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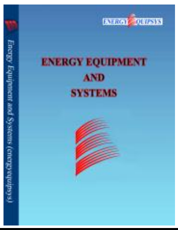

Aerodynamic design and economical evaluation of site specific horizontal axis wind turbine (HAWT)

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ABSTRACT

This paper presents the aerodynamic design and economical evaluation of a 200 kW site specific wind turbine for the province of Semnan in Iran. By designing site specific wind turbines, the cost of energy which is calculated out of the annual energy production and also the cost of manufacturing the rotor are minimized. The aerodynamic design is based on the well-known blade element momentum theory (BEM) which is integrated with annual wind distribution of the designated wind site to determine the net annual electricity yield for two designed rotors. In the first rotor, a linear fit approximation is used for the chord length and twist angle distributions for ease of manufacturing and to overcome technological barriers in Iran. In the second rotor, the optimum original nonlinear distribution of the blade is assumed. The RISØ-A-24 aerofoil is used and optimized for the design tip speed ratio of λ=8.93 for both rotors. Pitch angle control is also adopted here. A comparison is made between the aerodynamic performance and decrease of manufacturing costs for both rotors. The economic feasibility indicates that based on current electricity costs of 12 cent per kWh in Iran for renewable energies, a profit of 7.2 cent and 8.1 cent per each kWh generated power is achievable respectively by the linear and nonlinear rotor designs. Therefore, the scenario of reducing initial costs is not recommended unless technological shortcoming in manufacturing rotor cannot be avoided.

Keywords: Aerodynamic performance, BEM theory, Economical evaluation, Horizontal axis wind turbine (HAWT), Site specific

1. Introduction

1.1. Wind Energy

In consideration of the pertinent policies such as geographical position, environmental protection and government's tax allowance, many countries proffered huge funds on technology of wind-power electricity generation and so it developed very fast than compare with technology of thermal power. Utilizing of wind energy has been progressed by more than 50 countries in the whole world considerably [1]. Wind turbines have exhibited their ability to sustain whereas wind energy is a clean, raw material-costless, favorable renewable energy. The potential energy of wind is estimated to be about 6500MW in Iran [2]. Two sets of 500 kW Nordtank wind turbines were installed in Manjil and Roodbar in 1994. They produced more than 1.8 million kWh per year. These two sites are in the north of Iran, 250 km from Tehran, the capital of Iran. The average wind speed is 15 m/s for 3700 hours per year in Roodbar, and 13 m/s for 3400 hours per year in Manjil. After this successful experience, in 1996 the contract for 27 wind turbines was signed and they were installed by 1999 in Manjil, Roodbar and Harzevil. Harzevil is the third wind farm site near to Manjil. Manjil is about 800 meters above sea level and Harzevil is about 500 meters higher there are 21 installed wind turbines in Manjil, i.e. 1×500KW, 5×550 KW and 15×300 KW [3].

Semnan province is 95815 km^2. The province with 5.6% of the whole area of Iran is the sixth big province in the country. Semnan is located between N34°40' -N37°10' latitude and E51°59'–E57°4' longitude [4]. The province of Semnan is bordered from east by the province of Khorasan razavi, from north, Northern Khorasan, Mazandaran and Golestan provinces, from south, Yazd and Esfahan provinces, west, Tehran and Qom provinces. The center of province, Semnan is located at 228 km from Tehran

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and the distance from international waters of Persian Gulf and Caspian Sea in turn is 1600 and 200 km. This province includes 5 townships, 13 districts, 18 cities and 29 villages. According to the latest statistics in 2001, the population of the province is estimated to be 558000 that 73.5 percent were in urban area and 26.5 percent were rural dwellers [5]. In general, the dominant prevailing wind in the area is blowing from the northwest to the southeast and is called Tooraneh. Also, other winds in the province called Shahriari, Kavir and Khorasan winds, blow from west, south and east to west in different seasons of the year respectively [6]. Detailed statistical study of wind at 10m, 30m and 40m height in Semnan province is presented in [7].

Wind turbine are classified into two configurations based on their rotational rotor axis with respect to the ground: the older generation, lower–power vertical axis (e.g. Savonius and Darrieus rotor) and the higher power, horizontal-axis at wide commercial deployment (e.g. AWE series 54-900, 52-750, Vestas series v39, and v66, and Nordtank-300).

1.2. Wind Turbines

Recently, focus has been intensified on designing wind turbine rotors for maximum aerodynamic performance [8]. According to particularly challenges and difficulties to achieve a good efficiency and thus in obtaining better economic performance, any improvement in the aerodynamic design of wind turbines infers a significant benefit that increase. Clearly, blade aerodynamic forces that are essential to turbine energy capture produce shaft torque and rotation. Hence, more recent studies, is performed on lessening undesirable aerodynamic loads that wind turbines frequently endure during routine service. These high aerodynamic loads compel immoderate stresses on turbine blades and gearboxes, and shorten machine service life considerably [9].

1.2.1. Horizontal Axis Wind Turbine (HAWT)

The theoretical maximum for the power coefficient, C_p, marked by the Betz limit Cp_{max}=16/27=0.593. Modern horizontal axis wind turbines (HAWTs) work with C_p up to 0.5, nearby the Betz limit [10].

The blade element momentum (BEM) model is the most common model used in aerodynamic and aero elastic codes for wind turbine performance. Comparison of the BEM model with more accurate induction model that mentioned assumption is not exact in positions on the blade with great radial variation of the loading, as e.g. close to the tip and at the root [11]. Another basic deficiency of the BEM model is that it is a steady state model, whereas due to turbulent inflow on wind turbine rotors the loading is dynamic immensely [12].

In addition, developing of accurate non-linear aerodynamic models continually have demonstrated that state-of-the-art blade element momentum (BEM) models have their shortcomings, in accurately determining three-dimensional (3D) flow structures, such as separation, viscosity effects, tip and root vortices, as well as span wise flow [8].

1.3. Aerodynamic Design Optimizations for HAWT

In the development of modern commercial wind turbines, the size has contiguously increased to the latest multi-MW turbines. Generally, the two fundamental objectives of the design of a HAWT turbine are to maximize its annual energy production (AEP) and to minimize the cost of energy (COE) produced [13].

In order to maximizing the power coefficient, $C_{p,max}$ the blade shapes should be enhanced with rather large root chords and taper and relatively much blade twist. With raising size of rotor the root chord started thicken and impels to investigate on production methods and transportation possibilities on land. Glauert [14] initiated the calculation of the optimum windmill by making the power integral equation stationary. The resulting implicit relations between the velocity induction factors were solved through an iterative procedure. The detailed design of a wind turbine was relevantly described to deal models of rotor aerodynamics and optimization techniques [15-18]. In these investigations, optimization methods are described where a single objective function considers as well at each time with their constraints. There are a number of research works dealing with multiple objectives, namely maximum AEP and minimum COE, which is addressed where AEP and COE are combined by means of appropriate weight percents.

Fuglsang and Madsen [18] presented a multidisciplinary optimization method for designing horizontal-axis wind turbines. The objective required in their method was minimizing the cost of energy with multiple constrains that their optimization technique was validated by an under test 1.5 MW stall-regulated rotor. Also Fuglsang and Thomsen [19] incorporated the site characteristics into the design process of the 1.5–2.0 MW wind turbine rotors in various characteristics of terrain.

