DYNAMIC MODELING AND STARTING BEHAVIOR OF A SMALL HORIZONTAL AXIS WIND TURBINE

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ABSTRACT

Small, stand-alone wind turbines are a possible solution to the energy requirements of remote areas in Pakistan. However except for the coastal areas, wind speeds available in various areas of Pakistan are low to medium, especially in the northern areas. It is possible to produce significant power from a small wind turbine at low wind speeds provided the turbine can be started. In this paper "BEM function" and "Aerodynamic function" are used based on the Blade element momentum theory. These Matlab functions calculate the wind turbine blade parameters and aerodynamic forces that will act on wind turbine blades. Pro/E models were then developed on the basis of these parameters. Pro/E models were imported into ADAMS to calculate the output torques. Our analysis shows that most of the starting torque comes from the hub section of the blade. Various changes were incorporated into ADAMS models near the hub region of the wind turbine blade which showed an increase in the staring torque due to an increasein the blade angles and chord lengths. The wind turbine designs for the selected locations of Pakistan were successfully optimizedby improving their starting behavior.

KEY WORDS: *Small wind turbine; Blade element momentum theory; Horizontal axis wind turbine*

INTRODUCTION

Wind turbine is an ancient energy conversion device. In early days, a wind turbine was called a windmill and was used for milling wheat and corns. Today wind turbine is a mature source of energy and is used for the production of electrical energy in various parts of the world.

Large wind turbines can easily be installed at sites where wind speed is sufficiently high. However, for regions where wind speed is low to medium, overcoming the starting inertia of the wind turbine for startup is an issue. In order to start the wind turbine at this low wind speed both its material and profile should be refined for specific wind conditions[1,2]. Small, stand-alone wind turbines are the possible solution for the energy contained by the wind speed in these low wind areas.Changes in the wind turbine blade profile are requiredto increasethe lift force at startup[3]. Altering the blade twist angles and chord lengths changes the angle of incidence of the incoming wind on the wind turbine blade, resulting in change of lift and drag forces on the wind turbine. Exhaustiveamounts of tests at reduced and full scale are needed for evaluating the performance of wind turbine blade profiles. An alternative to experimental testing for performance evaluation of wind turbine profiles is the use of computer simulations. The designed profiles can then be incorporated into existing wind turbines[4].Clausen and Wood[5] tested wind turbine models with an upper power limit of 5 kW. He concluded that there is a need of improving the starting performance of small wind turbines. Singh and Ahmed[6] designed low Reynolds number aerofoil for horizontal axis wind turbine to achieve better startup and low wind speed performances. The lift and drag components of forces were measured at various angles of attack with a dynamometer. The lift coefficient was increased from 0.41 to 1.05 at a Reynolds number of 38,000 with angle of attack in a range of 0-18 degrees.Ahmed and Singh[7] designed low Reynolds number profiles for a wind speed range of 3 to 6 m/s at pitch angles of 15, 18, and 20 degrees to study their performance at the startup. The turbine performed best at a pitch angle of 18 degrees. Habali and Saleh[8] mixed two different airfoils for wind turbine blades having size less than 5 meters. A static proof-load test indicated that the blades could withstand loads 10 times the normal working thrust. A field performance test showed the rotorblade having an average power coefficient of 41.2%.Wichser and Klink[9] carried out performance measurements for 1.5MW turbines with different rotor diameter, cut-in, cut-out, and

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rated speeds at four different sites. Results showed that lower cut-in, cut-out, rated speeds, and larger rotor diameters yield an excess of 15–30% in wind power potential at these sites.

