

AERODYNAMIC DESIGN OF A 300 KW HORIZONTAL AXIS WIND TURBINE

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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 [1]. 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[2].

Semnan province is 95 815 km². 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 [3]. 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 [4]. 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 [5]. Detailed statistical study of wind at 10m, 30m and 40m height in Semnan province is presented in [6].

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 [7]. 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 [8] initiated the calculation of the optimum windmill by making the power integral equation stationary. The resulting implicit relations between the velocity induction factors were

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solved by an iterative procedure. The detailed design of a wind turbine was relevantly described to deal models of rotor aerodynamics and optimization techniques [9-12]. 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 [12] 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 [13] 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 [14] 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 [15]. Jureczko et al. [16] 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 [17]. Dong et al. [18] 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. [19] 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. [20] 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 [21-23]:

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 [24]. 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 [25]. 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.

3. Results and Discussion

Figure 1a shows that chord length distribution from the BEM analysis to a maximum value of 2.5 meter at nearly 10 percent from the blade root to the value of nearly 0.25 meters 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.

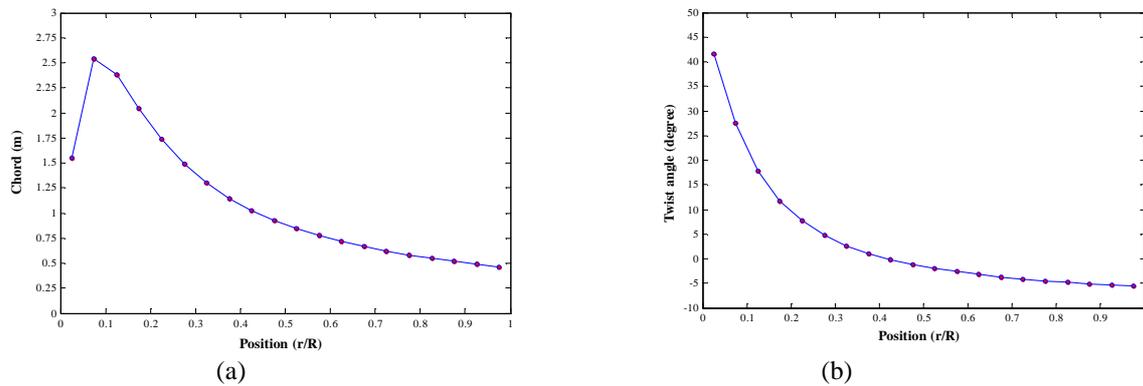


Figure 1. a) Chord length distribution; b) Twist angle distribution.

In Figure 2a, 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 degrees 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.

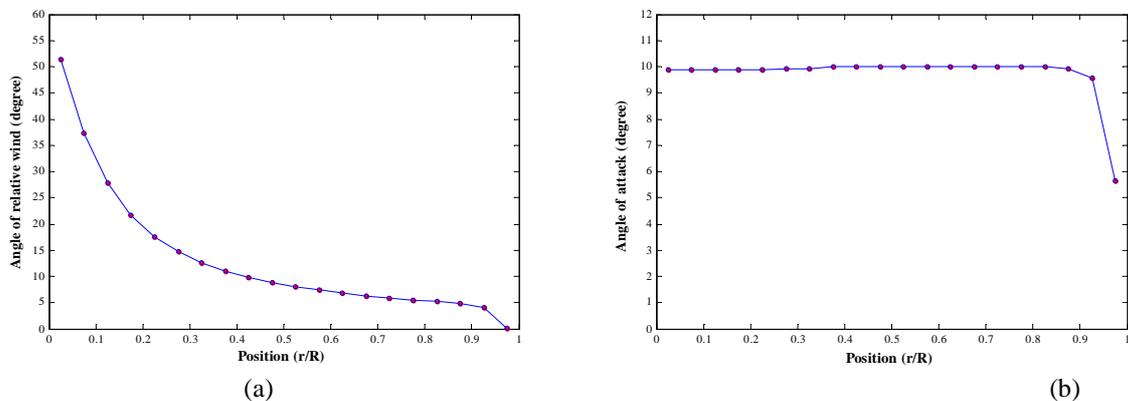


Figure 2. a) Angle of relative wind; b) Angle of attack.

Figure 3a demonstrates that for any angle of attack, C_l is almost constant to the value of 1.43 except at the tip which it drops to the value of 1.0. Drag coefficient distribution 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.