A multi-objective optimization method to design a stall-regulated HAWT was depicted by Benini and Toffolo [20] based on the coupling of an aerodynamic model equipping with the blade element theory and evolutionary algorithm. The main results obtained indicate that the minimization of COE requires large-sized HAWTs having high AEPs, but low blade loads and low blade weights. Tempel and Molenaar had described a cost effective flexible system for wind turbines [21].

Jureczko *et al.* [22] had presented optimizing using the varying characteristics the wind turbine rotors in the blade structural parameters such as stiffness, stability and material weight. The effect of changing the rotational rotor speed on the power performance of a stall-regulated, horizontal axis wind turbine was investigated experimentally and theoretically by Khalfallah and Koliub [23].

Dong *et al.* [10] has used an optimized design method based on Wilson and Schmitz analysis methods choosing principles of design parameters and multiairfoils in horizontal axis wind turbine (HAWT) generator system. The design results show that HAWT optimized design method based on Schmitz makes good agreement with Wilson method. Wenzhi *et al.* [1] designed a 1.2 MW wind turbine blade's profile based on BEM theory through improving on the Wilson algorithm and correcting the airfoil from the structure and processing angle. Xudong *et al.* [24] optimized wind turbine blades based on an aerodynamic/aero-elastic code that includes the structural dynamics of the blades and the Blade Element Momentum (BEM) theory.

In this paper, Blade Element Momentum theory (BEM) is used to design a HAWT blade for a 200 kW wind turbine. The airfoil is RISØ, produced by RISØ National Laboratory, Denmark, for a class of 200KW wind turbines. Desirable properties of this airfoil are related to enhancement of aerodynamic and structure interactions. The purpose of this study is to find a simpler linear modification to the shape of blades. Design parameters considered here are wind tip speed ratio, nominal wind speed and diameter of rotor. BEM is used for obtaining maximum lift to drag ratio for each elemental constitution of the blade. Obtaining chord and twist distribution at assumed tip speed ratio of blade, the aerodynamic shape of the blade in every part is specified which correspond to maximum accessible power coefficient. In order to simplify manufacturing of the blades, a linear approximation is employed for both chord and twist distribution. The design parameters are trust coefficients, power coefficient, angle of attack, angle of relative wind, drag and lift coefficients, axial and angular induction factors. The blade design distributions are presented against rotor radius for BEM results and also compared with the linear approximation.

1.4. Advantages of Pitch Control System for HAWT

In high wind speeds, it is noteworthy to be able to control and limit the rotational mechanical power. The power limitation may be done either by stall control, pitch control or active stall control. Pitch control system in wind turbines have become the more applicable type of installed wind turbines in recent years. For low wind speeds, the speed controller can continuously adjust the speed of the rotor to maintain the tip speed ratio constant to produce the maximum power coefficient, and to improve the efficiency of the turbine. For higher wind speeds however pitch angle regulation is required to keep the rotational speed constant. Small changes in pitch angle can reduce considerably the power output. Therefore, the purpose of the pitch angle control may be expressed as [25-27]:

1. Optimizing the power output of the wind turbine.
2. Regulating input mechanical power to avoid exceeding the design limits. Above rated wind speed, pitch angle control provides an effective way to control the aerodynamic power and loads produced by the rotor.
3. Minimizing vibrations and fatigue loads on the turbine mechanical component. Avoiding a generator from over speed by controlling the input mechanical torque. A pitching system has the of actively controlling the input mechanical torque. Although the acceleration of the generator has been limited by the pitch control, the speed of the generator may rise again after the controls have been removed.

The design procedure and power performance estimation of a pitch-controlled HAWT is discussed in the following sections. The relationship between power performance and rotor specific parameters is analyzed and presented.

2. Methods on Aerodynamic Design of HAWT's

2.1.Choosing Design Parameters

The design of the blade requires a great number of design variables parameters to control rotor shape and airfoil characteristics including: the rotor diameter D, the number of blade B, the chord of sections C and twist angle θ_t across the blade and the lift that depend on the angle of attack. However at first the family of airfoil should be specified. Fundamentally, the determination of the rotor size depends on the required energy and blown mean wind speed. As relative wind speed is the resultant of the stream wind speed, blade section speed and rotor induced flow. Lift force is the main force for operating the wind turbine to produce useful power. Thus Maximum lift-to-drag ratio is criterion for choosing the airfoil family.

2.1.1.Airfoils of Wind Turbines

Airfoils for HAWT are often designed to be used at low attack angle where the drag coefficient is usually much lower than the lift coefficient; especially, at blade tip airfoils with high Lift-Drag-Ratio (LDR), low roughness sensitivity, low noise character should be selected to insure the nearest optimum aerodynamic performance.

Griffiths [28] showed that the output power is greatly affected by the airfoil lift-to-drag ratio. A general aviation airfoil shape is NACA series, and dedicated airfoil shapes used in modern wind turbines are: S8 series developed by National Renewable Energy Laboratory (NREL) in USA, FFA-W series developed by FOI in Sweden, RISØ-A1 series developed by RISØ in Denmark, DU series developed by Delft University of Technology in Netherlands. It has been found in some applications that more than one airfoil shape can be used for the wind turbine blade design, but there will be bending between these airfoils which may add to uncertainties in the design process.

It is also worth emphasizing that with more accurate aerodynamic coefficients at high attack angles, the more accurate design and performance prediction can be obtained. But the aerodynamic coefficients of a rotating airfoil are different from the ones of a linear moving airfoil.

The coefficients from wind tunnel testing are acceptably accurate in steady flow, but not in stall conditions, these coefficients are always lack of accuracy or there is no coefficient measured at very high attack angles at all. In this project, the RISØ type airfoils are used [29]. In this class of airfoils, the different families of modern airfoils applied in wind turbines, are verified that with regarding verification of criteria relate to design of wind turbines, the airfoils RISØ-A1-24, FFA-W3-301, FFA-W3-241 and DU93-W-210 were proper choices from which RISØ-A1-24 is selected in this work.

The experimental results of RISØ-A1-24 are related to open test part of VELUX wind tunnel measurements with 1% turbulence. Details of these tests and measurement instruments are given in [30]. Also the tests were carried out in the Reynolds number equal to 1.6×10^6. The numerical results show a relative good agreement with experimental results. In the linear region of lift coefficient, the simulation with transition model is nearer to experimental data while computational results of quite turbulent flow are nearer to stall region. Simulations with transition model predicted stall in a higher angle attack than the tests. In our study however, the results of the transition model simulation is adopted for better accuracy in linear region.

2.2. General Method for Rotor Design

A generalized analysis on manufacturing, industrialization, and costs shows that the obtained chord length and twist angle from the theoretical analysis should be modified. Whereas the chord length and twist angle of the wind turbine are not linear, one procedure for this goal (e.g. simplification in CNC machining for blade's mold manufacturers) is applying fitted linear relationship on the chord length and twist angle curves separately. For this purpose, a computer code has been prepared in MATLAB program for implementing the developed model on the computer.