Simulating the performance of wind turbines using computer models has been a very popular method amongst scientists and engineers due to its cost effectiveness. Song and Ni[10] successfully performed dynamic analysis of a wind turbine using a combination of Solid Worksand ANSYS. The results from this study were incorporated in the production of wind turbine blades up to 20kW capacity.Thumthae and Chitsomboon[11]numerically simulated the performance of horizontal axis wind turbines (HAWTs) to determine the optimal angle of attack. Conservationequations were solved in a rotating reference frame wherein the blades and grids were fixed in relation to the rotating frame. The power outputs weremaximum at pitch angles of 4.12°, 5.28°, 6.66° and 8.76° at wind speeds of 7.2, 8.0, 9.0 and 10.5 m/s respectively. The optimal angles of attack were then obtained from the data. A. Sedaghat and Mirhosseini[12] used Blade Element Momentum theory (BEM) to design a HAWT blade for a 300 kW horizontal axis wind turbine. BEM specifies the aerodynamic shape of the blade by obtaining the chord and twist distribution at the assumed tip speed ratio of the blade.Wood and Wright[13], and Bechlyet al.[14]tested two different wind turbine designs each with a rated power of 5 kW, and found that idling period at the startup can be reduced by decreasing the angle of attack. Wood and Ebert[15]explained that increase in the idling time is due to large angles of attack at the start. As the angle of attack decreases slowly at the starting time, the torque is insufficient to start the wind turbine which results in increased idling time. To ease the startup, an increase in the blade angle near the hub needs to be considered.

In the current study ADAMS is used in combination with Pro/E and Matlab to improve the starting behavior of low wind, small HAWTs for feasible sites in Khyber Pakhtunkhwa (KPK).The wind speed available at various locations in Pakistan is slow to medium (less than 7 m/s)[17]. As a common practice, for wind speeds in the range of 1m/s to 6m/s small wind turbines are considered suitable[18]. Chaudry[19] has monitored wind speeds and its directions at various locations of KPK. Amongst these sites, six locations for this research work were selected. The wind speed data from suitable sites of northern areas of Pakistan, available from the work of Chaudhry and Hayat[16], and shown in Table 1 were used for wind turbine designs studied.

In the following section, the computer simulation technique developed for analyzingand modification of existing wind turbine models is discussed.

METHODOLOGY

Aplication of BEM theory requires the sectioning of thewind turbine blade into 'N' number of stations[20]. BEM theory is based on two main assumptions:Firstly, the wind flow at a certain radius from the centre of hub does not affect the flow at an adjacent radius so the forces acting on the individual sections on the blade can be summed up to find the overall forces on the blade. Secondly, the forces acting on various elements of the blade only depends on lift and drag coefficients. The nomenclature of a wind turbine profile is shown in Figure. 1.

In combination with blade element momentum theory, Wood's model[13]was used to suggest suitable wind turbine sizes for selected locations in KPK, and are shown in Table 2.

Table 1: Average wind speeds (m/s) measured at 30m above the Ground at various locations of KPK[16]

Site Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
Nizampur	1.60	2.89	1.53	0.46	0.94	1.58	1.73	1.75	2.462	2.19	1.73	2.06	1.74
Warsak	3.9	4.4	2.3	2.0	2.0	2.5	2.4	1.35	2.0	1.6	1.2	3.0	2.4
Ramatkore	0.75	0.82	2.05	2.84	1.41	2.68	2.09	1.74	2.21	2.27	0.78	0.80	1.70
Lorramiana	5.45	5.45	5.50	3.43	3.28	3.63	2.81	2.81	2.52	2.24	2.98	4.63	3.73
Cherat	4.5	4.8	4.4	4.4	4.4	3.6	3.4	3.5	3.9	3.4	4.1	4.0	4.2
Peshawar	1.2	1.6	1.6	1.4	1.2	0.9	1.3	1.5	1.5	1.0	0.8	0.8	1.23

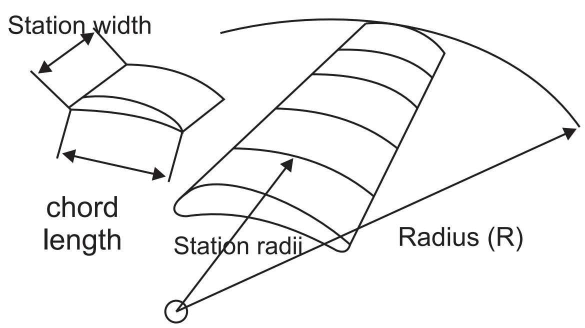

Figure.1 Blade element theory based model

Table 2: Sizes of wind turbines at selected locations of KPK

Location	Average wind speed (m/s)	Size of Turbine (meters)
Cherat	4.20	5
Peshawar	1.23	1
Warsak	2.40	2
Ramatkoore	1.70	1.5
Lorramiana	3.73	2.5
Nizampur	1.74	1.5

Figure 2 shows a flow chart of the methodology adopted to optimize the startup of low speed wind turbines. A code was developed in Matlab for obtaining wind turbine blade parameters and the magnitude and point of application on wind turbine blade. This information was then used to develop 3d models of the wind turbine in Pro/E. Finally dynamic analysis of the wind turbine blades was performed in ADAMS.

