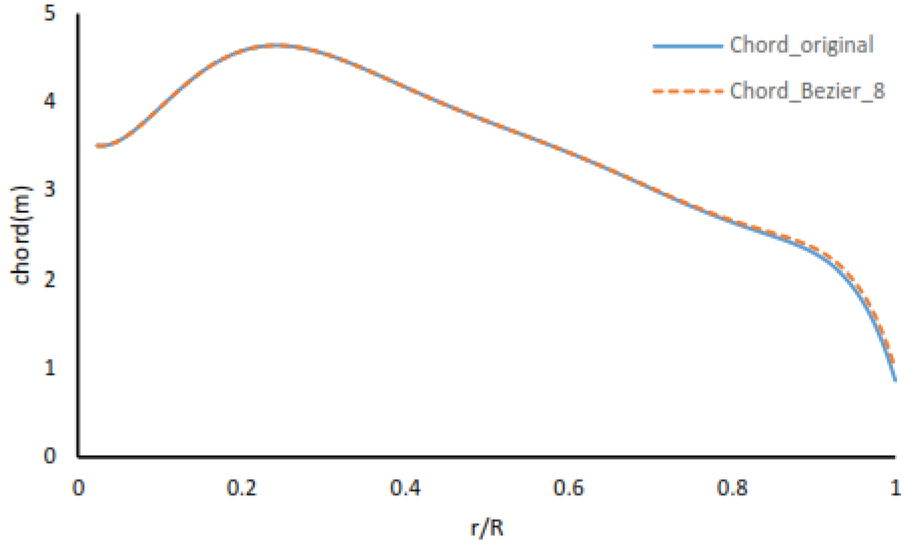

Fig.6. Chord distribution diagram in comparison with the corresponding fitted Bezier curve

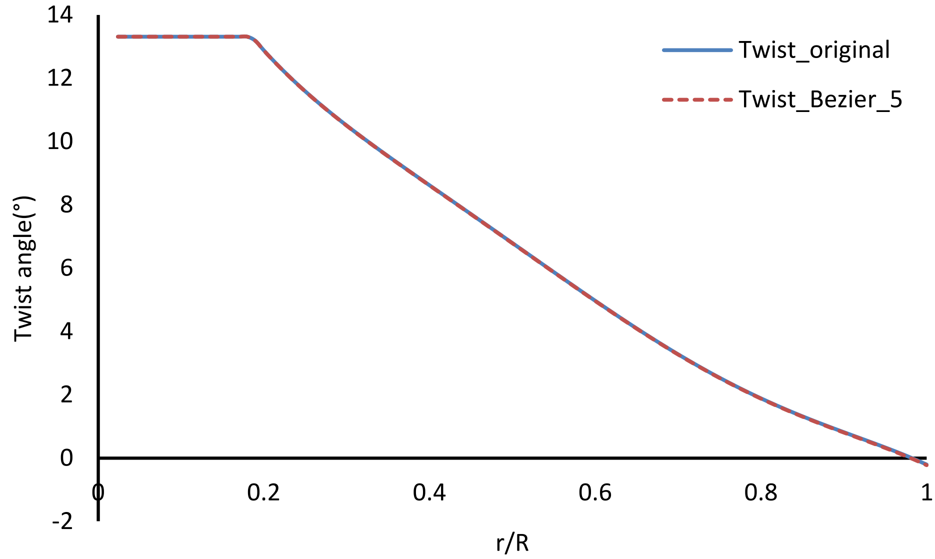

Fig. 7. Twist distribution diagram in comparison with the corresponding fitted Bezier curve

changed much compared to the initial geometry. This is an important issue from the structural and manufacturing point of view. In addition, the blade tip shape has been left almost unchanged by the assumed constraints because of its important effect on wind turbine noise and the wake behind it. The annual energy production of the specific probability density function was affected by twist angle. Wind speed that was prevalent according the probability density function was less than the rated wind speed. So, the twist angle was decreased in a way to put the airfoil in the best position to produce greater power. The optimal twist distribution is shown in Fig.9.