2.2.1.Rotor Design for 200 KW and Pitch Controlled Turbine

Design is begun with choosing of variety parameters of rotor and an airfoil. The primitive blade shape is determined using an optimum shape blade considering wake rotating. Ultimate blade shape and its performance are specified with iterative relations and including drag, tip losses and ease of manufacturing. These steps are explained in the blade design in the following sections.

2.2.2.Determining Main Parameters

First, the required output power from turbine should be specified. The rated wind speed is required to calculate the diameter of rotor. C_p and η are the power coefficient and the electrical-mechanical efficiency respectively, and are used to estimate the diameter of the rotor. For the design wind turbine power of 200 KW, the maximum allowable generated power is 200 KW; hence the rotor diameter is calculated based on the rated (mean cubic) wind speed which is defined as

$$U_{meancubic} = \sqrt[3]{\int U^3 f_{Weibull}(U)dU} \quad (m/s) \quad . \tag{1}$$

For Haddadeh region in province of Semnan in Iran, the average wind speed and the corresponding rated wind speed is calculated to be 5.85 and 8 respectively [7]. The meteorological masts with 40m height were installed in suitable coordinates by power ministry in the latitude of 36° 25' and longitude of 54° 73'.

According to the type of application, we can choose a tip speed ratio, λ. For a water pumping windmill, for which greater torque is needed, we use $1<\lambda<3$. For electric power generation, we normally use $4<\lambda<10$. The machines with higher speeds use less material in the blades and have smaller gearboxes, but require more sophisticated airfoils [31].

Normally in design procedures three blades are chosen. If fewer than three blades are selected, there will be a number of structural problems that must be considered in the hub design. In this work, we used a better method for selection of λ and C_p.

The method uses figures of C_l-α and C_d-α from experiment and approximate by a linear equation in flat regions and a quadratic equation in curve regions. Thus a maximum value for (C_l/C_d) can be obtained that in this case is 143. Choosing B=3 (number of blades), the values λ_{opt} and $C_{p,max}$ can be obtained from [31]

$$C_{p,\max} = \left(\frac{16}{27}\right)\lambda\,[\lambda + \frac{1.32+\left(\frac{\lambda-8}{20}\right)^2}{B^{2/3}}]^{-1} - \frac{(0.57)\lambda^2}{\frac{Cl}{Cd}\left(\lambda+\frac{1}{2B}\right)} \quad . \tag{2}$$

Figure 1 shows a group of $C_{p\text{-}\lambda}$ curves where optimum values of tip speed ratio, λ_{opt} ,correspond to the maximum power coefficient, $C_{p,max}$.

In Fig.1, the RISØ-A-24 aerofoil data was used for the maximum lift to drag ratio equals to 143 to obtain the optimum tip speed ratio. The optimal tip speed ratio is obtained to be λ_{opt} =8.9327 for the corresponding maximum power coefficient of $C_{p,max}$=0.5183.

Rated wind speed is defined as 8 m/s, at which the biggest probability in the annual energy distribution occurs. The power generated by a wind turbine can be expressed as [31]

$$P = C_P \eta \, \tfrac{1}{2} \rho \pi R^2 U^3 \quad , \tag{3}$$

with

$$\lambda = \frac{\Omega R}{U} \quad , \tag{4}$$

where Ω is the turbine rotor angular speed and R is the radius of the wind turbine; i.e. length of blade [31]. Thus corresponding HAWT rotor diameter is calculated to be equals to 46m; considering rotor hub diameter. As a basic, design parameters are defined for the HAWT with constant rotational speed and variable speed (e.g. 200KW), is maximal blade tip speed that according to erosion problems and taking noise into account is assumed to be 78 m/s [32].

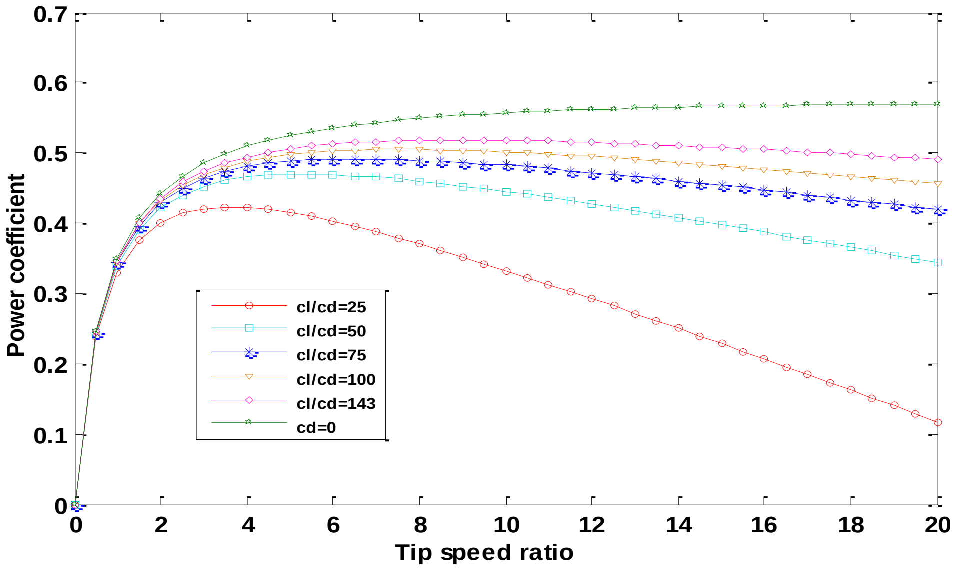


Fig. 1. Power coefficient (C_p) versus blade tip speed ratio (λ)

A complete methodology for defining the blade shape and for calculating the rotor's design parameters are given in [31].

2.2.3. Rotor design using BEM theory

Considering the rotor as an actuator disk which its effects are a sudden drop in pressure and assuming constant speed at the rotor, the linear momentum theory is used for air flow through a one dimensional tube. From Betz theory, an ideal wind turbine reduces wind speed to two third of the free stream value. Since the wind turbine produces a useful torque for generating power, the conservation of moment of momentum must be satisfied by employing a wake rotation downstream of the wind turbine in some annular control volumes. In actuator disk theory, friction drag is ignored which is not realistic. In order to modify this shortcoming, blade element theory is considered to incorporate the effects of drag force exerted on each elemental constitution of blade. The design with wake rotation took into account the generation of rotational kinetic energy in the wake, which resulted in less energy extraction by the rotor than it would be expected without wake rotation. Adopting the procedure discussed in Manwell [31], one may calculate the power coefficient through an iterative method form

$$C_p = 8/\lambda^2 \int_{\lambda_h}^{\lambda} F\lambda_r^3 \acute{a}(1-a)[1-(C_d/C_l)\cot\varphi]d\lambda_r \quad , \qquad (5)$$

where F is tip loss correction factor, a is axial induction factor, $\acute{a}$ is angular induction factor, $\lambda_r = r\Omega/U$ is the local speed ratio for an element of blade at radial distance of r. The element dimension is c as the local chord length and dr as the width of element. The drag to lift ratio (C_d/C_l) corresponds to the local airfoil section. Using the optimum blade shape as a guide, the blade shape i.e. chord length and twist angle which can be modified for ease of manufacturing and reducing costs; however, in expense of losing aerodynamic performance. For ease of fabrication, linear variations of chord and twist may be chosen.

