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Research Article

Observation of the Starting and Low Speed Behavior of Small Horizontal Axis Wind Turbine

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This paper describes the starting behavior of small horizontal axis wind turbines at high angles of attack and low Reynolds number. The unfavorable relative wind direction during the starting time leads to low starting torque and more idling time. Wind turbine models of sizes less than 5 meters were simulated at wind speed range of 2 m/s to 5 m/s. Wind turbines were modeled in Pro/E and based on the optimized designs given by MATLAB codes. Wind turbine models were simulated in ADAMS for improving the starting behavior. The models with high starting torques and less idling times were selected. The starting behavior was successfully improved and the optimized wind turbine models were able to produce more starting torque even at wind speeds less than 5 m/s.

1. Introduction

From ancient times the kinetic energy of the wind is used for various household activities like milling of wheat and corns. In the 1980s blade element momentum theory was presented. Based on blade element momentum theory various wind turbine designs were proposed for various wind conditions. In areas of high wind speeds large wind turbines can be installed. For areas of low and medium wind speeds small wind turbines are installed. It is not possible to start wind turbine at low wind speeds, so changes should be made in the existing wind turbine models in order to increase their sensitivity [1, 2]. The wind turbine material should be such that it can withstand the environmental impacts and also it should have a density in a specific range [3]. To increase the lift force in order to start the wind turbine at wind speeds various designs must be tested. In developing countries the practical experimentation is not possible so computer simulations are usually carried out to get the optimized design for a specific area [4]. Clausen and Wood [5] also worked on improving the starting behavior of horizontal axis wind turbines and they concluded that the root region of the wind turbine blade is responsible for generating the initial torque. Singh and Ahmed [6] practically made various wind turbine models of wood with low Reynolds number and they suggest various models for low and medium wind speed areas. Singh and Ahmed [7] tested various low Reynolds profiles for various low wind speeds and at various pitch angles. Habali and Saleh [8] carried out the static proof-load and field performance tests and then they designed a wind turbine model with 41.2% power coefficient. Song and Tan [9] designed 20 kW wind turbine blades. The optimized blade parameters were produced using MATLAB and the dynamic analysis was performed using ANSYS and Solid Works. Wichser and Klink [10] measured wind speed at a height between 70 and 75 meters above the ground level for

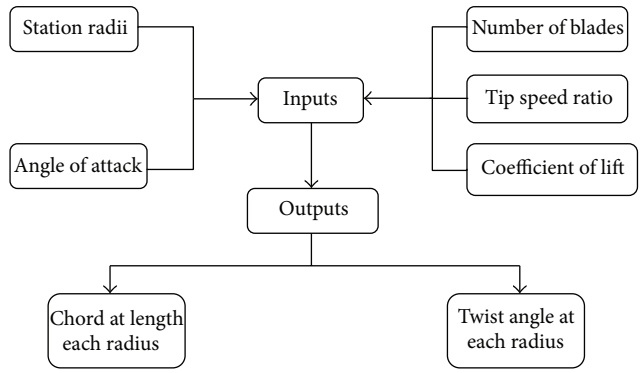

Figure 1: Block diagram for the determination of blade parameters.

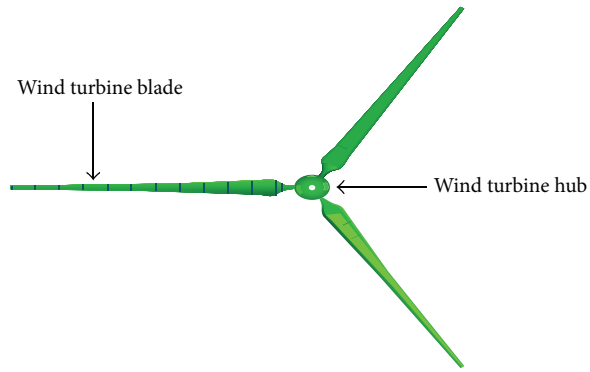

Figure 2: Initial Pro/e model.

three different sites of USA. They concluded that wind power production can be increased from 15 to 30 percent if small wind turbines are installed with improved starting behavior.