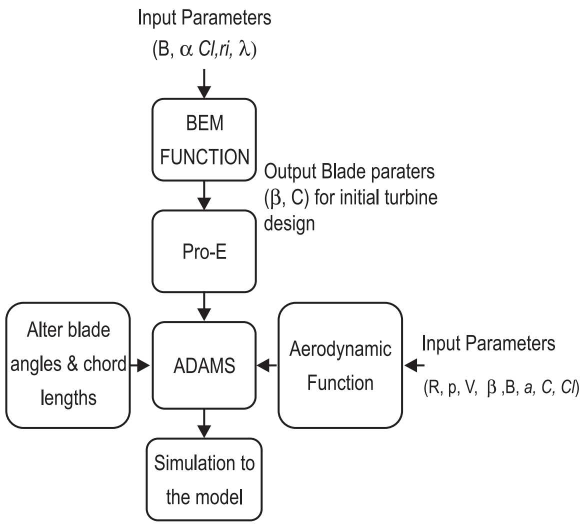

Figure 2: Flow chart for Modeling and Simulation of wind turbine blades.

Initial design of the turbines was carried out using the BEM theory, Wood's Models[13], and the work of Larson[21]. The input parameters (stations radii, number of blades, angle of attack, coefficient of lift and tip speed ratio) were used to get the blade parameters (chord length and twist angles at different radii values).These blade parameters are compared with the research work of John Larson[21] which gave almost same blade parameters. (Figure 3)

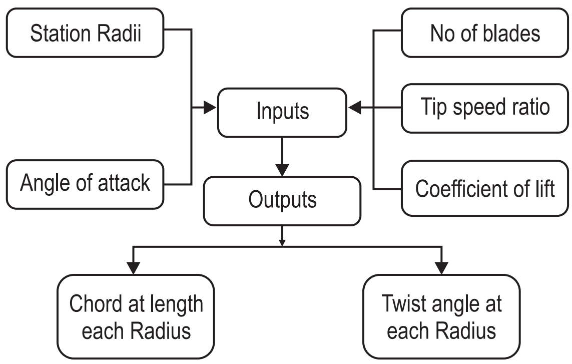

Figure3: Block diagram for the determination of blade parameters

The blade parameters were then used as inputs for finding the magnitude and point of application of the aerodynamic forces using an iterative process. Wind speed, number of blades, chord length distribution and the twist angle distribution are inputs to the iterative process.The axial and angular induction factors are two important parameters in determining the energy capture of a specific wind turbine for specific wind speed conditions. These values were initially set to zero; angle of incidence, angle of attack, coefficient of lift and drag at various stations of the wind turbine blade were calculated. The induction factors were then incremented and all the parameters mentioned above were calculated again. The process continued until the values of the calculated variables converged (Convergence level was set at a value of 0.01). Finally, the code calculated the coordinates of the point of application of forces (Figure 4).

The blade parameters obtained from the MATLAB code were used to develop models of wind turbines in Pro/E. For developing a wind turbine model in Pro/e the whole length of blade was divided into various sections. Blade profile for each station was defined by entering the blade twist and blade chord lengths. The initial Pro/E models are imported into ADAMS and simulated for investigating the output

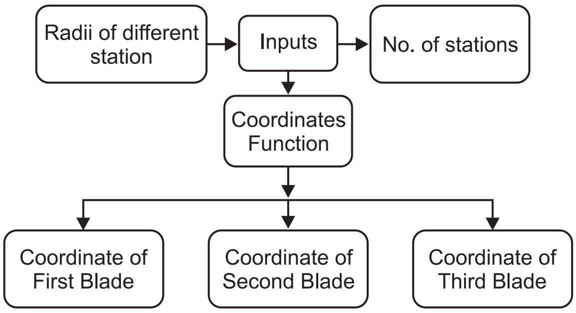

Figure.4 Coordinates of forces application points

torque and other output parameters.

