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Design and Parametric Investigation of Horizontal Axis Wind Turbine

ABBAS Zulkarnain[1*], *ABBAS Saqlain*[1], *BUTT Zubair*[2], *PASHA Riffat Asim*[3]
(1. School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China; 2. Department of Mechatronics Engineering, University of Engineering and Technology Taxila, Chakwal 48800, Pakistan; 3. Department of Mechanical Engineering, University of Engineering and Technology Taxila, Taxila 47080, Pakistan)

Abstract: This research focuses on design and calculations for the horizontal axis wind turbine to fulfill energy demands at small scales in Pakistan. This is the design to produce about 5 kilowatts of electricity to share the load of average home appliances. Area chosen for this research is Pasni, Balochistan in Pakistan to build the wind turbine for electricity. Design values are approximated by appropriate formulas of wind energy design. In current research, turbine blade profile is designed by blade element momentum (BEM) theory. Warlock wind turbine calculator is used to verify the design parameters like wind speed, tip speed ratio (TSR) and efficiency factor. Effects of wind speed, wind power, TSR, pitch angle, blade tip angle, number of blades, blade design and tower height on power coefficient are analyzed in this research. Maximum power coefficient is achieved at a designed velocity of 6 m/s. Design analysis is also performed on simulation software ANSYS Fluent. It is observed that designed velocity parameter of this research is very suitable for the turbine blade, so blade designing is perfect according to wind speed range.
Key words: horizontal axis wind turbine, Warlock wind turbine calculator, planetary gear box
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0 Introduction

Pakistan is the country which is facing serious problem of energy crisis nowadays. Pakistan was categorized the 36th lowermost country in 2012 in the field of power utilization with an average power usage of 43 watts per capita which is considered one-seventh of the world's average energy usage[1]. This is the result of massive gap in the existing available potential and the net power generation that is remarkably enhancing with the passage of time. It is essential to eliminate this energy problem in Pakistan by using renewable energy resources as Pakistan is rich in renewable energy resources. Modern renewable energy technologies can provide reasonable alternatives to overcome this energy crisis which is being faced by different developing countries including Pakistan[2]. Four types of renewable energy resources are available in Pakistan. These resources are solar energy, wind energy, hydro power and biomass potential[3]. These resources contain large potential that can be utilized to overcome the electricity crisis in Pakistan. Pakistan's existing installed power generation capability is near bout 20 GW. Now the current government of Pakistan has presented a plan for power generation up to 2030 that supposes an installed capability of over 162 GW[4-5]. Wind turbine technology is advancing at a very high rate. Wind energy is an economical and environment-friendly source to get electricity. Pakistan has large wind passage that is extending from southern Sindh to coastal Baluchistan[6]. Monthly average wind speed is 7—8 m/s at particular places near the Keti Bandar-Gharo passage and a huge potential around 20 GW of wind energy is available. It is an economical and feasible alternative for conventional energy resources[7-8]. There are certain advantages of wind energy, such as minimum cost of energy, maximum annual energy production and noise free environment-friendly way. The explanation of "small wind" is essential. In the wind energy industry, the word "small" remained vague and its meaning had been changing with time[9-11]. A new term that defines wind turbine with an average rated power from 0.006 to 300 kW is generated due to lack of a reliable and agreed definition. The term "small wind" is expressed by its ability to generate electricity at small scale that can be used to provide power to household appliances or to fulfill many electricity loads[12]. Only 40-inch (1 inch = 2.54 cm) LED television, available in markets, usually consumes 200 watts of available electricity potential. If a battery can totally overcome the variations in supply and demand, it is predictable that a 180 W wind energy turbine can suitably keep the television to be switched on for consecutive four hours per day[13-14]. Onshore

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∗**E-mail:** zulkar-abbas@sjtu.edu.cn

wind turbine is a type of wind turbine that is placed on land. Onshore wind turbine is available in multiple ranges like from 0.05 to 3 MW of generating capacity of electricity daily[15]. The wind turbine situated in seas or oceans is named as offshore wind turbine. A wind turbine having the blade rotation that is perpendicular to the ground axis is classified as vertical axis wind turbine. Another type of wind turbine is also available in which blade rotation is parallel to the axis of ground, and it is known as a horizontal axis wind turbine. Horizontal axis wind turbine is more known than vertical axis turbine, and generally consists of three blades[16]. As regards horizontal axis wind turbine, hub height can be estimated from the ground to the center of the hub, and the rotor diameter is calculated by circular arc made by the rotation of blades around an axis. The average amount of energy produced by a wind turbine is considered as turbine mean power output, and it is usually calculated in kilowatts or megawatts[17].