For example, if a_1, b_1, and a_2, are coefficients for the chosen chord and twist distributions, then the chord and twist can be expressed as [31]

$$c_i = a_1 r_i + b_1 \quad , \qquad \theta_{T,i} = a_2(R - r_i) \quad , \qquad (6)$$

where r_i is the radius from the blade root for part i^{th}. Because in BEM method, the length of the blade should be divided to N parts that counter of this parts is shown by index 'i'.

2.3. Computation of Annual Output Power

For a wind turbine with pitch control system, the speed range is divided to the two regions for calculation of output power once is cut-in speed until rated speed and another is rated speed until cut-out speed. The annual output power could be obtained from the designed turbine [31] using

$$\overline{P}_w = \int_0^\infty P_w(U)p(U)dU \qquad (7)$$

In this relation, $P(U)$ is Weibull distribution and $P_w(U)$ is power equation that is generated by turbine at working limit with specified speeds and is given as

$$p(U) = \left(\frac{k}{c}\right)\left(\frac{U}{c}\right)^{k-1} \exp\left[-\left(\frac{U}{c}\right)^k\right] \quad . \qquad (8)$$

2.4. Economical Evaluation

During the last 15 years, the focus has been on lower production costs of wind turbines. The early large experimental wind turbines of the eighties were extremely expensive due to individually manufactured prototypes for the associated extensive research and development programs. The early produced relatively small wind turbines in Denmark and in USA were cost for more than 5000 $US per kW rated power. Today, series-produced commercial wind turbines are available for less than1500 $US per kW.

This price level allows the economic use of wind energy even in the lower inland wind regimes [33].

Annual costs of wind turbine during the *n* years can be estimated in initial a year using

$$C_{OM} = mC_I \quad , \tag{9}$$

where C_I is the initial investment of the project and C_{OM} is the operation and maintenance cost. Also m is the percentage that determines the C_{OM} as function of C_I. Maintenance and operation cost for *n* years to initial year can be calculated by

$$PW\ (C_{OM})_{1-n} = mC_I \left[\frac{(1+I)^n - 1}{I(1+I)^n} \right] \quad . \tag{10}$$

The net present worth of all cost including operation, maintenance and the initial investment is given as

$$NPW\ (C_A)_{1-n} = C_I \left[1 + m \left(\frac{(1+I)^n - 1}{I(1+I)^n} \right) \right] \quad . \tag{11}$$

Therefore, yearly cost of operation for the turbine is

$$NPW\ (C_A) = \frac{NPW\ (C_A)_{1-n}}{n} = \frac{C_I}{n} \left[1 + m \left(\frac{(1+I)^n - 1}{I(1+I)^n} \right) \right] \quad . \tag{12}$$

The energy generated (E_I) by the wind turbine in one year is accumulated as

$$E_I = 8760 \times P_R \times CF \quad , \tag{13}$$

where P_R and CF are the rated power and capacity factor respectively. The capacity factor is defined by the ratio of the actual power generated to the rated power output [34]. That is,

$$Capacity\ factor = \frac{P\ MWh}{(365 days)\times(24h/day)\times(200kW)\times 1MW\ /1000kW} \quad . \tag{14}$$

For the modified blade, the capacity factor is CF=0.43, whilst for the original optimum design, the value is CF=0.54. The cost of 1kWh wind-generated electricity is then approximated as

$$C = \frac{NPW\ (C_A)}{E_I} = \frac{C_I}{8760n} \left(\frac{1}{P_R CF} \right) \left[1 + m \left(\frac{(1+I)^n - 1}{I(1+I)^n} \right) \right] \quad . \tag{15}$$

3. Results and Discussion

3.1. Computation of Blade Shapes

Figure 2 shows that chord length distribution as well as twist angle is bigger at inner sections of blade (near the root) and it is smaller at outer sections of blade.

The modified chord length and twist angle distributions are shown in Figs. 2a and 2b. The chord length of the blade's root and tip is obviously smaller than the result of the theoretical calculation. Also the twist angles of the blade's root are smaller than the result of the theoretical calculation. The linear fit cannot be used for the first element due to complex numbers obtained at this point.

Twist angle of blade tip is about 5.63 degree in nonlinear state which causes less startup speed. The negative twist angle causes the elements of blade tip had a proper attack angle in startup slow wind speeds; although in high wind speeds, stall probably occurs in blade edge sections. Therefore modification in twist distribution should lead to finding the real attack angle until optimal attack angle can be estimated correctly.

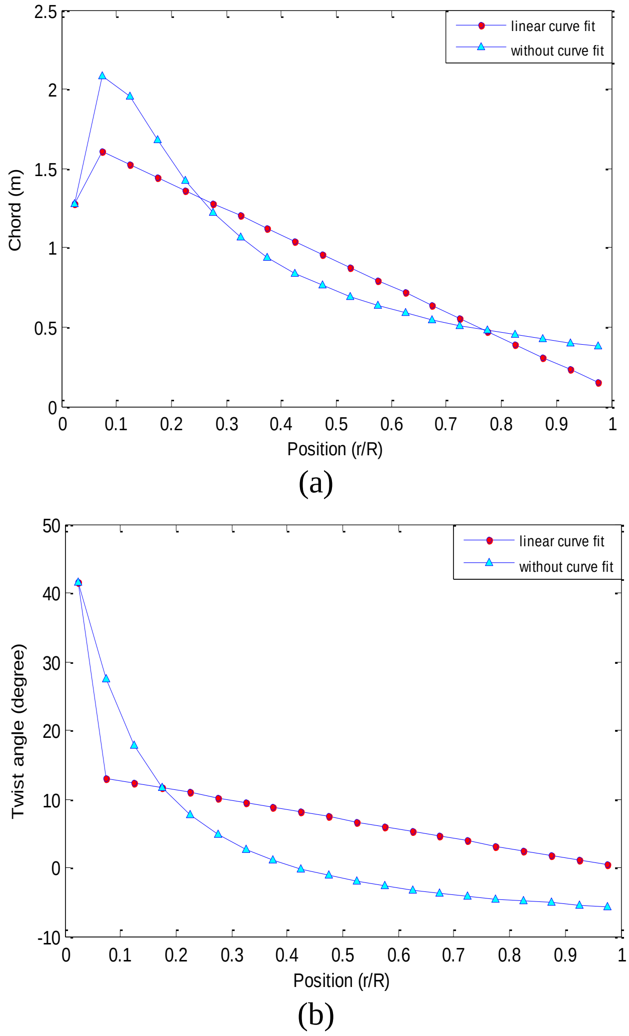
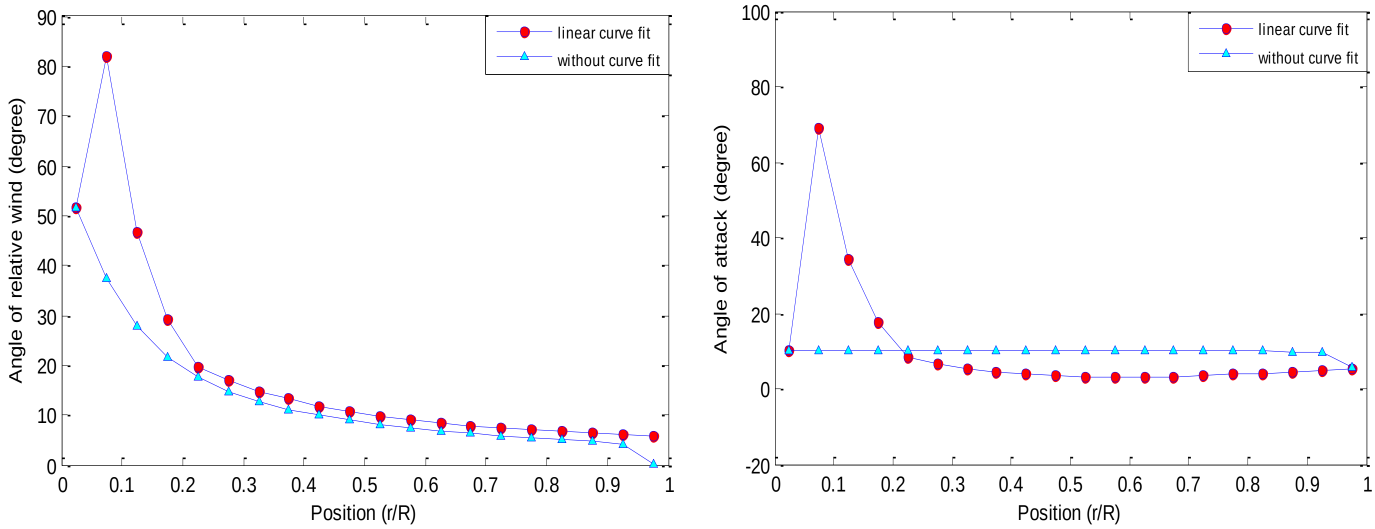