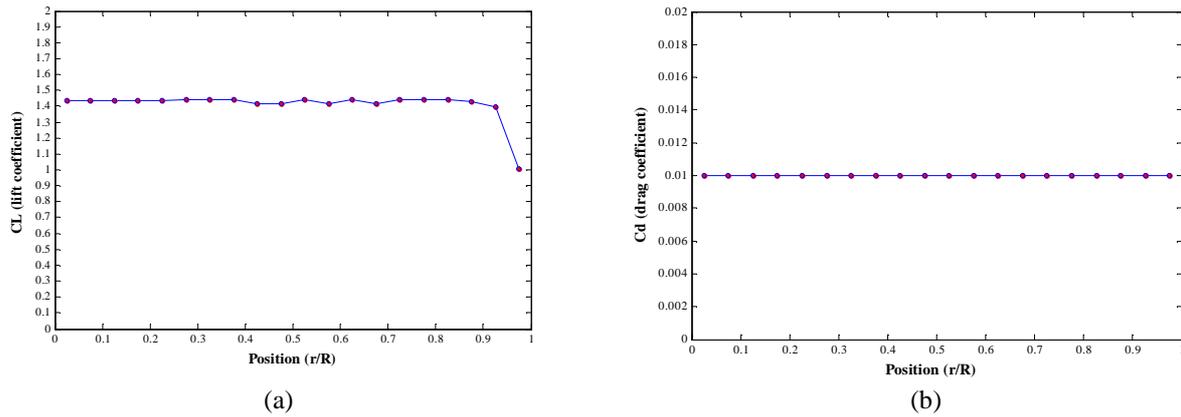


Figure 3. a) Lift coefficient; b) Drag coefficient.

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.

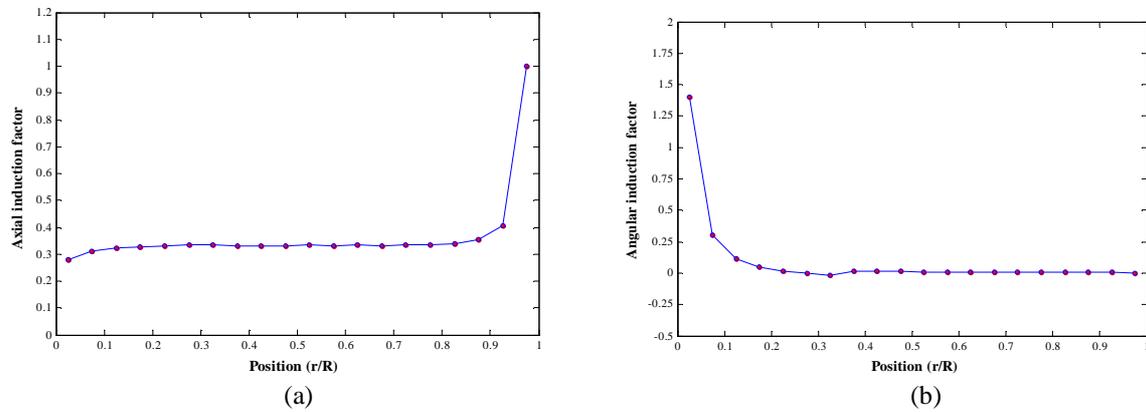


Figure 4. a) Axial induction factor; b) Angular induction factor.

Figure 5a shows the local thrust coefficient, C_t , 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.

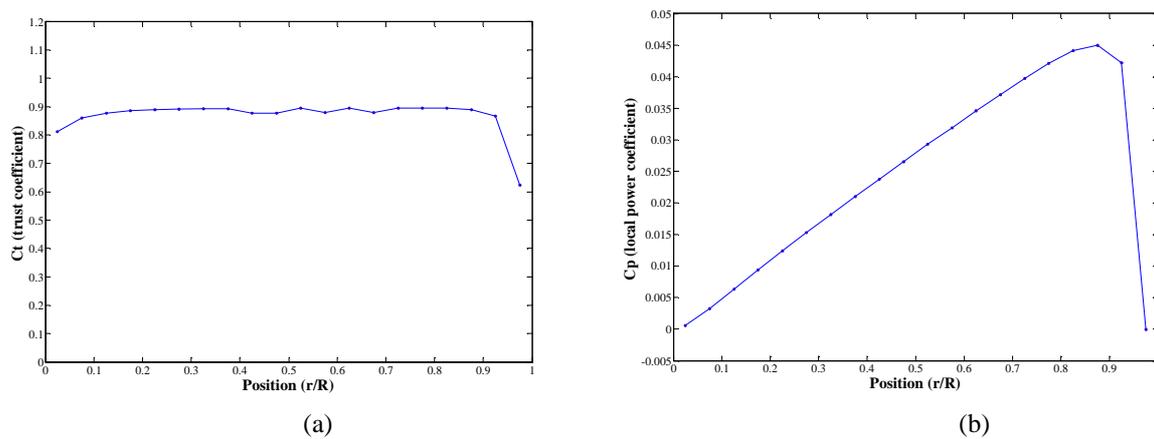


Figure 5. a) Trust coefficient; b) Local power coefficient

Referring to Figure6, it is observed that C_p increases with λ up to its optimum value, then it decreases with a quickly rate.