The chord length also affects torque, power output, and the thrust force. Figure 10 indicates that the optimized power output is less than the initial power output in each operational wind speed and especially the rated power is decreased by 3% because of the use of smaller chords. The outcome is the same for the thrust, illustrated in Fig.11. But the reduction in thrust is more than that of power due to the effect of a reduction in of the twist in each element.

Different percentages of optimized geometry and original geometry were calculated as shown in Fig.12. However, the annual energy production is decreased by 2% and the rated power is decreased by 3% but cost for producing is reduced by17%, decreasing the cost of energy by 15%. This is an acceptable and economical result, which, at the same time, does not much lowering the aerodynamic efficiency. The other point is that thrust force decreased around 6%, allowing the use of lighter material for future structural analysis and manufacturing.

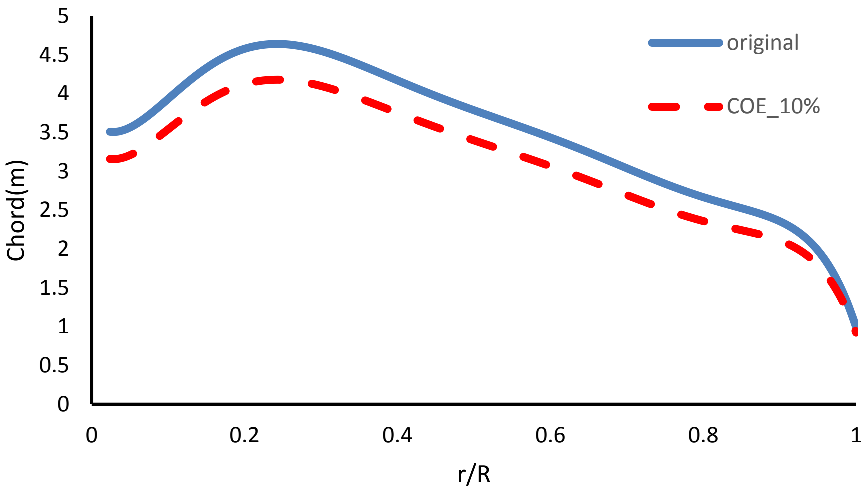

Fig.8. Optimal chord distribution in comparison with the original geometry

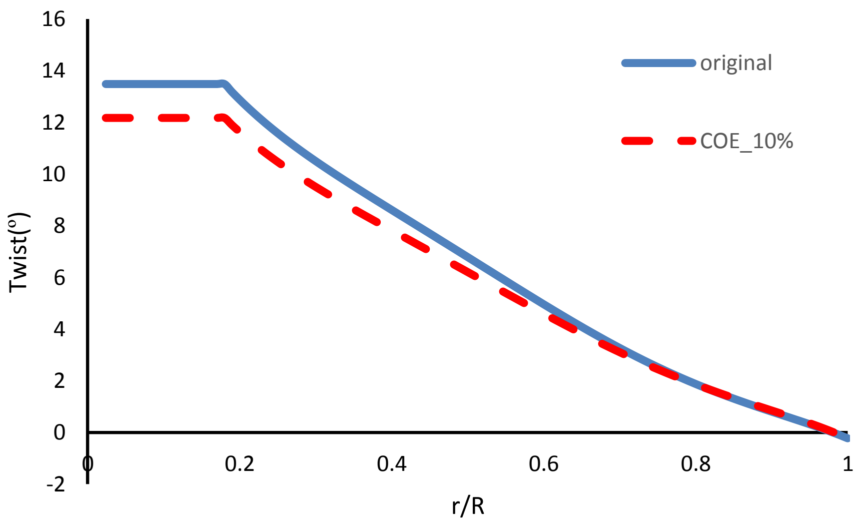

Fig.9. Optimal twist distribution in comparison with the original geometry

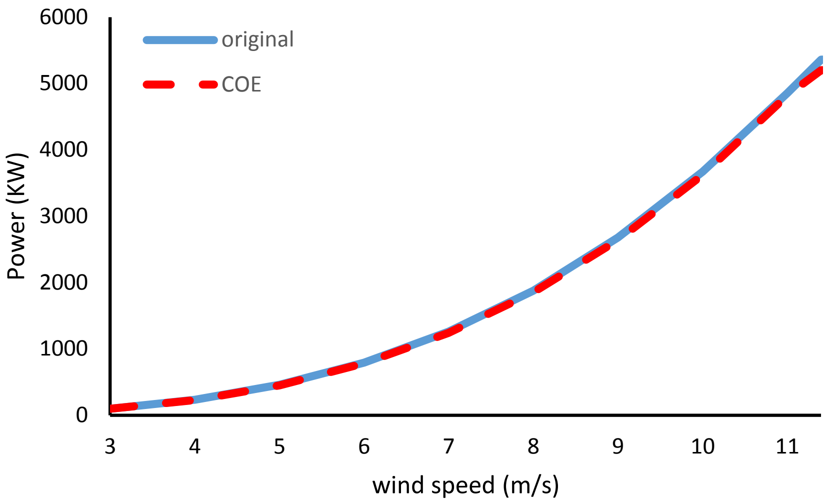

Fig.10. Optimal and initial Power output in different operational wind speeds

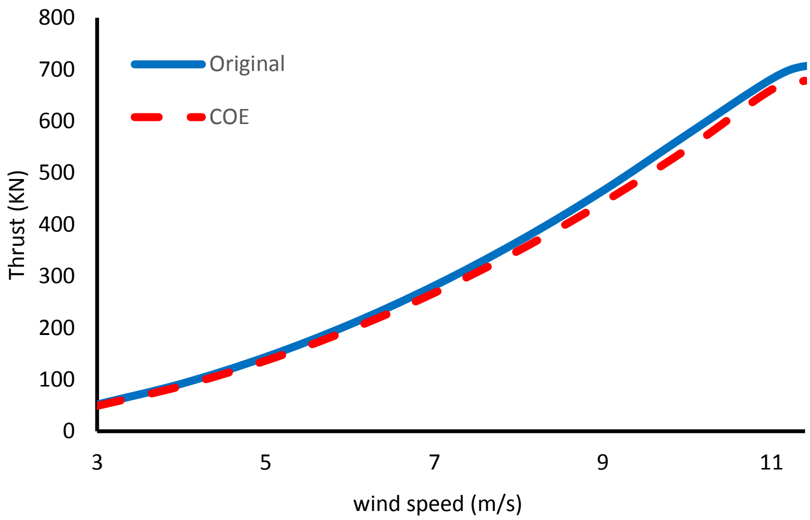

Fig.11. Optimal and initial thrust force in different operational wind speeds

Fig.12. Comparison of different parameters of optimized wind turbine and original wind turbine

4. Conclusion

The aerodynamic optimization of the NREL 5MW wind turbine blade is performed by the GA algorithm and modified BEM code. The Bezier curve was used for blade geometry parameterization and the Bezier control points were assumed to be the design optimization variables. A rational and operational cost model was used to determinate the relative cost of the wind turbine blade in the optimization process. Twist and chord distribution of each blade element were optimized for the best COE as an important and common objective function for a megawatt wind turbine for a given blade radius and airfoil profiles. The results show that optimized blade has smaller chord length in each section. The chord length is distributed more smoothly along the span in the optimized design. The twist angle, also is reduced in each section too. Therefore, the torque and power output and thrust force are decreased in every operational speeds; especially in rated wind speed. The AEP is decreased by 2% and the rated power is reduced by 3% but the cost for producing is lowered by 17%. Accordingly, the cost of energy is decreased by 15%. This is an acceptable and very economical result that does not change the aerodynamic efficiency very much. Moreover the blade tip shape is remains nearly constant in the light of the 10% allowable changing range for the variables as the optimization constraint. Moreover, the thrust force decreased around 6% which is important in wind turbine structural analysis.

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