Basic purpose of this research is to design horizontal axis wind turbine to fulfill energy demands in Pakistan. Warlock wind turbine calculator is used to test designed parameters like wind power, tip speed ratio (TSR), pitch angle, blade tip angle, number of blades, blade design and tower height. A permanent magnet 3-phase alternating current (AC) electrical generator of 1 kW is suggested for this design. Maximum power coefficient is achieved at a designed velocity of 6 m/s. Designed values and calculations of current research are also verified by simulation software ANSYS Fluent. It is observed that blade designing is perfect according to wind speed range.

1 Design and Calculations

Site is selected in Pasni, Balochistan. Gearing method is planetary gear box. Electrical generator is 1 kW, 3-phase and AC. Other parameters used for designing the desired wind turbine model are given in Table 1.

Tower material is stainless steel. Blade materials include wood epoxy, carbon filament and reinforced fiber. Rotation speed of generator is enhanced with planetary gear box. It is required to select such a generator for this research which gives 1 kW and almost 480 r/min. Therefore, permanent magnet 3-phase AC electrical generator is chosen for this purpose. Gear mechanism for these specifications should have a gear ratio of 3 : 1. This thought can find the gear mechanism. Class insolation is F; housing material is aluminum; shaft material is 45# steel; grade of protection is IP54; other specifications of the selected permanent magnet 3-phase AC electrical generator for this research are given in Table 2.

Kinetic energy of the wind flow is utilized by wind turbines. The rotors of the wind turbines are used to decrease the wind speed from uninterrupted wind far in front of rotors to a reduced air stream velocity behind the rotors. The total power of the wind stream is theoretically equal to the rate of kinetic energy of the wind stream:

Table 1 Parameters for appropriate design of wind turbine

Parameter	Value
Average wind resource/$(\mathrm{m\cdot s^{-1}})$	6
Wind velocity range/$(\mathrm{m\cdot s^{-1}})$	3.9—8.5
Swept area/$\mathrm{m^2}$	26.04
Rotor diameter/m	5.76
Hub height/m	10
Cut-in wind speed/$(\mathrm{m\cdot s^{-1}})$	3
Cut-out wind speed/$(\mathrm{m\cdot s^{-1}})$	25
Rated wind speed/$(\mathrm{m\cdot s^{-1}})$	6
Air power density/$(\mathrm{m\cdot s^{-1}})$	1.225
Rated output/kW	1
Peak output/W	2 938.94
Rotor speed/$(\mathrm{r\cdot min^{-1}})$	160
TSR	8

Table 2 Specifications of electrical generator

Parameter	Value
Production/kW	1
Wind speed range/$(\mathrm{m\cdot h^{-1}})$	20—22
Generator rotation speed/$(\mathrm{r\cdot min^{-1}})$	460
Mass/kg	55
Designed voltage/V	24—220
Start-up torque/$(\mathrm{N\cdot m})$	20

$$P_{\text{tot}} = \frac{v^2}{2}\dot{m}, \tag{1}$$

where P_{tot} is the total power of the wind stream, $\dot{m}$ is the mass flow rate, and v is the velocity of the wind that enters turbine. The mass flow rate is determined as

$$\dot{m} = \rho A v, \tag{2}$$

where ρ represents the incoming wind density, and A represents the cross sectional area of the wind stream. Substituting Eq. (2) into Eq. (1) yields

$$P_{\text{tot}} = \frac{1}{2}\rho A v^3. \tag{3}$$

From Eq. (3), it is clear that the total power of a wind stream is directly proportional to its cross-section area, density, and cube of the wind stream velocity.

A low-speed wind tunnel is utilized in current research. The wind tunnel has intake section with 4 m × 4 m cross-section, and test section with 1.4 m width, 1.4 m height and 14.6 m length. Maximum speed in test section can be 30 m/s. Turbulence level is 25%

but this turbulence intensity does not affect the downstream flow of turbine. Sensors installed on the wind tunnel are used to take the values for wind speed, temperature and humidity. Reading of wind turbine sensors involves shaft torque/bending, blade strain gauge, balance strain gauge, blade pitch and rotor speed. Remote control unit is used for data logging, processing and visualization. Overview of inside test section of wind tunnel and data acquisition system is shown in Fig. 1.

