Analysis of Wind Energy Potential and Optimum Wind Blade Design for Jamshoro Wind Corridor

Umaid Ali Syed, Rafiullah Khan, Athar Masood

To cite this version:
Umaid Ali Syed, Rafiullah Khan, Athar Masood. Analysis of Wind Energy Potential and Optimum Wind Blade Design for Jamshoro Wind Corridor. Mehran University Research Journal of Engineering and Technology, Mehran University of Engineering and Technology, Jamshoro, Pakistan, 2017, 36 (4), pp.781-788. <http://publications.muet.edu.pk/index.php/muetrj/article/view/22/14>. <hal-01691342>

HAL Id: hal-01691342
https://hal.archives-ouvertes.fr/hal-01691342
Submitted on 23 Jan 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Distributed under a Creative Commons Attribution 4.0 International License
Pakistan is facing energy crisis since last decade. This crisis can be effectively handled by utilizing alternative energy resources. Pakistan has a huge wind energy potential of about 50,000 MW. The contribution of coastal area of Sindh, Pakistan in the total wind energy potential is about 43,000 MW. The Jamshoro wind corridor has the highest wind potential of all coastal areas of Sindh. In this paper a wind blade design has been developed and optimized for Jamshoro wind corridor. The theoretical blade design include the airfoil selection, appropriate chord length selection and optimization of twist angle. The designed blade has been analyzed using Q-blade. Considering the Jamshoro wind conditions, blade of around 43 meters have been designed and optimized theoretically. Then the theoretical design is also been checked and verified in Q-blade. Theoretical optimization includes using different combinations of NACA profiles and using exhaustive iterative method to get optimized twist angle. This ensures the design with maximum power output with respect to wind speed of Jamshoro. For low wind speeds, theoretical results and simulated results in Q-blade were almost same but for high wind speeds, results were significantly different due to limitation of iterations in theoretical design.

Key Words: Wind Blade, Blade Element Theory, Q-Blade, Wind Energy Potential.
The main focus of this paper is to design an optimum wind blade for the Jamshoro wind corridor that can produce maximum power output and this can only be achieved when it can harness maximum wind energy. Fig. 2 shows steps to design an optimum wind blade. Equations used for optimization of twist angle and chord length distributions are have been deduced from BEM (Blade Element Momentum) theory[4]. Different blade profiles have been analyzed and then combination of best blade profiles have been used and then verified in Q-blade.

2. BLADE DESIGN PROCEDURE

Following are the steps for designing the wind turbine blade [5]:

(1) Power output from wind turbine can be calculated as follows:

$$\text{P} = C_p \eta 0.5 \rho \pi R^2 V^3$$  (1)

Where $P$ is the power output, $C_p$ is performance coefficient, $\eta$ is the mechanical and electrical efficiencies, $R$ is the tip radius, $V$ is the wind velocity.

---

(a) MONTHLY AVERAGE WIND SPEEDS (M/S) FOR DIFFERENT STATIONS IN SINDH AT 50M [3]

(b) MONTHLY AVERAGE WIND POWER DENSITY (WATT/M²) FOR DIFFERENT STATIONS IN SINDH [3]

FIG. 1. MONTHLY AVERAGE WIND DATA FOR DIFFERENT STATIONS IN SINDH

FIG. 2. STEPS FOR DESIGNING OF AN OPTIMUM WIND TURBINE BLADE
The value of Power Coefficient \((C_p)\) is being set by Betz limit which sets an upper limit of 0.59 of the theoretically achievable energy from the available wind energy. Normally power coefficient \((C_p) = 0.4\) [6-7].

\(\eta\) can be assumed around 0.9 because it accounts to losses occurred in mechanical components e.g. generator, gearbox etc. of wind turbine [8].

Tip speed ratio \((\eta)\) is normally selected from 6-9 as it has vital role in converting kinetic energy into electrical energy [9-10].

Number of blades is to be selected from Table 1 [11]. It has the vital role in maintaining the geometrical stability of the blade.

After selecting number of blades, optimum airfoil is to be chosen. Optimum airfoil should have high lift to drag ratio as well as it ensures stability of the blade. That’s the reason thick airfoils are being used near hub and thin airfoils are used near tip.

After selecting airfoils, aerodynamic conditions for each airfoil will be selected. It is common to consider 80\% of the \(C_L\) (airfoil lift coefficient) for calculating optimized twist angle for each section [12].