In this research work wind speed and direction data were taken from PMD (Pakistan Meteorological Department) for various sites of KP (Khyber Pakhtunkhwa). Optimized designs were then proposed for these locations. Optimized designs were made using MATLAB coding, ADAMS simulation, and PRO/E modeling.

The optimized designs were then installed at the selected location of KP (one model for each location made of wood) and the output parameters (torque and rpm) were measured which shows a huge improvement as compared to conventional wind turbine models installed in similar wind speed locations.

2. Simulation Setup

The main aim of this project was to propose optimized designs for the selected locations of KP. According to the wind speeds and work of Wood [10] sizes were selected for wind turbines in these locations of KP. The sizes and wind speeds of the selected locations are shown in Table 1.

MATLAB coding was done based on the blade element momentum theory. A MATLAB function with the name parameter was used to obtain the blade parameters (chord and twist distribution). The block diagram for this MATLAB function is given in Figure 1.

Table 1: Size of wind turbines at selected locations of KP.

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

As shown in Figure 1 the parameter MATLAB function takes the station radii, number of blades, tip speed ratio, coefficient of lift, and angle of attack as inputs and at output we get the chord and twist angle distribution.

Wind turbine models were made in Pro/E environment based on the parameters obtained from MATLAB function. A wind turbine model made in Pro/E is shown in Figure 2.

A second MATLAB function calculates the aerodynamic forces on various stations of wind turbine blades. The block diagram for this function is shown in Figure 3.

The MATLAB function as shown in Figure 3 takes the blade parameters (chord and twist distribution) and wind speed as inputs and after a successive iteration process we get the aerodynamics forces at various stations on wind turbine blades.

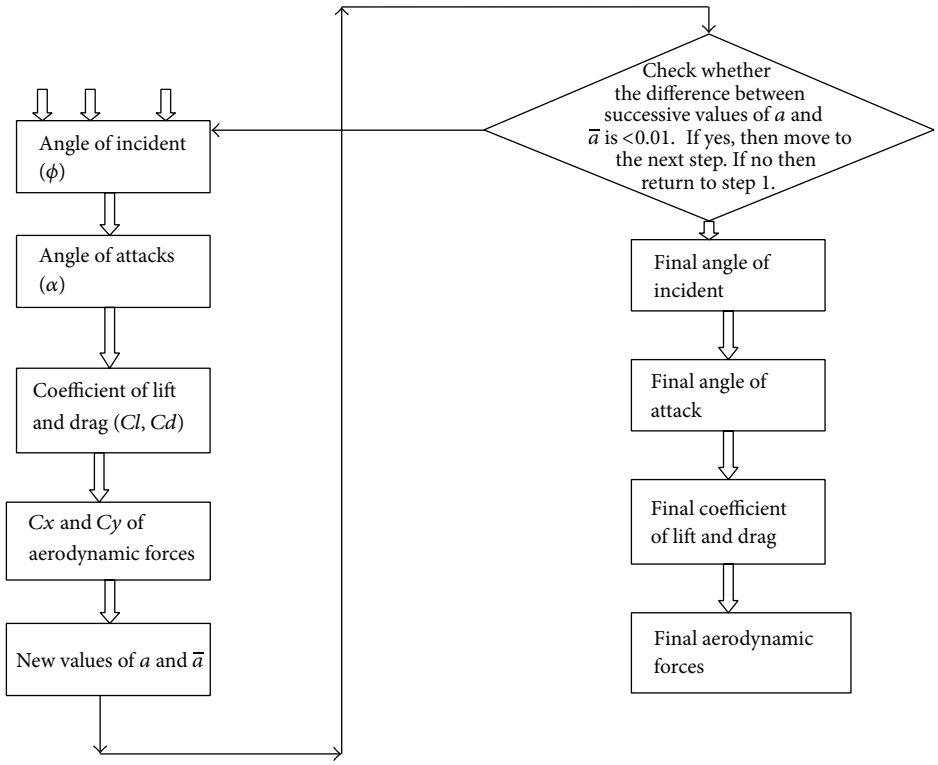

Figure 3: Logic diagram for the determination of aerodynamic forces.