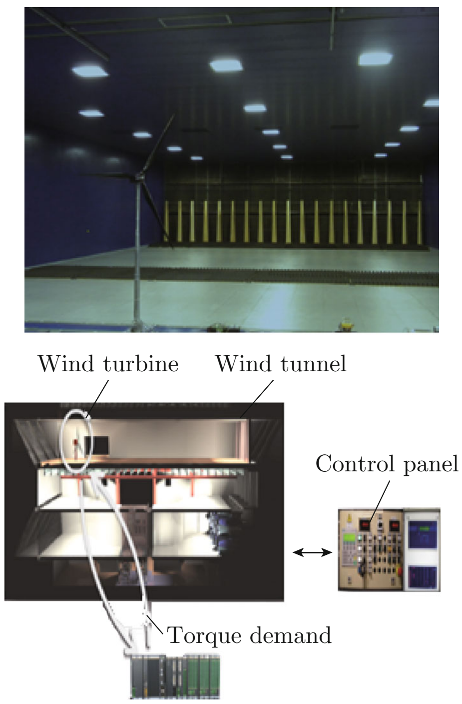

Fig. 1 Overview of inside test section and data acquisition system

Experimental values for the designed wind turbine are provided, as shown in Fig. 2, where u is the wind speed, and P_W is the power contained in the wind passing with speed u through the wind turbine.

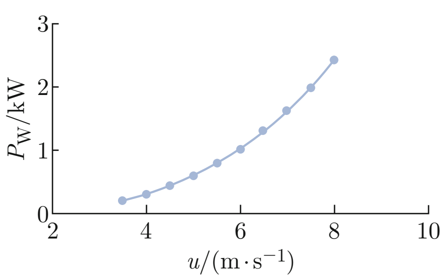

Fig. 2 Relationship between wind power and wind speed

From Fig. 2, it is clear that there is an exponential behaviour between wind speed and wind power. In modern turbines, blades catch the wind as it strikes on the surface and utilize this wind to spin the shaft of attached generator. The rotating shaft of wind turbine generator transforms mechanical energy into electric potential. Due to a large ratio of wind speed to turbine blade radial-velocity, the aero foil section at the hub is usually angled into the wind direction. Impact of wind direction and wind speed is explained in Fig. 3, where β is the pitch angle and ϕ is the yaw angle.

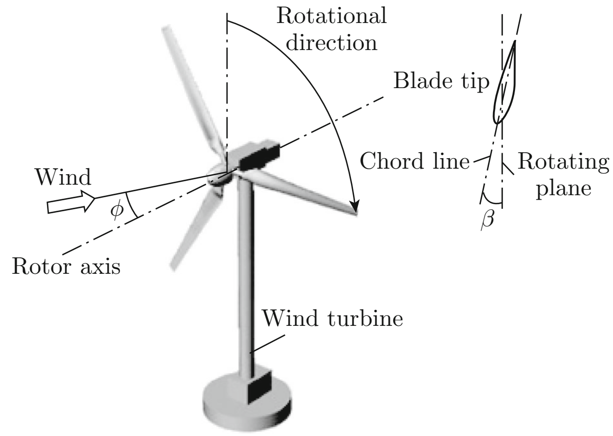

Fig. 3 Effect of wind speed and wind direction on blade design

If the wind strikes at an angle that is relative to the main chord line, then it can affect the lift and drag forces. As a result, variations occur in angular velocity and torque for shaft as well. Speed of spinning shaft is mainly affected if changes in blade tip angle take place due to wind direction. The blade design in current research is “smart blades” which can adjust their shape accordingly with variable wind conditions.

In current research, turbine blade profile is designed by blade element momentum (BEM) theory. Different parameters like chord length for given aero foil section, angle of twist and rotation speed at specific positions along the span of blade are obtained by this theory. BEM theory does not produce good results if the data for air foil cross-section have been demonstrated for rotational motion. Therefore, analysis of computational fluid dynamics (CFD) is also made in this research to verify the blades design.

Blade design specifications for rated power output of wind turbine involve blade length, hub diameter, chord length, chord length at blade tip and blade twist. The blade length is 2.88 m, the hub diameter is 0.28 m, and the chord length is 0.09 m. As coefficient of lift increases, the power increases. Experimentally, it is found that the twist angle value which gives the maximum power is 17°. The arrangement/number of blades that produces the maximum amount of power is a great matter of concern.

