AERODYNAMIC DESIGN OF A 300 KW HORIZONTAL AXIS WIND TURBINE

M. Mirhosseini[1], M. Alaian, A. Sedaghat, A.A. Alemrajabi

Department of Mechanical Engineering, Isfahan University of Technology,
Isfahan 84156-83111, Iran

Abstract

In this research, Blade Element Momentum theory (BEM) is used to design a HAWT blade for a 300 kW horizontal axis wind turbine. The airfoil is Risø, produced by RISØ National Laboratory, Denmark, for a class of 300KW wind turbines. 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. 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 versus rotor radius for BEM results.

Keywords: Horizontal axis wind turbine (HAWT); Aerodynamic design; BEM theory; chord; twist.

1. Introduction

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 95 815 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 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 558 000 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].

2. Aerodynamic of a Horizontal Axis Wind Turbine (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, Cp_{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

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[1] E-mail: m.mirhosseini@me.iut.ac.ir

were solved by 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 multiple objectives, namely maximum AEP and minimum COE, 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 multi-airfoils 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 300 kW wind turbine. The airfoil is RISØ, produced by RISØ National Laboratory, Denmark, for a class of 300KW wind turbines. Desirable properties of this airfoil are related to enhancement of aerodynamic and structure interactions.

2.1. Rotor Design for 300 KW and Pitch Controlled Turbine

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]:

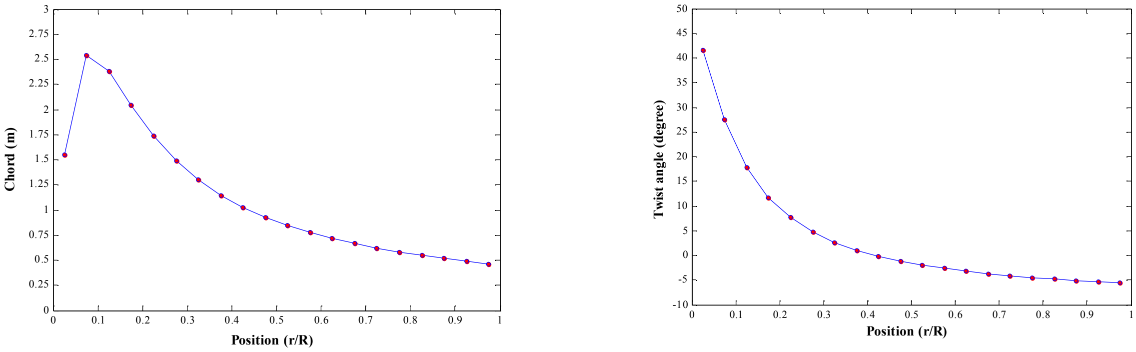
1. Optimizing the power output of the wind turbine.
2. Regulating input mechanical power to avoid exceeding the design limits. Above rated wind speed, pitch angle control provides an effective way to control the aerodynamic power and loads produced by the rotor.
3. Minimizing vibrations and fatigue loads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

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. 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 is 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‹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 1.6×106. 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.

3. Results and Discussion

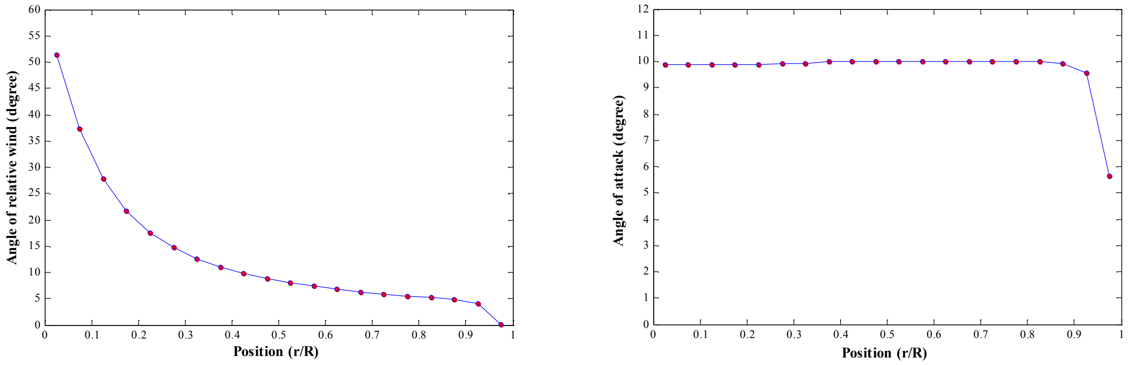
Figure1a shows that chord length distribution from the BEM analysis to a maximum value of 2.5 metere at nearly 10 percent from the blade root to the value of nearly 0.25 meteres at tip. Figure 1b shows the twist angle distribution across the blade length varying from 40 degrees in root to nearly –5 degrees near tip of blade. The negative twist angle causes the elements of blade tip had a proper attack angle in slow startup wind speeds. Although in high wind speeds, stall probably occur 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.