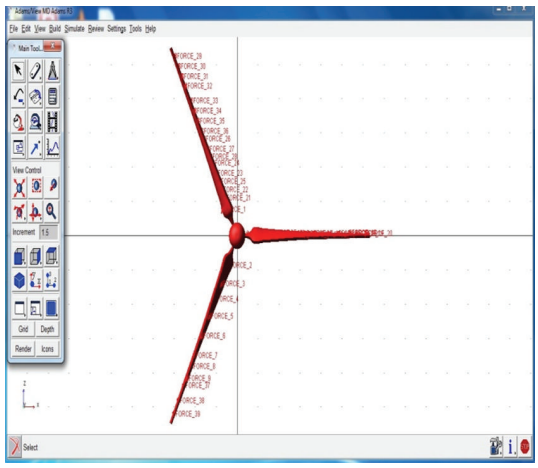

Figure 4: ADAMS model with wind forces applied on its blades.

The Pro/E models were imported into ADAMS environment and the aerodynamic forces were applied on their blades. A wind turbine model with forces applied in ADAMS environment is shown in Figure 4.

Various models were simulated in ADAMS environment and the models with more starting torque were selected. The complete simulation process is explained in Figure 5.

3. Model Descriptions

The wind turbine model used for simulation has the following blade parameters. The distance between the leading and trailing ends of wind turbine blade is known as chord length (c). The distance from the centre of hub to blade tip is termed as blade radius (R). The distance from the hub to any station is termed as the station radii (r). The width of any station is termed as station width (dr). Each station of the wind turbine blade is twisted at a certain angle with respect to the previous station; this angle is known as the twist angle (γ). For the same wind speed the aerodynamic effects on various stations of the blade will be different because each station has a different chord length and a different twist angle. According to blade element momentum theory the blade was divided into a number of segments known as stations (in our case 15).

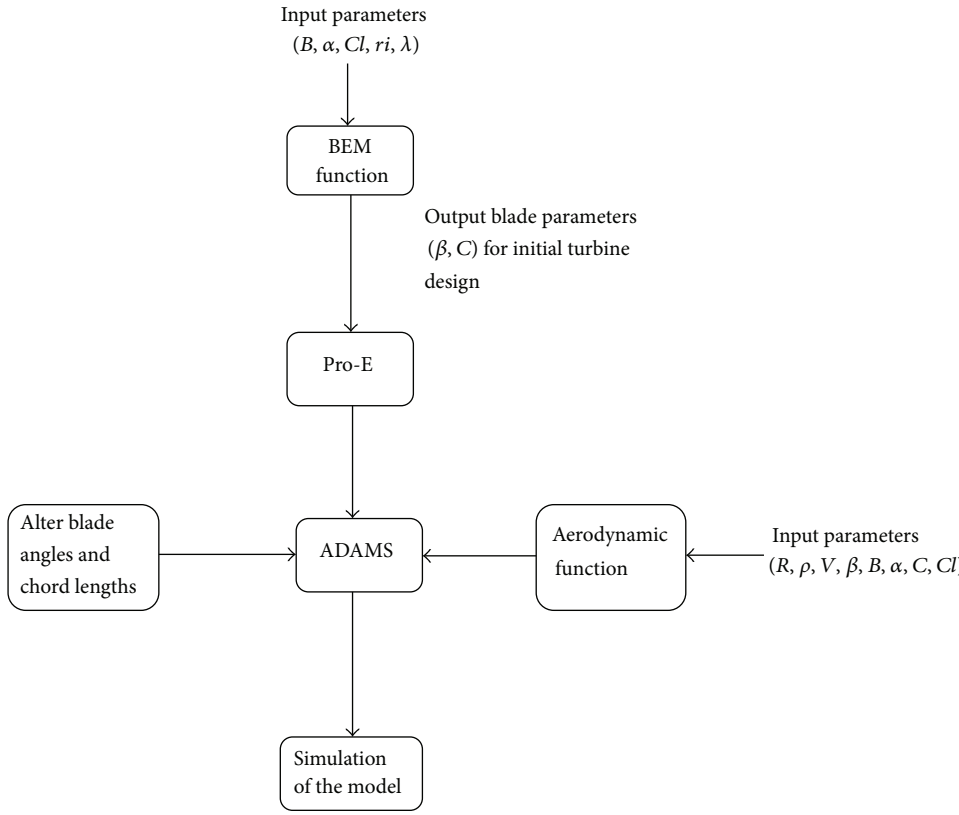

Figure 5: Flow chart for modeling and simulation of wind turbine blades.