Fig. 2. a) Chord length distribution
b) Twist angle distribution

In order to compare the effects of linear and nonlinear chord and twist, the results from this point forward are presented for both linear and nonlinear designs.

In Fig. 3a, it can be seen that the angle of relative wind is larger than the optimized theoretical distribution at all parts of the blade especially in sections near the blade root. Favorably, the part of the blade at the tip does not contribute too much to the power.

Figure 3b shows a constant angle of attack, α, on full length of the blade with slightly decrease at the tip of blade for the nonlinear blade, while for linear blade, this curve has a maximum near the blade root and suddenly decrease up to r/R=0.225 and then decrease slightly across the middle sections up to the



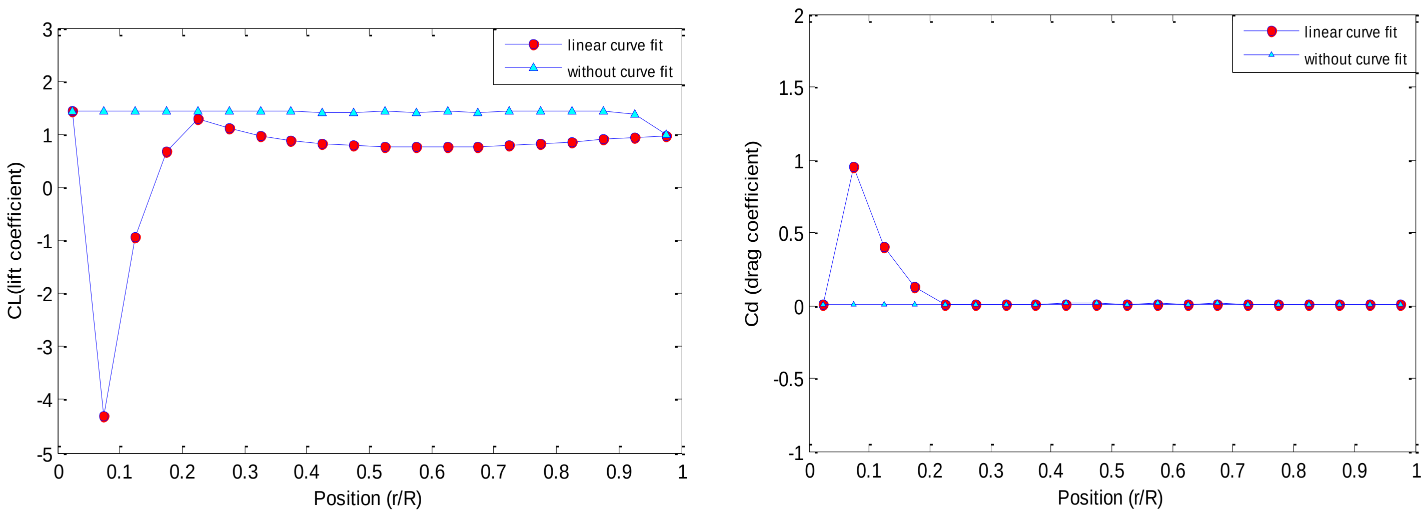
(a) (b)

Fig. 3. a) Angle of relative wind, b) Angle of attack

last elements at the blade tip. It should be noted that α can be expected to deviate from the design α due to the azimuthal averaging. Also the tip correction is implicitly included in the result; therefore, α can be regarded as a kind of 'tip-corrected' angle of attack.

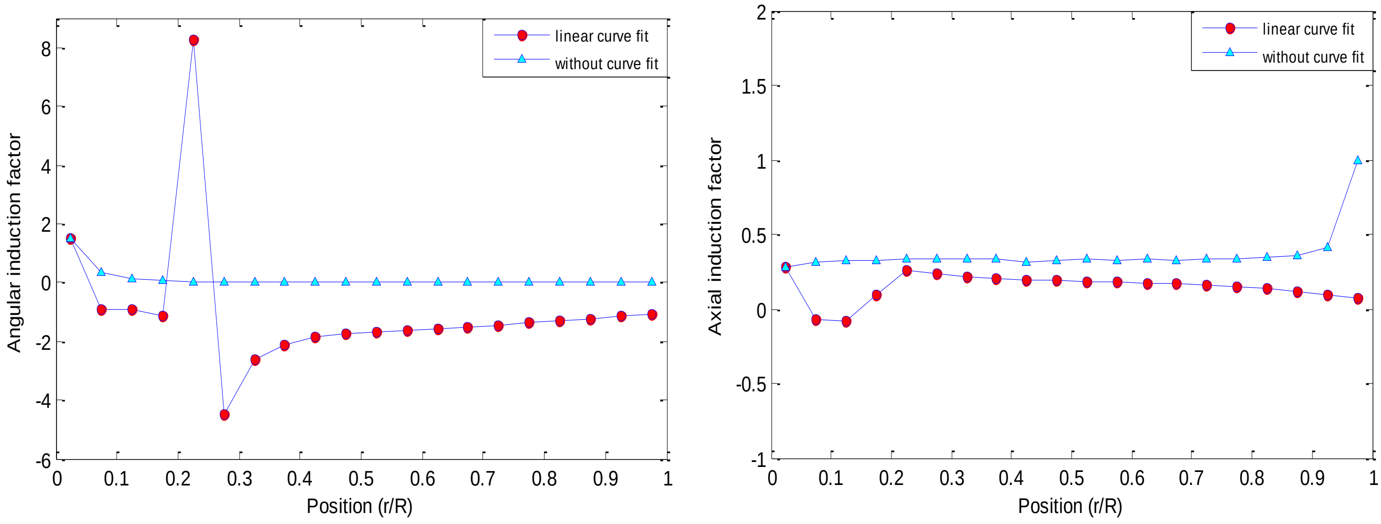
From Fig. 4a, for any angle of attack, C_l is smallerthan the theoretical design. As observed at near the root (where α is larger than 10º), C_l drop is very big that cause to be negative. Thus this causes reduction of the mechanical power of the wind turbine. As shown in Fig. 4b, where the angle of attack is larger than 10º near the root; therefore, C_d by sequence of linear curve fitting is larger than the design C_d.