The work of Wood and Wright[13] showed that for wind speeds less than 8 m/s and wind turbine sizes smaller than 6 meters, the idling time is normally less than one minute. Therefore,in most of the simulations, the simulation time was set to one minuteto study the starting behavior.The run time direction of force may be space fixed or body moving.At the wind turbine,, there is a rotation pattern of wind about the wind turbine blades, so the body moving run time direction option was chosen for the analysis.The effect of these forces changes with time since at the starting time, the direction of wind is assumed to be normal to the wind turbine, but as the wind turbine starts rotating, the effective wind direction is changed.

For validation of the simulations, the output torque values obtained were compared with experiments conducted in open environment with cross flow of wind on an s809 profile (Figure. 5).Reasonably good agreement between experiment and numerical findings can be noted. The slight difference is due to the cross wind factor.

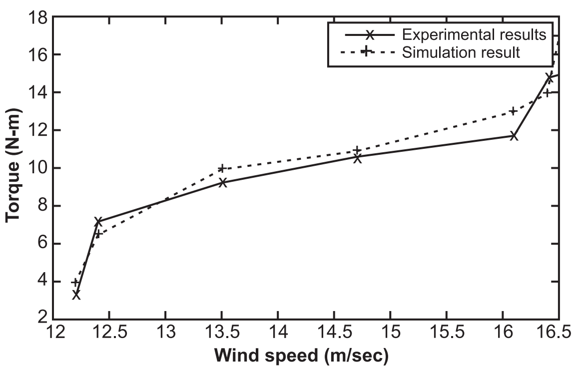

Figure 5: Wind speed versus torque for experimental and simulation results

Theaccuracy of simulations was gauged by comparing the predicted torque with the performance estimate of a 10m wind turbine blade modeled at a wind speed of 20m/s by Mehfooz[22]. The torque for this turbine was found to be 5498 Nm with a coefficient of performance of 0.38. For similar conditions, the ADAMS simulations gave an output torque of 5567 Nm. For wind conditions almost similar to Cherat region, Mendez and Greiner[23] performed chord and twist angle optimization. Their final chord and twist angle distribution was also found to be in good agreement with final design of this research. The optimized blade parameters for Cherat region discussed below are also in good agreement with the wind turbine design obtained by Somers[24] and Grainer[25]. The sensitivity of the simulations to the number of sections was also analyzed by modeling a turbine with 27 sections, with results similar to those discussed below.

RESULTS AND DISCUSSION

The output power of wind turbine depends upon both the output angular velocity of wind turbine and output torque. In order to study the starting behavior of wind turbines at least one of these two parameters must be monitored. The torque at the output is monitored in this research work. The focus of this research is to bring changes in wind turbine blade profile so that the output torque increases during the initial startup. The output graphs for the selected locations of KPK are shown in the following Figures 6 through 10.

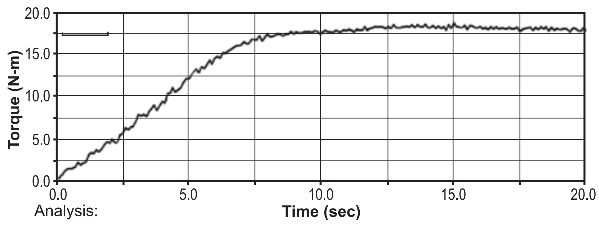

Figure: 6 Output torque for the initial design of Warsak region

The simulation results of the wind turbine for Warsak region is shown in Figure.6. This graph shows the variations of output torque with respect to time. The graph shows a torque of 12.5 N-m after 5 seconds and the torque magnitude become steady after 9 seconds. To increase the output torque during the initial startup, changes were made to the initial models.