(a) (b)

Figure 1. a) Chord length distribution; b) Twist angle distribution.

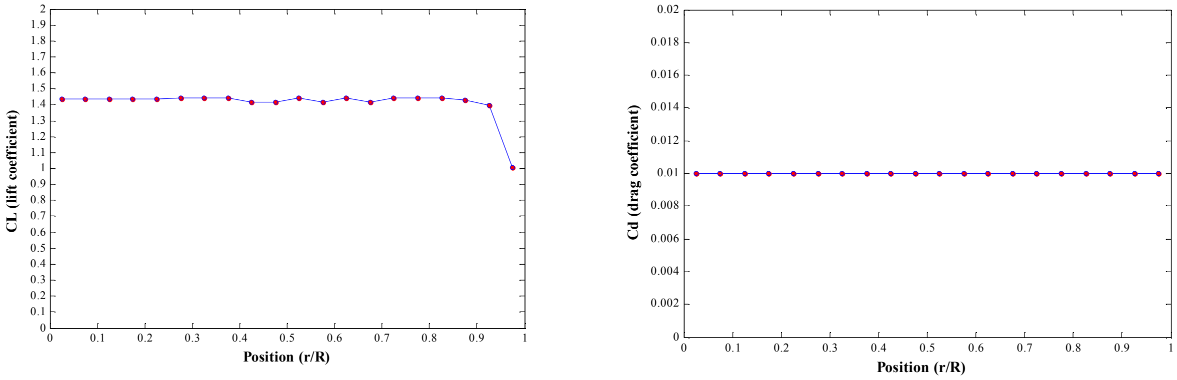
In Figure2a, the angle of relative wind is varying from 52 degrees in root to 0 degrees at tip producing the much desirable angle of attack value of 10 degress as shown in Figure 3b. The angle of attack, α, is constant for the full length of the blade except from 90 percent near to tip that rapidly decreases to values of 6 degrees due to tip losses.



(a) (b)

Figure 2. a) Angle of relative wind; b) Angle of attack.

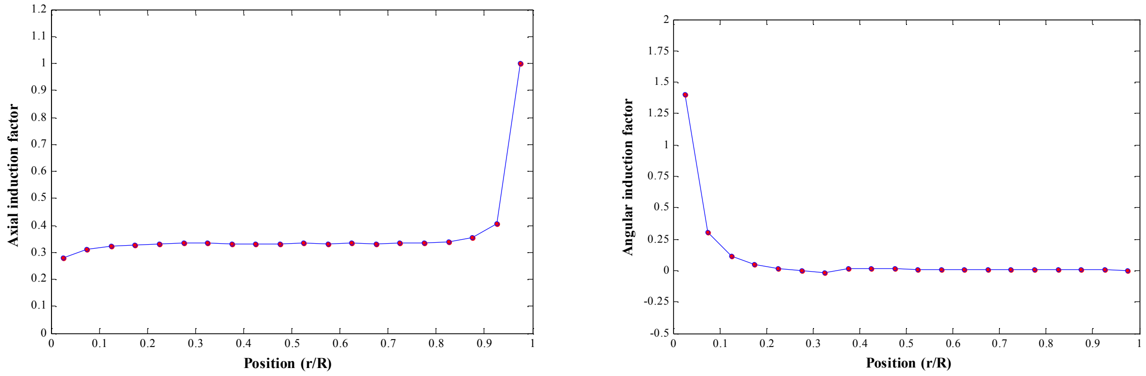
Figure 3a demonstrates that for any angle of attack, Cl is almost constant to the value of 1.43 except at the tip which it drops to the value of 1.0. Drag coefficient distribusion is shown in Figure 3b which exhibit a constant value of 0.01 everywhere. This provides a lift to drag ratio of 143 nearly for 90 percent of the length of blade a very desirable value for wind turbine blades.



(a) (b)

Figure 3. a) Lift coefficient; b) Drag coefficient.