Table 2: Blade parameters for the wind turbine model.

Serial number	Blade station	Local radius meters	Local radius mm	Local radius inches	Chord width meters	chord width inches	Blade angle beta degrees
1	1	0.15	150	5.905512	0.1679	6.610236	14.5
2	2	0.2	200	7.874016	0.1608	6.330709	13.6
3	3	0.25	250	9.84252	0.1537	6.051181	12.7
4	4	0.3	300	11.81102	0.1466	5.771654	11.8
5	5	0.35	350	13.77953	0.1395	5.492126	10.9
6	6	0.4	400	15.74803	0.1324	5.212598	9.9
7	7	0.45	450	17.71654	0.1253	4.933071	9.1
8	8	0.5	500	19.68504	0.1182	4.653543	8.2
9	9	0.55	550	21.65354	0.1111	4.374016	7.3
10	10	0.6	600	23.62205	0.104	4.094488	6.3
11	11	0.65	650	25.59055	0.0969	3.814961	5.4
12	12	0.7	700	27.55906	0.0898	3.535433	4.5
13	13	0.75	750	29.52756	0.0827	3.255906	3.6
14	14	0.8	800	31.49606	0.0756	2.976378	2.7
15	15	0.85	850	33.46457	0.0685	2.69685	1.8

The overall effect on wind turbine blade was found out by adding the effects on the individual blade elements. The details of the blade parameters are given in Table 2.

The torque output from the simulation was compared with the experimental results. The experiments were carried out in open environment with cross flow of wind on wind turbine rotor. The cross flow of wind caused a slight difference between the experimental and simulation results. The agreement between the output of simulation and experimental results shows us that we can analyze various wind turbine

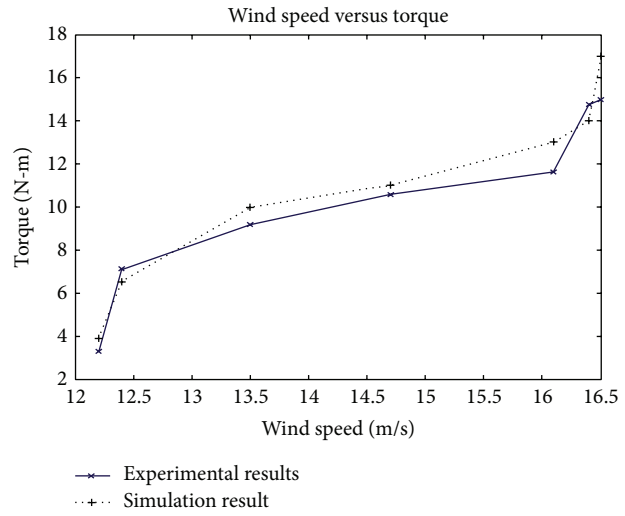

Figure 6: Comparison between experimental and simulation results.

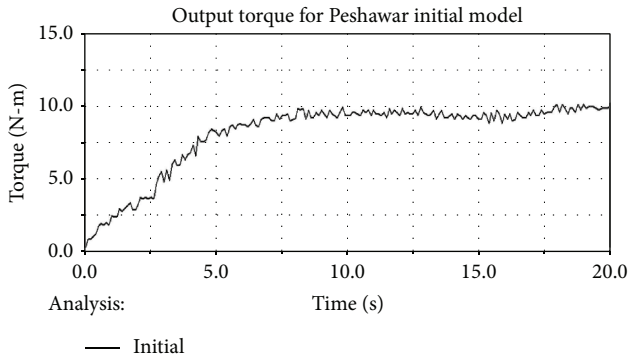

Figure 7: Output torque for the initial design of Peshawar region.

models using this simulation setup. The comparison is shown in Figure 6 which shows a good agreement between the experimental and the simulation results.

In order to validate the simulation results from ADAMS software, the output torque is compared with the experimental results for the same wind conditions. For a wind turbine blade design modeled by [11, 12], the torque comes out to be 5498 Nm. For this wind turbine design the blade diameter was 10 m and the wind speed was selected to be 20 m/sec. A MATLAB function within simulation gives the coefficient of performance for this wind turbine model to be 0.38. The coefficient of performance along with other parameters is used to find out the power from the equation: $P = C_{p\eta 1/2\rho\pi R^2 V^3}$. The next torque is found out from the equation $T = P/\Omega$. For the same model and for the same wind conditions ADAMS simulations give the output torque of 5567 Nm.