Power coefficient is the amount of conversion efficiency which can be derived from wind power. Here, C_p represents the power coefficient and λ represents

TSR. From Fig. 4, it is clear that C_p is maximum for 6 blades as compared with 2 and 3 blades. There is a drawback for increasing the number of blades because it increases cost, weight and drag coefficient for wind turbine. If aero foil rotor blade is efficiently designed, then these optimum values can be raised to 25%—30% by increasing the speed at which the rotor rotates, and consequently more power is generated.

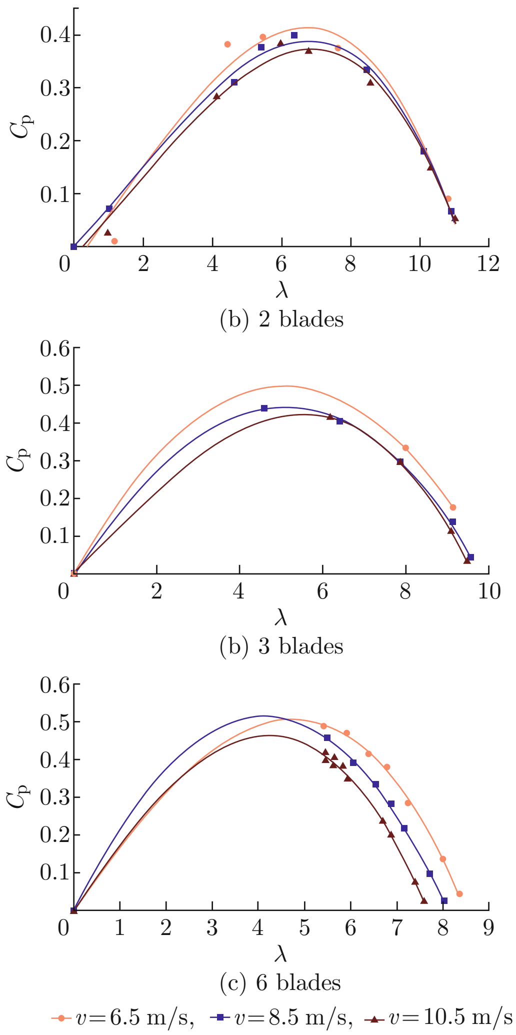

Fig. 4 Relationship between C_p and TSR for different number of blades at a pitch angle of 0°

As regards badly designed wind turbine blades, if TSR is very low, the turbine likely slows down or stalls. If TSR rises to higher value, then turbine can spin at high speed through the turbulent air, and optimal power cannot be obtained from the wind due to blurring blades that behave like a solid wall to incoming wind. As a result, wind turbine can be extremely affected due to risk of structural failure. Therefore, the number of blades plays an important role in design of wind turbine because optimal TSR depends upon the total number of blades. As shown in Fig. 4, a well-designed wind turbine has an optimal TSR of 6—7 along with 3 blades.

When wind speed is 5—10 m/s, 10% variation can be observed in the power coefficient. The ideal value of blade pitch angle depends on the wind potential at the location of the operation. The most favorable blade pitch angle for operation of the wind turbine is small. Angle of twist required for current design depends on exact angle of attack chosen for aero foil and TSR. It can be examined in Figs. 4(b) and 5. The tower height h determines the required wind velocity for the design. At a higher altitude, the wind velocity gets increased. Logarithmic law or power law is mostly used to model the height effect ζ. For exponential law, it can be represented as

$$\zeta = (h/h_\mathrm{ref})^a\,, \tag{4}$$

where h_ref is the reference height, and a is the wind shear coefficient. For logarithmic law, it can be represented as

$$\zeta = \ln(h/z_0)\Big/\ln(h_\mathrm{ref}/z_0), \tag{5}$$

where z_0 is the ground surface roughness. It is unfavorable to use higher height. An optimal tower height should be chosen to maximize the turbine-site matching index (TSMI).