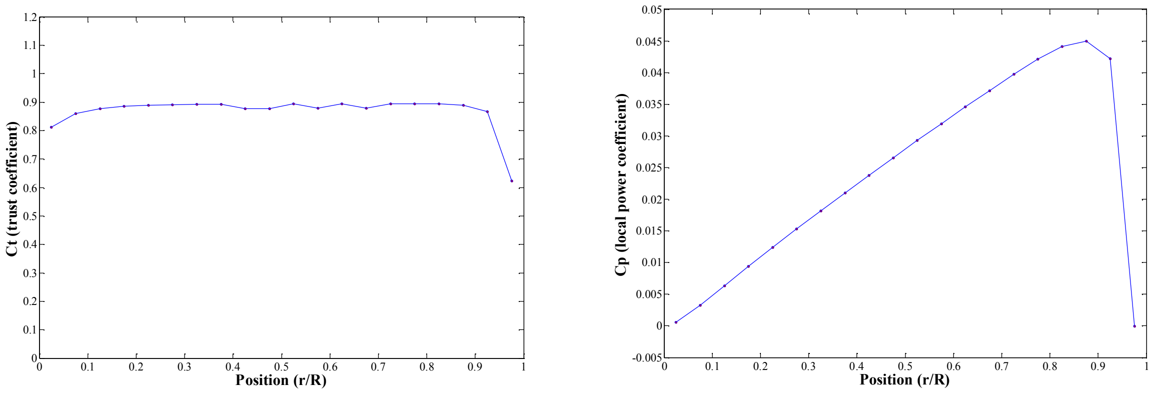
Figure 4a shows that the axial induction factor is about 1/3 on most of the blade length (0.125<r/R<0.875) which increases to a value about one near tip of the nonlinear blade. However, the angular induction factor attain high values near the root (1.3) which reduces to zero at about 10 percent away from the root of blade.



(a) (b)

Figure 4. a) Axial induction factor; b) Angular induction factor.

Figure 5a shows the local thrust coefficient, Ct, which is almost equals to the constant value of 0.9 except at the blade tip that decreases to 0.6. Figure 6b shows the power coefficient for the rotor blade which possess its maximum near tip at 90 percent of the blade length.



(a) (b)

Figure 5. a) Trust coefficient; b) Local power coefficient

Referring to Figure6, it is observed that Cp 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 $\lambda=8.9327$ that in linear case changes and translates to the left side and causes the total power coefficient is decreased.

According to Figure7, a third degree polynomial curve as a function of U is obtained (the values of Cp remain constant at maximum points before reaching to Urated. The power control regions of wind turbine are shown as a function of wind speeds, its results are shown in Figure 8. Clearly, the primary predicted wind rotor output power at the rated power is about 246 kW, which is larger than the rated power (300 kW) of this HAWT, the difference between values is due to electrical and mechanical losses.

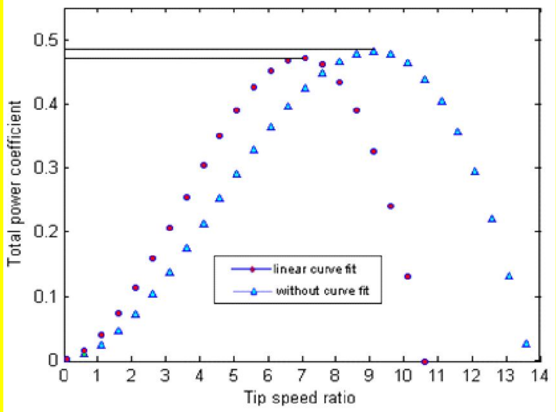


Figure6. Power coefficient versus λ

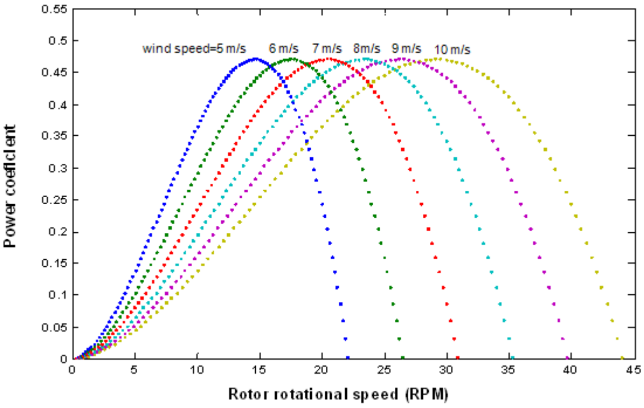


Figure 7. power coefficient versus rotor rotational speed

Figure 7 shows the power coefficient versus the rotor rotational speed with linear approximation for chord and twist distributions. This figure for six wind speeds such as 5-10 (m/s) is shown. According to Urated=8(m/s) and putting it in above equation, P=196 794.78 W is obtained (almost equal to rated power of 300 KW, HAWT), namely that more than the mentioned rated speed, the power curve is shown as a constant value which is equal to power 300 KW. It emphasizes correct solution method that is obtained from linear.

Thus, the predicted aerodynamic characteristics of the mentioned 300KW HAWT are reasonable and reliable. Figure10 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 the case with constant rotational speed and variable speed is shown. 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, in other words running at a fixed rotational speed, therefore 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 Figure10 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 Cp that can be obtained for the applied pitch angle.