In Fig. 4b, because the values of the attack angle is not higher than 10 degrees in the case without linearization, the drag coefficient curve remain constant at 0.01. Figure 5a shows that the axial induction factor is about 1/3 on most of the blade elements (0.125<r/R<0.875) for the nonlinear blade, deviated near blade tip from a=1/3. To obtain the maximum efficiency of an aerodynamic horizontal axis rotor, the design should look for that the axial induction factor should be the nearest as possible at values around 1/3 mainly the disk of the rotor. On the other hand, the maximum power coefficient (Betz limit) occurs at an axial induction factor of 1/3. Hence, the rotor has almost reached the maximum power coefficient. It should be noted that the local induction factors shown are averaged over the rotor disc. The axial induction factor shown for the case with linear approximations is lower at elements near the root and increase and then is gradually decreases towards the tip. The angular induction factor, a´, shows a decrease from first to second element and then is relatively constant for the nonlinear blade (see Fig. 5b).



(a) (b)

Fig. 4. a) Lift coefficient, b) Drag coefficient



(a) (b)

Fig. 5. a) Axial induction factor , b) Angular induction factor

The angular induction factor contributes mostly to the shaft torque and the output power. A bigger shaft torque will increase the load of the transmission system and reduce the lifetime of the gearbox. In this figure, for the linear blade, peaks are observed between 0.2<r/R<0.3 that, are due to change in the chord length and twist angle distributions.

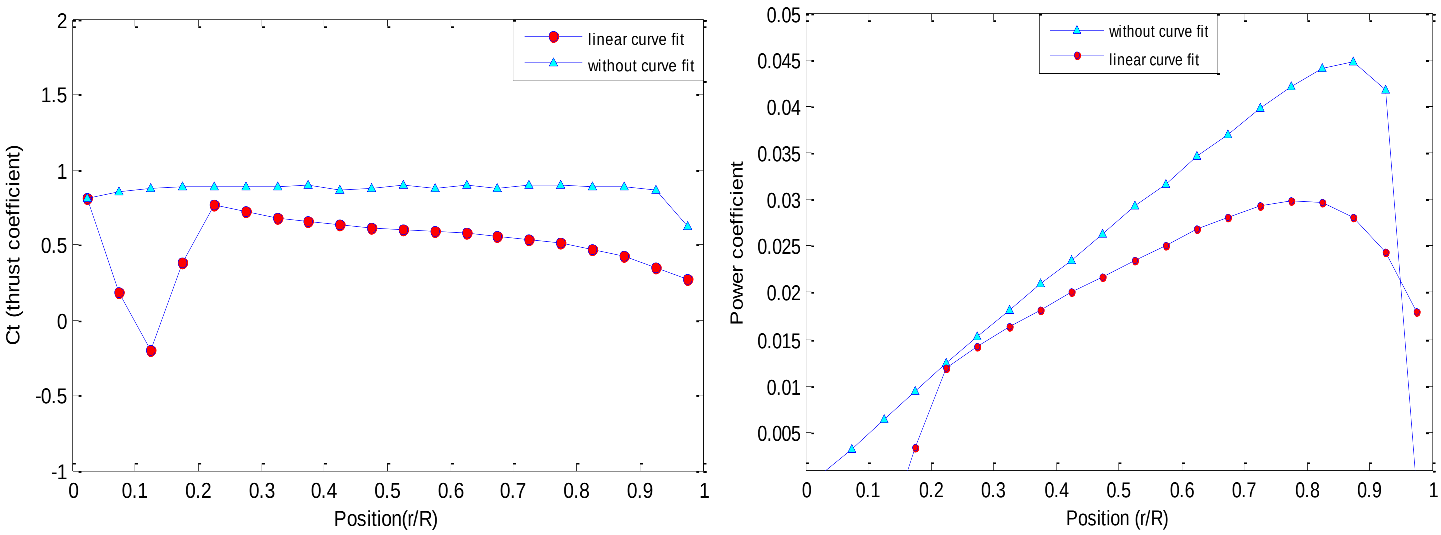
Figure 6a shows that the local thrust coefficient, C_t is constant for the nonlinear blade except at the blade tip position where a decrease of C_t is observed. The deviations between the two curves are observed in the innermost parts of the linear blade. From r/R=0.225 on, C_t is slightly decreased to the blade tip. A bigger thrust would shorten the lifetime of the blade and increase the cost.

Figure 6b shows comparisons of power coefficient between the theoretical and linear optimized rotors in each section. From the figure, it is seen that the theoretical designed rotor has power coefficient more than the linear optimized rotor. At the tip, both C_p and C_t decrease due to tip corrections.

3.2. Computation of Turbine Power Coefficient

Referring to Fig. 7, it is observed that C_p increases with λ up to its optimum value, then it decreases with a quickly rate. As it is expected, maximum power coefficient in nonlinear case is at λ=8.9327 that in linear case changes and translates to the left side and causes the total power coefficient is decreased. The optimum range of the TSR for optimized linear rotor is observed to be between 6 and 7, therefore the design TSR at which $C_{p,max}$ occurs is also reduced by about 25%.

Also the dome of optimized power coefficient with linear approximations is narrower than that one.



(a) (b)

Fig. 6. a) Trust coefficient, b) Local power coefficient

Figure 8 shows the power coefficient versus the rotor rotational speed with linear approximation for chord and twist distributions. This figure shows six wind speeds such as 5-10 (m/s).

According to Fig. 8, a third degree polynomial curve as a function of U is obtained (the values of C_p remain constant at maximum points before reaching to U_{rated} .So by using $P=1/2\rho C_p \pi R^2 U^3$ and having Cp=0.472, R=23m,ρ =1.225 (kg/m^3) a relation is obtained for the range of wind speed between cut-in and rated wind speed. The rotor speed at below rated wind speeds is proportional to the wind speed for obtaining maximum energy yield.

In pitch control system, the blades is pitched to reduce the power coefficient at wind speeds more than rated to keep the rotor speed more or less constant at the rated rotor speed and to produce a constant output power. The power control regions of wind turbine are shown as a function of wind speeds, its results are shown in Fig. 9.

Clearly, the primary predicted wind rotor output power at the rated power is about 246 kW which is larger than the rated power (200 kW) of this HAWT, the difference between values is due to electrical and mechanical losses. It is also observed that from cut-in wind speed to cut-out wind speed, rotor's output power increases to the maximum at the rated wind speed and then keeps constant under the regulation of blade pitch; whereas the wind turbine must be protected against mechanical overloads and possible risk of damages at strong wind.