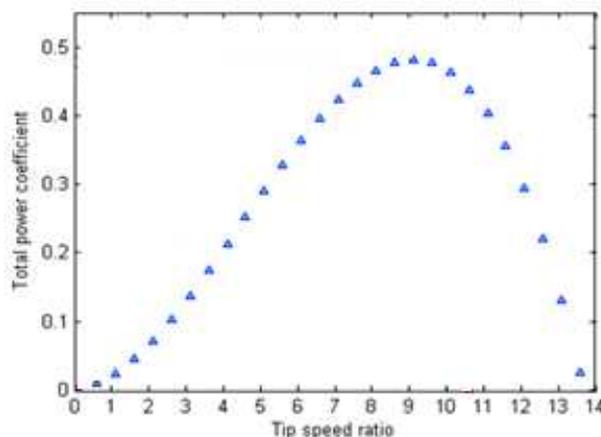


Figure 6. Power coefficient versus λ

4. Conclusion

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References

- [1] News letter from Iranian society of solar energy. A report on the largest wind turbine in Germany with a capacity of 4.5MW; 2003.
- [2] Kazemi Karegar H, Zahedi A, Ohis V, Taleghani G, and Khalaji M, "Wind and solar energy development in Iran". Centre of Renewable Energy Research and Application, North Amir Abad, Tehran/Iran; 2006.
- [3] Iran chamber society [Internet]. [Cited 2011 Feb 12]. Available from: http://www.iranchamber.com/provinces/25_semnan/25_semnan.php
- [4] Irano-British Quarterly Magazine No.25 [Internet]. [Cited 2011 Jan 18]. Available from: <http://ebookbrowse.com/semnan-pdf-d50786496>
- [5] Semnan Meteorological Organization. <http://www.semnanmet.ir>
- [6] Mirhosseini M, Sharifi F, and Sedaghat A, "Assessing the wind energy potential locations in province of Semnan in Iran" J. Renew Sustain Energy Rev. 15, 449–59 (2011).
- [7] Morgan C.A, Garrad A.D, editor. Milborrow D.J, "The Design of Optimum Rotors for Horizontal Axis Wind Turbines, Wind Energy Conversion", *Proceedings of 1988 Tenth BWEA Wind Energy Conference*, Mechanical Engineering Publications Ltd. 1988, London, P. 143–7.
- [8] Glauert H., "Aerodynamic theory". In: Durand WF, editor. 4th Vol. Division L. Airplane propellers, chapter XI. Berlin, 1935, pp. 324–30 (reprinted New York: Dover; 1963).
- [9] Belessis M.A, Stamos D.G, and Voutsinas S.G, "Investigation of the Capabilities of a Genetic Optimization Algorithm in Designing Wind Turbine Rotors", *Proceedings of European Union Wind Energy Conference and Exhibition*, 1996, Goteborg, Sweden; p. 124–7.
- [10] Selig M.S, and Coverstone-Carroll V.L, "Application of a Genetic Algorithm to Wind Turbine Design" ASME J. Energy Resour Technol. 118 (1), 22–28 (1996).
- [11] Giguere P, Selig M.S, Tangler J.L, "Blade Design Trade-Offs Using Low-Lift Airfoils for Stall-Regulated HAWTs", NREL/CP-500-26091, 1999, National Renewable Energy Laboratory, Golden, CO.
- [12] Fuglsang P, and Madsen H.A, "Optimization Method for Wind Turbine Rotors" J. Wind Eng Ind Aerodyn. 80, 191–206 (1999).
- [13] Fuglsang P, and Thomsen K, "Site-specific design optimization of 1.5–2.0 MW wind turbines" J. Solar Energy Eng. 123, 296–303 (2001).
- [14] Benini E, and Toffolo A, "Optimal Design of Horizontal-Axis Wind Turbines Using Blade-Element Theory and Evolutionary Computation" J. Solar Energy Eng. 124, 357-63 (2002).
- [15] Tempel J.V.D, and Molenaar D.P, "Wind turbine structural dynamics" Wind Eng. 26 (4), 211–20 (2002).

- [16] Jureczko M, Pawlak M, and Mezyk A, "Optimisation of wind turbine blades" *J. mater Process Technol.* 167, 463–71 (2005).
- [17] Khalfallah M.G, and Koliub A.M, "Suggestions for improving wind turbines power curves" *Desalination.* 209, 221-9 (2007).
- [18] 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.
- [19] 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.
- [20] Xudong W, Shen W.Z, Zhu W.J, Sørensen J.N, and Jin C, "Shape Optimization of Wind Turbine Blades" *Wind Energ.* 12, 781–803 (2009).
- [21] Suryanarayanan S, and Dixit A, "Control of large wind turbines: Review and suggested approach to multivariable design", *Proceedings of the American Control Conference*; 2005, Portland, USA, p. 686-90.
- [22] Burton, T., Sharpe, D., Jenkins. N., and Bossanyi. E., "Wind energy handbook", John Wiley & Sons Ltd, Chichester,UK (2001).
- [23] DNV/Risø. "Guidelines for design of wind turbines". 2nd ed. Jydsk Centraltrykkeri, Denmark, 2002.
- [24] Bertagnolio F, Sørensen N, Johansen J, Fuglsang P. Wind Turbine Airfoil Catalogue. RISØ National Laboratory, Roskilde, Denmark, 2001 Aug.
- [25] Fuglsang P, Antoniou I, Sørensen NN, Madsen HA. Validation of a wind tunnel testing facility for blade surface pressure measurements. RISØ-R-981(EN), RISØ National Laboratory, Denmark.