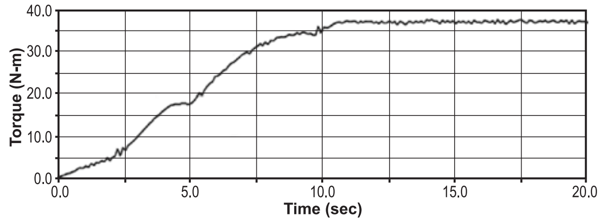

Figure.7 Output torque for the initial design of Cherat region

The simulation results of the wind turbine for Cherat region is shown in Figure 7. This graph shows the variations of output torque with respect to time. The graph shows a torque of 18.5 N-m after 5 seconds and the torque magnitude become steady after 11 seconds. This value of torque is not sufficient to start wind turbine. To increase the output torque changes are made in these initial models to increase the output torque during the initial startup.

Next the experiments were divided by modifying the wind turbine blade near the hub region. First the blade angle near the hub is increased. Output graphs of the torque shows that by increasing the blade angle the starting torque increased and the idling time decreased. Next the blade angles near the hub are increased, as a result the starting torque decreased and the idling time increased. Similarly by increasing the chord lengths near the hub of the wind turbine, the starting torque increased and the idling time decreased.

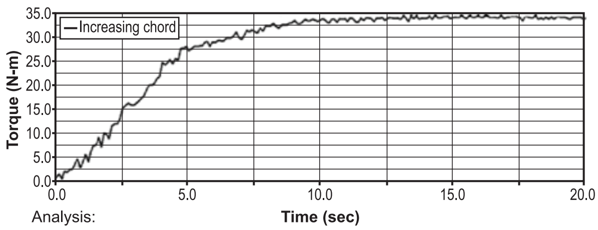

Figure: 8 Output torque for the increasing chord design of Cherat region

The simulation results of the increasing chord lengths wind turbine for Cherat region is shown in Figure 8. When the chord length was increased near the hub it was noted that the idling time become less and the torque achieved was more as compare to the initial model for Cherat region.

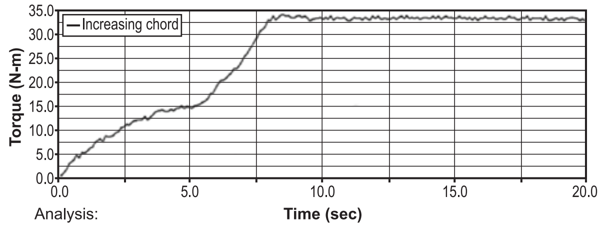

Figure: 9 Output torque for the decreasing chord design of Cherat region

For the same wind conditions of Cherat region when the blade profile was changed by decreasing the chord lengths in the sections near to hub of the wind turbine the output torque was decreased (Figure 9).

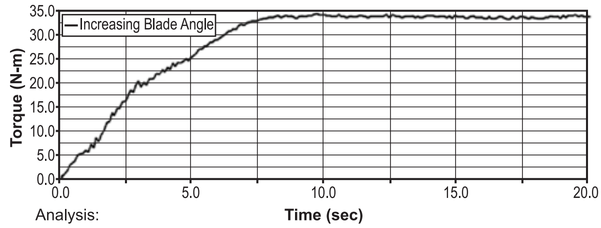

Figure: 10 Output torque for the increasing blade angle design of Cherat region (Figure 10)

By increasing the blade angles in the region near the hub it was noted that the idling time starts to decrease and the torque achieved was more as compared to the initial model for Cherat region.

CONCLUSIONS

Optimized wind turbine designs were obtained for various locations of Pakistan. Three bladed wind turbines of various sizes and blade profiles were simulated in the software. Startup is not usually theprimary concern of the designer; however a simple method of predicting a turbine'sstarting performance is useful, particularly if sitting turbines in low or unsteadywinds. The method described in this research was found suitable for this purpose.

In order to optimize the starting performance while maintaining good power performance it was revealed that maximum starting torque was generated near the hub, and maximum powerextractingtorque came from the tip region.It was further proved that increasing the cord lengths and blade angles near the hub region increases the output Torque, angular velocity and angular acceleration and decreases the idling time thereby enabling the wind turbine to reach the rated speed I minimum time.

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