For considering safety, the turbine is shut down at speeds exceeding cut-out wind speed.

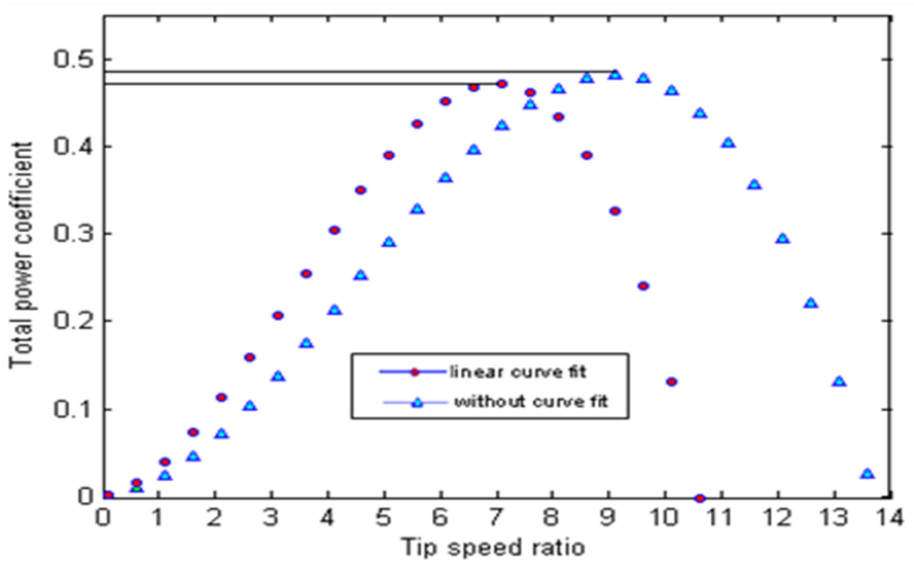


Fig. 7. Power coefficient (C_p) versus tip speed ratio (λ)

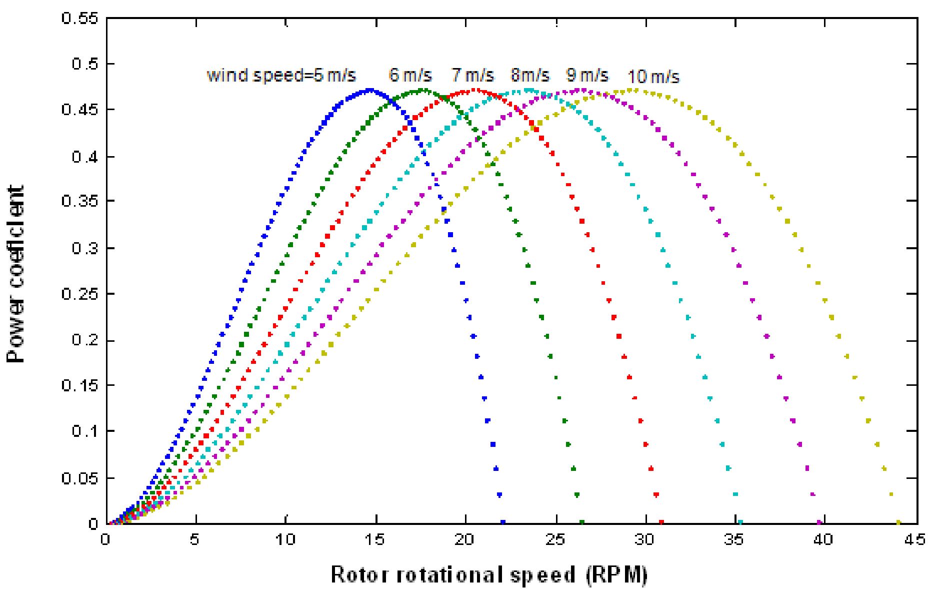


Fig. 8. Power coefficient versus rotor rotational speed

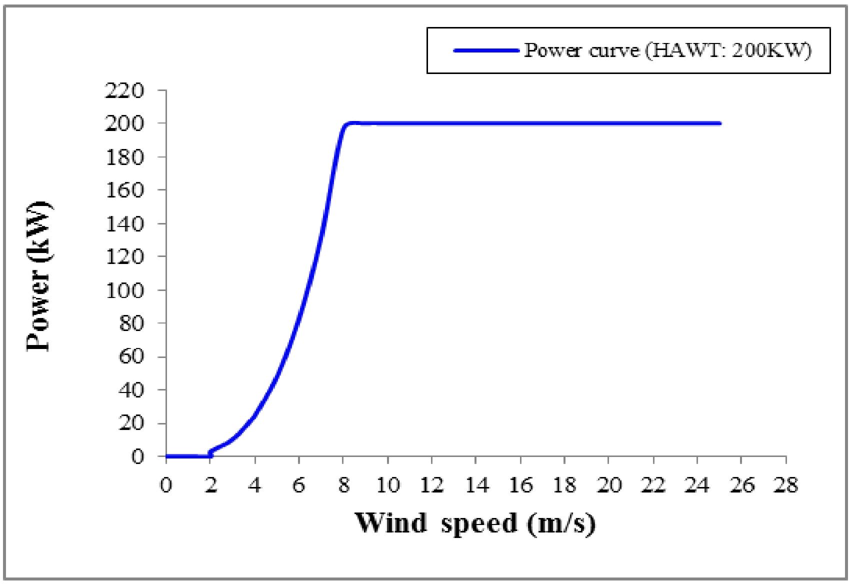


Fig. 9. Power curve of the linearized blades 200 kW wind turbine

By considering mechanical and electrical losses (η=0.8 mechanical-electrical efficiency), power relation is obtained for beginning region until rated speed as:

$$P_w(U) = 384.3648\ U^3$$

According to U_{rated}=8(m/s) and putting it in above equation, P=196794.78 W is obtained (almost equal to rated power of 200 KW, HAWT), namely that more than the mentioned rated speed, the power curve is shown as a constant value which is equal to power 200 KW. It emphasizes correct solution method that is obtained from linear.

Thus, the predicted aerodynamic characteristics of the mentioned 200KW HAWT are reasonable and reliable.

Figure 10 shows output power of rotor versus rotor rotational speed with linear chord and twist distributions, with considering mechanical and electrical losses. In this figure, output power of rotor for both cases of constant rotational speed and variable speed are depicted. One way of obtaining variable speed with an asynchronous generator is to apply a so-called double feed induction generator (DFIG). Some stall and pitch regulated wind turbines using asynchronous generators, running at a fixed rotational speed, have two generators: one which is efficient at lower wind speeds and one which is efficient at higher wind speeds.

If another type of generator had been used, one which is able to run at different rotational speeds, the turbine could be operated at the optimum rotational speed for each wind speed, as indicated in Fig. 10, by the operational line that intersects all the top points in the curves for the different wind speeds. All points on this line correspond to the highest C_p that can be obtained for the applied pitch angle.