4. Results and Discussions

After simulation settings and forces application the initial Pro/e models for the selected locations were simulated.

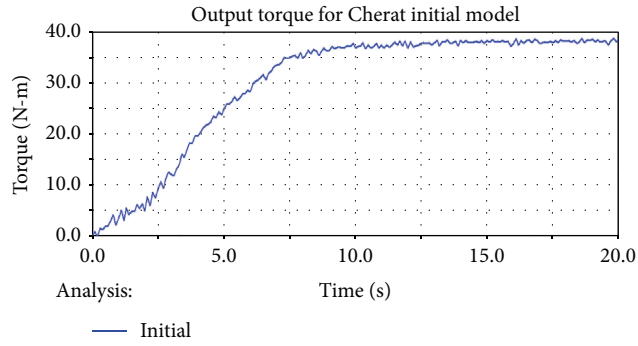

Figure 8: Output torque for the initial design of Cherat region.

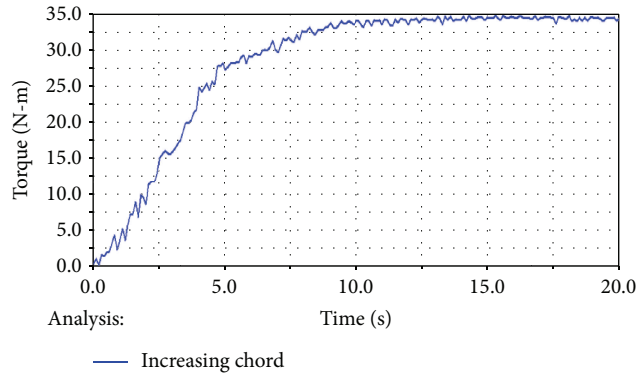

Figure 9: Output torque for the increasing chord design of Cherat region.

First of all the initial wind turbine designs were imported into ADAMS. After simulating, those initial models graphs from ADAMS postprocessor for each selected location were obtained. The output power of wind turbine depends on both the output rpm of wind turbine and the out torque of wind turbine. 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 is to bring changes in wind turbine blade profile so that the output torque increases during the starting time. Various wind turbine models were simulated in ADAMS environment and the output torque was recorded. The output torque for the initial models is shown in Figures 7 and 8.

The wind turbine blade parameters were altered near the hub region and the new wind turbine models were then simulated in ADAMS environment. The output graphs for torque are shown in Figures 9, 10, 11, and 12.

Figures 9–12 show that the starting torque increases by increasing the chord lengths and twist angles near the hub region of horizontal axis wind turbines.

The optimized wind turbine models for the selected locations of KP are shown in Table 3.

Table 3: Optimized wind turbine designs for the selected locations of KP.

Ramatkore	Chord distribution	0.314		0.288		0.253		0.232		0.186		0.164		0.153		0.121		0.110		0.101		0.08		0.076		0.06	0.047	0.03		
	Twist distribution	0.406		0.383		0.362		0.328		0.231		0.210		0.188		0.156		0.123		0.101		0.06		0.041		0.03	0.027	0.02		
Lorramiana	Chord distribution	0.432		0.391		0.353		0.330		0.276		0.251		0.243		0.217		0.191		0.183		0.16		0.153		0.13	0.101	0.09		
	Twist distribution	0.464		0.443		0.418		0.376		0.271		0.230		0.211		0.189		0.145		0.107		0.06		0.031		0.020	0.018	0.01		
Nizampur	Chord distribution	0.314		0.288		0.253		0.232		0.186		0.164		0.133		0.121		0.110		0.101		0.08		0.076		0.06	0.047	0.03		
	Twist distribution	0.406		0.383		0.362		0.328		0.231		0.210		0.188		0.156		0.123		0.101		0.06		0.041		0.03	0.027	0.02		
Peshawar	Chord distribution	0.199		0.181		0.160		0.146		0.110		0.102		0.099		0.087		0.079		0.066		0.05		0.040		0.02	0.017	0.01		
	Twist distribution	0.392		0.372		0.352		0.322		0.220		0.191		0.163		0.121		0.108		0.081		0.03		0.021		0.02	0.017	0.01		
Cherat	Chord distribution	0.980	0.909	0.846	0.792	0.744	0.701	0.663	0.629	0.597	0.458	0.418	0.400	0.383	0.368	0.354	0.341	0.329	0.318	0.307	0.297	0.288	0.279	0.271	0.265	0.256	0.249	0.242		
	Twist distribution	0.411	0.344	0.292	0.250	0.217	0.189	0.165	0.145	0.128	0.096	0.083	0.071	0.061	0.052	0.043	0.036	0.029	0.023	0.017	0.012	0.007	0.002	−0.001	−0.005	−0.008	−0.012	−0.015		