After selecting airfoil aerodynamic conditions, blade is divided into 10-20 sections [13]. Each section has got its own airfoil so individual section can be optimized.

\[
C = \left(\frac{16 \pi}{B C_L}\right) \sin^2 \left(\frac{1}{3 \tan^{-1} \left(\frac{R}{\lambda a}\right)}\right)
\]

(2)

\[
\rho V^2 \Re = \frac{L}{V} = \rho VL/\mu
\]

(3)

\[
\beta = 90^\circ - \frac{2}{3} \tan^{-1} \left(1/\lambda\right)
\]

(4)

\[
a = \left(1 + \frac{4 \cos^2 \beta}{C_L \sin \beta}\right)^{-1}
\]

(5)

\[
a' = \left(\frac{1 - 3a}{4a - 1}\right)
\]

(6)

\[
a' = \left[\frac{\sigma'CL}{4\lambda \cos \beta}\right] \left(1 - a\right)
\]

(7)

(10) Iterative process is being adopted for twist angle. Following are the steps.

| TSR | 1 | 2 | 3 | 4 | >4 |
|-----|---|---|---|---|----|
| No. of Blades | 8-24 | 6-12 | 3-6 | 3-4 | 1-3 |

**TABLE 1. TSR AND NUMBER OF BLADES**
(a) Calculate solidity ($\sigma'$) and $\beta$.
(b) Choose appropriate $C_L$ and $C_D$ for the angle of incidence.
(c) Calculate $a$ and $a'$ again until $\Delta a$ and $\Delta a'$ converges.

3. WIND TURBINE BLADE DESIGN FOR JAMSHORO

The input parameters for the blade design for Jamshoro are presented in the following section. These parameters will be used to compute theoretical design. Later, simulations in Q-blade will be performed to validate the design.

3.1 Input Parameters

In July Jamshoro has got the highest wind speed of 13.9 m/s and in January lowest wind speed of 5 m/s. Keeping in view the above conditions, following parameters were selected for the design:

1. Power Coefficient ($C_p$) = 0.4 [14-15].
2. Efficiency ($\eta$) = 0.9 [16-17].
3. Tip speed ratio ($\lambda$) = 7 [18-19].
4. 3 blades have been chosen as per Table 1.
5. After analyzing their aerodynamic characteristics i.e. lift coefficients and lift to drag ratio, three NACA profiles i.e. NACA 4412, 4415 and 4418 have been selected with their lift coefficients as 1.45, 1.45 and 1.48, respectively.
6. Each section has its own airfoil. Normally 80\% of the airfoil lift coefficients is used to calculate blade twist. In our case for NACA 4418 it is 1.18 and for NACA 4415 and NACA 4412 it is 1.16 [20].

(7) Blade consists of 17 sections[21].
(8) Total blade tip radius is 43.25 for wind speed of Jamshoro ranging from 5-13.9 m/s, to get maximum power output. If small radius such as 3 or 5 meter is selected then there is no power output at wind speed of 5 m/s which is unacceptable due to the fact that there will be no power output for 6 months (January, February, March, October, November and December). But if radius is 43.25 meter then we get good power output of 162 KW from one wind turbine.

3.2 Theoretical Design of Blade

Power output of the blade was calculated using equation 1 by substituting $C_p = 0.4$, $\eta = 0.9$, $R = 43 m$. For wind speed of 5 m/s, the power output was 161.9 KW. For wind speed of 13.9 m/s, the power output was 3.48 MW. The design Table 2 summarizes the results of the theoretical blade design.

First four sections are just used for strengthening the blade. The calculation for 5th section is presented in Appendix-I. Calculation results for all sections are summarized in Table 3.

4. THEORETICAL DESIGN VERIFICATION USING Q-BLADE

While simulating the blade design in Q-Blade software, first of all NACA profiles were declared as shown in Fig. 3. In the second step the section wise blade profile was created. After that the $C_{L}/C_{D}$ versus angle of Attack graphs of each section of blade was simulated. Fig. 4 shows the $C_{L}/C_{D}$ versus Angle of Attack graphs for 5th section of blade. The maximum value of $C_{L}/C_{D}$ occurred for 5th section and it was equal to 140 at $\alpha=6^\circ$. For other section this value was decreased and minimum value occurred for 17th section and it was equal to 100 at $\alpha=6^\circ$. The power coefficient versus tip speed ratio graph was obtained by
Q-blade simulation and is shown in Fig. 5. Power vs Wind Speed graph in Q-blade simulation is shown in Fig. 6.