The maximal rotational speed of HAWT can be obtained as Ω_{max}=78/R=3.39 rad/s (ω_{max}=32.38 rev/min). By considering the behavior of DFIG, it is supposed that $\omega_{max}/\omega_{min}$ is 2.2, therefore, the lowest rotor rotation speed is ω_{min}=14.72rev/min and Ω_{min}=1.54 rad/s. Also the maximal design wind speed is V_{max}=78/λ_D=8.73 m/s and the minimum design wind speed is V_{min}=$\Omega_{min}R/\lambda_D$=3.97 m/s. Between V_{max} and V_{min}HAWT, operation is at optimum design point. Therefore, in this case the turbine is equipped with an asynchronous generator forcing the blades to rotate at the constant ω_{max}= 32.38r/min, indicated by the vertical line. It is seen that the turbine is running most efficiently at a wind speed higher than rated wind speed. As mentioned above, due to noise emission, the tip speed is limited to approximately 78m/s.

3.3. Results of Annual Output Power

The Weibull distribution constants, k (dimensionless) and c (m/s) are related to feasibility study of wind potential of Haddadeh region of Semnan province [7] that is considered at height 40m (Table 1.) Output power integration must be divided two parts: before and after the rated speed. A program was written which computes annual output energy that it is equal to 745.5MWh for the modified blade with linear distribution of the blade and 932 MWh for the nonlinear blade profile.

3.4. Results of Economical Evaluation

As mentioned in the previous sections, the current cost of designed wind turbines is approximately $1500 per 1 kW power generated. Other initial costs including installation, transportation, custom fee and grid integration is assumed about 40% of the turbine cost.

Total cost can be reduced by10% if the modified wind turbine with linear blade is used; therefore, we may adopt initial cost to be reduced from 40% to 30% here. Useful life of the system is 15 years. Annual operation and maintenance costs plus the land rent come to 6% of the turbine cost [33]. Also the real rate of interest, i, may be taken as 20%. By the above assumption installation cost and total initial

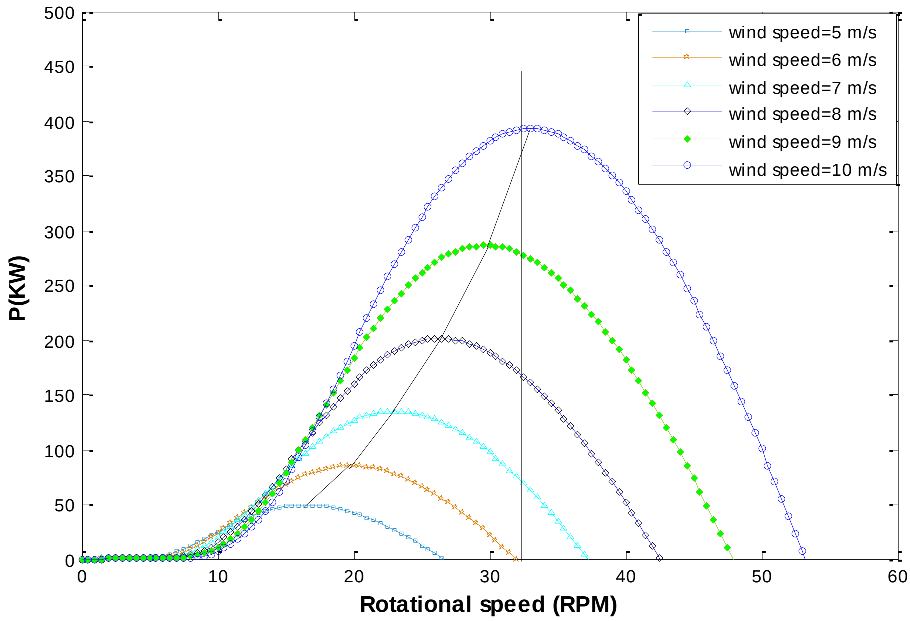


Fig. 10. Output power versus rotational speed (constant rotational speed and variable speed control system)

investment for the modified 200 kW wind turbine calculated as following:

$$\text{Installation cost} = 300000 \times \frac{30}{100} = 90000\,\$$$

$$\text{Total initial investment} = 300000 + 90000 = 390000\,\$$$

For the original turbine, total initial investment cost is 420000$. Therefore, the cost of 1 kW h of electricity produced by the modified wind turbine would be

$$C = \frac{390000}{8760 \times 15}\left(\frac{1}{200 \times 0.43}\right)\left[1 + 0.06\left(\frac{(1+0.2)^{15} - 1}{0.2(1+0.2)^{15}}\right)\right]$$
$$= 0.045\$/kWh\ .$$

While for the original blade with the capacity factor of 0.54, the cost value C is calculated to be 0.039 $/kWh; in Iran, the electrical power production by any renewable energy is valued $0.12 per kWh as instructed by renewable organization of Iran (SUNA).

According to power production from the HAWT at the mast height of 40 meters in Haddadeh region of Semnan province, the annual electricity production is 745.5 MWh for the modified linear blade turbine whilst it is equals to 932 MWh for the original optimum wind turbine. Based upon calculations, the electricity production costs is 4.8 cents per kWh which provides a net benefit of 7.2 cents per kWh for the modified linear wind turbine while a net benefit of 8.1 cents per kWh is obtained if the original optimum nonlinear wind turbine is used.

Therefore, the scenario of reducing initial costs with 1 cents deficit has no economic gain and is not recommended unless the manufacturing and technological shortcoming cannot be avoid.

Table 1. Important parameters in aerodynamic design

Weibull distribution constants	m/s	k=1.567 , c=6.5 224
Rated power	W	200 000
Rated wind speed	m/s	8
Aerodynamic power coefficient		0.49
Number of blade: B		3
Design tip speed ratio		8.9 327
Mechanical and electrical efficiency		0.8
Radius of rotor	m	23
Design attack angle	degree	10

4.Conclusion

To assist moving faster towards the world of carbon free and to withstand against increasing CO2 emission into our environment and to rectify the problem ofglobal warming, imminent international efforts and collaborations are required to further develop and enhance use of wind energy and other renewable resources. This work attempts to address some issues and to preliminary design a site specific 200 kW wind turbine based on manufacturing and economical capabilities and also power demands in the province of Semnan. This study has focused on economic feasibility of reducing some technological barriers on making rotor blades of a 200 kW HAWT by using linear approximation on the blade chord length and twist angle distribution. The aerodynamic design aspects of the wind turbine and the power output are assessed when the modified linear and nonlinear designed wind turbines are installed in Haddadeh in the province of Semnan. The annual yield of wind energy and the cost of produced electricity are evaluated for both the linear and nonlinear designs of the 200 kW HAWT. In the original nonlinear design, the overall power coefficient C_P reached the value of 0.49 whereas in design with linear blades the value of 0.36 is merely obtained. A considerable reduction in output power of about 187 MWh is observed annually when the linear simplified aerodynamic design is used to compensate manufacturing shortcomings. Our calculations indicate that a net benefit of 8.1 cents per kWh is achievable for the original wind turbine while this reduces to a net benefit of 7.2 cents per kWh when the linear design is adopted. Therefore, this clearly shows that unless technological barriers cannot be avoided the scenario of reducing initial costs is not recommended.

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