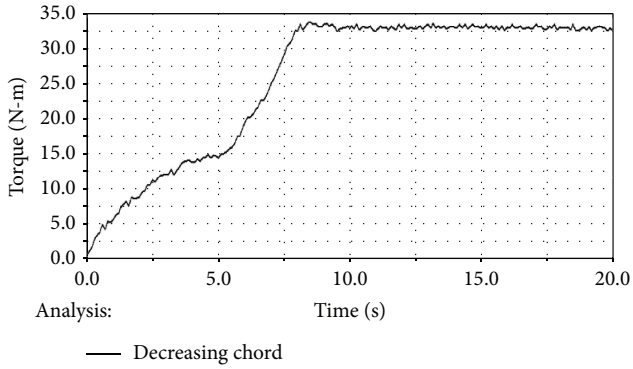

Figure 10: Output torque for the decreasing chord design of Cherat region.

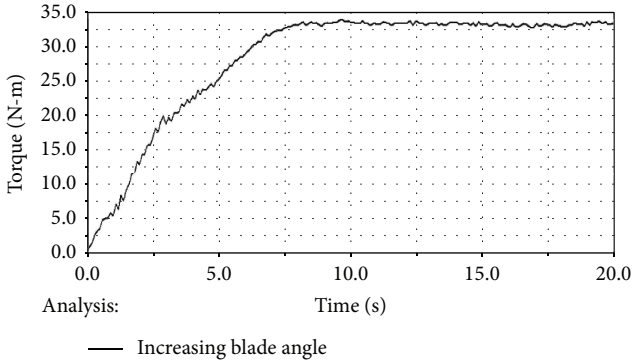

Figure 11: Output torque for the increasing blade angle design of Cherat region.

5. Conclusions

Wind turbine designs were proposed for low and medium wind speed locations of Pakistan based on the comparison between simulation and experimental results. Simulations were carried out by interfacing ADAMS and MATLAB software. For each low wind speed location the main aim was to improve the starting behavior of wind turbine models. Wind turbine models were modeled in Pro/E and were then simulated using ADAMS and MATLAB.

Various wind turbine models were modeled in Pro/E by varying chord length and blade angles. The simulation results show that increasing the chord lengths and blade angles near the hub region increases the output torque, angular velocity, and angular acceleration.

Increasing the chord lengths and blade angles near the hub decreases the idling time, so the wind turbine reaches its rated speed in minimum time.

6. Future Recommendations

Optimized wind turbine models were achieved based on simulation and experimental results. Actual wood models were made based on the chord and blade twist data of optimized designs. These wood models were tested and the output power was more as compared to previous wind turbine

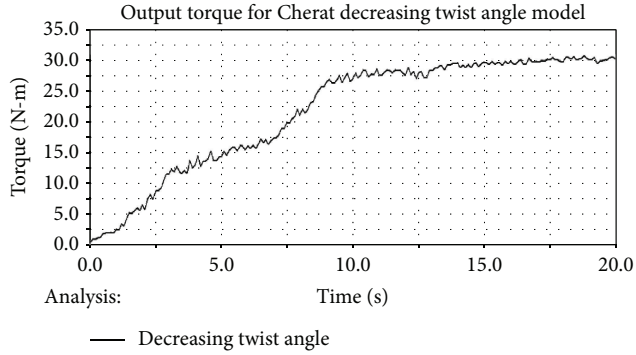

Figure 12: Output torque for the decreasing blade angle design of Cherat region.

models designs for the same wind speeds. The next step of the research is to practically install wind turbine models in the proposed locations.