The theoretical calculation revealed a power output value of 161.9 KW at 5m/s wind speed. The Q-blade simulation results give slightly higher power output of 163KW. Also simulated power output for 13.9m/s wind speed is 4MW but theoretical power output is 3.48MW. The power difference between theoretical and simulated design is small for minimum wind speed of 5m/s. On the other hand, the power difference between theoretical and simulated design is significant for maximum wind

| No. | Pos (m) | Twist Angle | Chord Width (m) | Aerofoil | Reynold Number (million) |
|-----|---------|-------------|-----------------|----------|--------------------------|
| 1.  | 0       | 6.4         | 2.5             | Circular Foil | D=1.2                  |
| 2.  | 1.5     | 6.4         | 3               | Circular Foil | D=1.2                  |
| 3.  | 3.5     | 6.4         | 4               | Circular Foil | D=1.2                  |
| 4.  | 6.5     | 6.4         | 5               | Circular Foil | D=1.2                  |
| 5.  | 8       | 6.4         | 5.21            | NACA-4418 | 0.172                  |
| 6.  | 11      | 6.5         | 4.4             | NACA-4418 | 1.45                   |
| 7.  | 14      | 6.65        | 3.7             | NACA-4418 | 1.22                   |
| 8.  | 17      | 5.95        | 3.21            | NACA-4418 | 1.06                   |
| 9.  | 20      | 5.48        | 2.81            | NACA-4418 | 0.92                   |
| 10. | 23      | 5.9         | 2.55            | NACA-4415 | 0.84                   |
| 11. | 26      | 4.8         | 2.29            | NACA-4415 | 0.75                   |
| 12. | 29      | 3.8         | 2.08            | NACA-4415 | 0.68                   |
| 13. | 32      | 2.7         | 1.9             | NACA-4412 | 0.62                   |
| 14. | 35      | 2.1         | 1.75            | NACA-4412 | 0.57                   |
| 15. | 38      | 1.7         | 1.62            | NACA-4412 | 0.53                   |
| 16. | 41      | 1           | 1.51            | NACA-4412 | 0.49                   |
| 17. | 43.25   | 0.5         | 1.43            | NACA-4412 | 0.47                   |

| No. | Pos (m) | Twist | No. | Pos (m) | Twist |
|-----|---------|-------|-----|---------|-------|
| 5.  | 8       | 6.4   | 12. | 29      | 3.8   |
| 6.  | 11      | 6.5   | 13. | 32      | 2.7   |
| 7.  | 14      | 6.65  | 14. | 35      | 2.1   |
| 8.  | 17      | 5.95  | 15. | 38      | 1.7   |
| 9.  | 20      | 5.48  | 16. | 41      | 1     |
| 10. | 23      | 5.9   | 17. | 43.25   | 0.5   |
| 11. | 26      | 4.8   |     |         |       |

TABLE 2. WIND BLADE PROFILE DESIGN FOR DIFFERENT SECTIONS OF THE BLADE

TABLE 3. TWIST ANGLE CALCULATION FOR WIND BLADE DESIGN
speed of 13.9 m/s, this is due to the fact that for simulated design, the Q-blade software uses BEM theory for optimization of the wind blade which changes power coefficient to 0.47. Theoretical and simulated power outputs during different months of the year have been compared in Fig. 7.

The blade designed for the Jamshoro wind corridor has been optimized according to the wind speed data presented in Fig. 1. However, if the wind speed become higher than the maximum observed speed of 13.9 m/s, the corresponding Reynolds number will be higher. In such case the blade should be redesigned. The Reynolds number is given by Equation (3). This equation implies that for higher Reynolds number the cord length should be decreased accordingly, resulting in dull blade. The variation of chord length with wind energy is illustrated in Fig. 8. It has been shown that chord length decrease linearly with wind velocity.

FIG. 3. SHOWING WIND BLADE IN Q-BLADE HAVING 17 SECTIONS

FIG. 4. CD/CL VS. ANGLE OF ATTACK FOR DIFFERENT SECTIONS

FIG. 5. POWER COEFFICIENT VS TSR GRAPH

FIG. 6. COMPARISON POWER VS. WIND SPEED GRAPH OBTAINED FROM Q-BLADE SIMULATION

FIG. 7. MONTH WISE THEORETICAL AND SIMULATED POWER OUTPUTS

FIG. 8. ILLUSTRATION OF THE VARIATION OF CHORD LENGTH WITH RESPECT WIND VELOCITY
5. CONCLUSIONS

Wind blade was designed in accordance with BEM theory for wind conditions of Jamshoro. Also basic parameters for wind blade design were identified and analyzed and then using those parameters, theoretical design was prepared and then verified with Q-blade. The theoretical results reveal that for minimum wind speed equal to 5m/s (in January), the power is equal to 161.9KW. For the high wind speed equal to 13.9m/s (in July) the power is 3.48MW. The Q-blade analysis showed that for minimum wind speed of 5m/s power is 163KW. For high wind speed equal to 13.9m/s, the power is 4MW. The power difference between theoretical and simulated design is small for minimum wind speed of 5m/s, In case of maximum wind speed, the difference between theoretical and simulated design is more because Q-blade uses BEM theory for optimization of the wind blade. It has changed the power coefficient to 0.47 that results in higher coefficients.