The maximal rotational speed of HAWT can be obtained as Ωmax=78/R=3.39 rad/s (ωmax= 32.38 rev/min). By considering the behavior of DFIG it is supposed that ωmax/ωmin is 2.2, and therefore the lowest rotor rotation speed is ωmin=14.72 rev/min and Ωmin=1.54 rad/s. Also the maximal design wind speed is Vmax=78/λD=8.73 m/s and the minimum design wind speed is Vmin=ΩminR/λD=3.97 m/s. Between Vmax and Vmin HAWT operates at optimum design point. Therefore in this case the turbine is equipped with an asynchronous generator forcing the blades to rotate at the constant ωmax= 32.38 r/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.

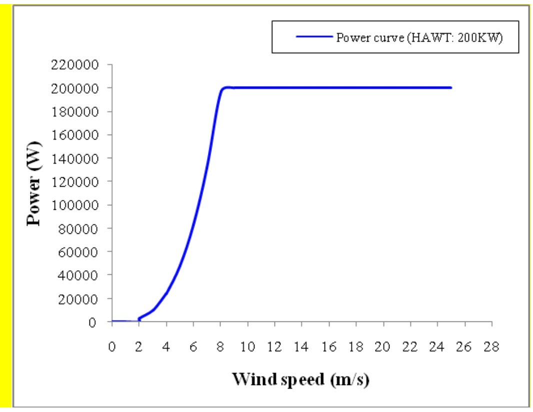


Figure 8. Power curve of the linearized blades 200 KW wind turbine

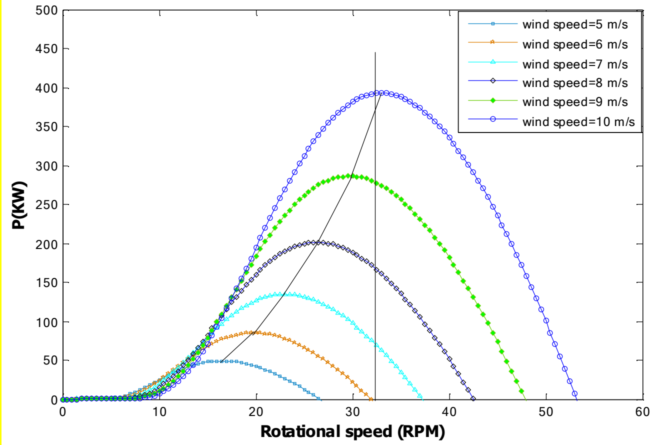


Figure9. Output power versus rotational speed (Constant rotational speed and variable speed control system)

4. Conclusion

The purpose of this study is to find an optimized aerodynamic design method based on BEM method which maintains ease of manufacturing. 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. Also in this paper, tip speed ratio (TSR) choosing for HAWT was investigated from another viewpoint. The overall power coefficient CP reached a value of slightly above 0.49 whereas in design with linear blades is merely obtained the value of 0.36. More results have indicated that a considerable reduction in the power output occurs when the linear simplified aerodynamic design is used to decrease manufacturing costs. Also in this study the pitch control system was used that is the most common methods to control the generated wind turbine rotor power and the corresponding annual power generation for the province of Semnan using a simplified linear rotor was evaluated.

References

[1] Wenzhi L, Fuhai ZH, Jianxin W, and Changzeng L, “3D Modeling Methods of Aerodynamic Shape for Large-Scale Wind Turbine Blades”, *International Conference on Information Technology and Computer Science*, 2009, IEEE Conference; DOI 10.1109/ITCS.2009.10; P. 7-10.
[2] Johansen J, Madsen HA, Gaunaa M, and Bak C, “Design of a Wind Turbine Rotor for Maximum Aerodynamic Efficiency”, Wind Energy. 12, 261–73 (2009).
[3] Schreck SJ, and Robinson MC, “Horizontal Axis Wind Turbine Blade Aerodynamics in Experiments and Modeling”, IEEE Transactions Energy convers. 22(1), 61-70 (March 2007).
[4] Dong L, Liao M, Li Y, Song X, and Xu K, “Study on Aerodynamic Design of Horizontal Axis Wind Turbine Generator System”, *International Conference on Energy and Environment Technology*, 2009, IEEE Conference; DOI 10.1109/ICEET.2009.208; p. 841-4.
[5] Madsen, H.A. “A CFD analysis of the actuator disc flow compared with momentum theory results”, *Proceedings of the 10th Symposium on Aerodynamics of Wind Turbines*, IEA Joint Action, Edinburgh, 1996, 109–124.
[6] Madsen HA, and Rasmussen F, “A Near Wake Model for Trailing Vorticity Compared with the Blade Element Momentum Theory”, Wind Energy. 7, 325–41 (2004).
[7] Griffiths, R.T. “The effect of airfoil characteristics on windmill performance”, Aeronaut J. 81(7):322-6 (1977).
[8] Manwell, J. “Wind energy explained: theory, design and application”, *John Wiley & Sons Inc*, 83-138 (2002).