Pitch control, if introduced in these wind turbine models, will help in staring and also help to minimize the rotational speed of wind turbine models during high speed wind.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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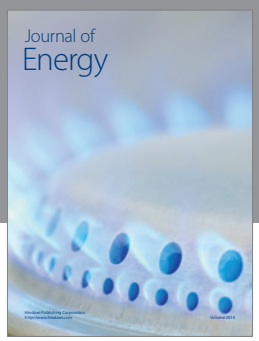

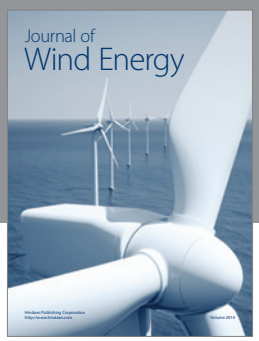

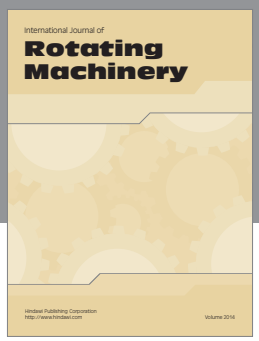

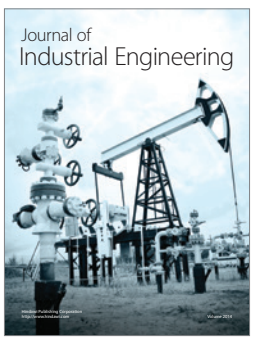

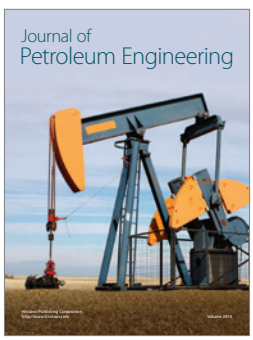
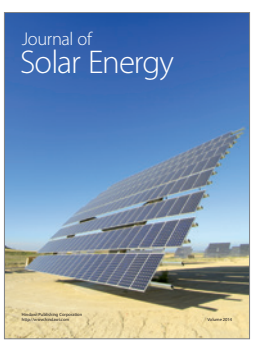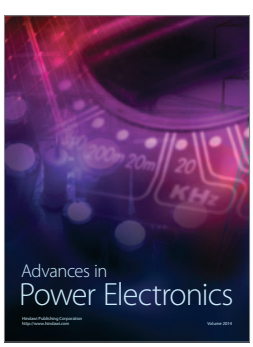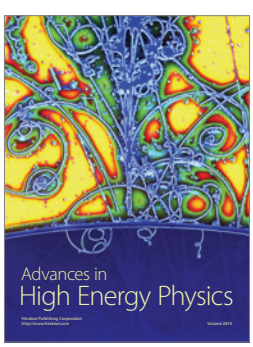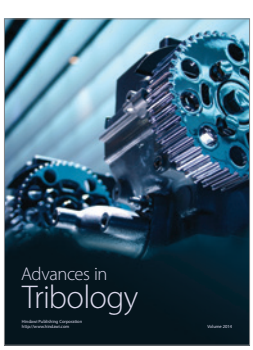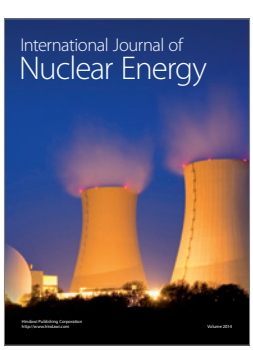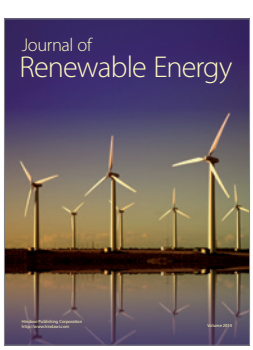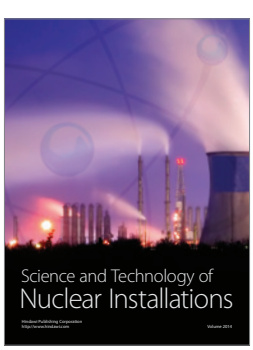
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