The design presented in this paper can be validated with HARP which is a MATLAB optimization toolbox. Similarly the optimization can be performed with respect to efficiency using optimization function and optimization algorithms for achieving maximum efficiency. However the efficiency optimization should be performed such that the cost of design is unaffected.

APPENDIX-I. 5TH SECTION ITERATION PROCESS
ACKNOWLEDGEMENTS

The authors highly acknowledge the Dr. Saeed Badshah, and Engr. Mujahid Badshah, International Islamic University, Islamabad, Pakistan, for their valuable discussions in the design process of wind turbine blade.

REFERENCES

[1] State of Industry Report National Electric Power Regulatory Authority, pp. 112, 2014.
[2] Medium Term Development Framework 2005-2010: An Overview by Ministry of Planning, Government of Pakistan, 2005.
[3] Chaudhry, Q.Z., “An Investigation of Wind Power Potential of Gharo, Sindh, Pakistan”, Pakistan Journal of Metrological, Volume 6, No. 11, pp. 1-6, 2007.
[4] Prasad, N., Janakiram, S., Prabu, T., and Sivasubramaniam, S., “Design and Development of Horizontal Small Wind Turbine Blade for Low Wind Speeds”, No. 1, pp.75-84, 2014.
[5] Li, H., and Chen, Z., “Design Optimization and Site Matching of Direct-Drive Permanent Magnet Wind Power Generator Systems”, Renewable Energy, Volume 34, No. 4, pp.1175-1184, 2009.
[6] Adaramola, M., “Wind Turbine Technology: Principles and Design”, CRC Press, 2014.
[7] Ackermann, T., “Wind Power in Power Systems”, John Wiley & Sons Ltd., Volume 140, Chichester, UK, 2005.
[8] Hau, E., “Wind Turbines, Fundamentals, Technologies, Application, Economics”, 2nd Edition, Springer, Berlin, Germany, 2006.
[9] Burton, T., “Wind Energy Handbook”, John Wiley & Sons Ltd., Chichester, UK, 2011.
[10] McCosker, J., “Design and Optimization of a Small Wind Turbine”, Rensselaer Polytechnic Institute, 2012.
[11] Goett, H.J., and Kenneth, W.B., “Tests of NACA 0009, 0012, and 0018 Airfoils in the Full-Scale Tunnel”, 1939.
[12] Mokhtar, A., and Setiawan, J.D., “The Aerodynamics Design of Horizontal Axis Wind Turbine Blade Using Computational Fluid Dynamic”, http://www.academia.edu, 2012.
[13] Claessens, M.C., “The Design and Testing of Airfoils for Application in Small Vertical Axis Wind Turbines”, M.Sc. Thesis, Faculty of Aerospace engineering, Delft University of Technology, November 9, 2006.
[14] Timmer, W.A., “An Overview of NACA 6-Digit Airfoil Series Characteristics with Reference to Airfoils for Large Wind Turbine Blades”, American Institute of Aeronautics and Astronautics, 2012.
[15] Abd Aziz, P.D., “A Simulation Study on Airfoils using VAWT Design for Low Wind Speed Application”, 4th International Conference on Engineering Technology and Technopreneurship, 2014.
[16] Raluca, D.I., Sorin, V., and Mircea, I., “Rotor Design for Vertical Axis Wind Turbines, Suitable for Urbanseashore Environment or Naval Industry Implementation”, International Conference on ISTM , Volume 9, 2014.
[17] Ionescu, R.D., Ioan, S., and Mircea, I., “Forces and Torque Analysis of an Urban Small Power Vertical Axis Wind Turbine (Numerical Results)”, Acta Technica Napocensis-Series: Applied Mathematics, Mechanics, and Engineering, Volume 57, No. 3, 2014.
[18] Naishadh, G.V., and Sathya, NG., “Aero-Structural Design Optimization of Composite Wind Turbine Blade”, Ph.D. Thesis, Embry-Riddle Aeronautical University, 2013.
[19] Aryal, B.U., “Design and Analysis of a Small Scale Wind Turbine Rotor at Arbitrary Conditions”, Rentech Symposium Compendium, Volume 4, September, 2014.
[20] Alish, J., and Saijal, K.K., “Multi-Objective Design Optimization of Wind Turbine Blade using Genetic Algorithm”, International Journal of Engineering Research & Technology, Volume 3, No. 12, pp. 875-882, December, 2014.
[21] Li, H., and Chen, Z., “Design Optimization and Site Matching of Direct-Drive Permanent Magnet Wind Power Generator Systems”, Renewable Energy, Volume 34, pp. 1174–1185, 2009.