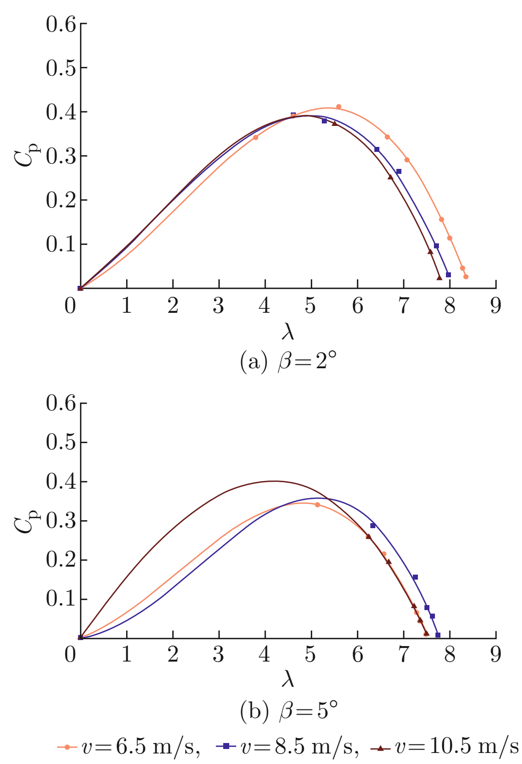

Fig. 5 Relationship between C_p and TSR for 3 blades at different pitch angles

2 Results and Discussion

The power coefficients are measured for 0°, 2°, 5° and 10° because rotor operates best at small blade pitch angle. The power coefficient is very small at higher blade pitch angle. In that case, it becomes very difficult to consider such small power coefficient for operation of a wind turbine. Figure 4(b) shows the relations between TSR and power coefficient for three different wind velocities. It shows that the maximum of C_p is 0.5 for TSR at 5 and pitch angle at 0°. The comparison of Fig. 5(b) with Figs. 4(b) and 5(a) shows that the power coefficient decreases for the same wind speed with the increase of the pitch angle. It reveals that when the pitch angle increases, the normal force on blades also rises. This occurs because when the pitch angle increases, the turbine blade is further parallel to inlet flow direction and consequently the power coefficient decreases. The maximum of TSR always relies on the number of blades in wind turbine rotor. If the number of blades decreases, the wind turbine rotor rotates fast to extract power from wind up to a large extent.

It can be analyzed that as the pitch angle increases, the power coefficient decreases. According to the Betz's law with a corresponding efficiency of 40%, TSR is taken as 8. TSR can be calculated by

$$\lambda = \frac{\omega R}{v}, \tag{6}$$

where $v = 6\,\mathrm{m/s}$, $\omega = 2\pi N$, R is the rotor radius, and N is the rotor speed. Blade tip angle can be calculated by

$$\alpha = \frac{16\pi R}{9n\lambda C_\mathrm{L} R}, \tag{7}$$

where C_L is the lift coefficient, and n is the number of blades. Now TSR for maximum power can be calculated as

$$\lambda_\mathrm{max} = \frac{4\pi}{n}, \tag{8}$$

where $n = 3$. Therefore, there is

$$\alpha = \frac{16\pi\lambda_\mathrm{max}}{36\pi\lambda C_\mathrm{L}}.$$

The formula infers that if blade tip angle increases, TSR increases. If rotor radius increases, λ_max also increases. If the number of blades increases, λ_max decreases. The electrical power to be extracted is

$$P = C_\mathrm{p} P_\mathrm{W}. \tag{9}$$

The power coefficient C_p represents the amount of power converted by the wind turbine. Because the input P_W cannot be controlled, improvement in wind power performance, i.e., increasing C_p, is necessary. Momentum theory can be applied to determine this coefficient:

$$P_\mathrm{theo} = C_\mathrm{p} P_\mathrm{W} = C_\mathrm{p} \frac{\rho}{2} \frac{\pi D^2}{4} v^3, \tag{10}$$

where P_theo is theoretically calculated wind power, and D is the rotor diameter. Experiment is performed to find out the optimum C_p at different wind velocities and TRSs. Table 3 shows that as the wind velocity increases, TSR decreases.

Table 3 Experimental results of power coefficient

$v/(\mathrm{m\cdot s^{-1}})$	λ	C_p
4.5	10.717 87	0.580 368
5.0	9.640 80	0.568 674
5.5	8.769 16	0.517 411
6.0	8.038 40	0.398 538
6.5	7.420 06	0.313 461
7.0	6.890 06	0.250 974
7.5	6.430 72	0.204 051
8.0	6.028 80	0.168 133

Wind velocity selected for this research corresponds to C_p at 0.4. At lower wind velocities, the rotor spins with blades that operate efficiently in flow pattern. Rotor blade always generates a turbulent wake whenever it faces the air stream. If the coming blade in the spinning rotor passes through this wake, it can extract less power from the wind due to turbulence. So vibration stress can be induced in it. If rotor rotates very slowly at a lower wind velocity such as 4.5 m/s, then the air striking each rotor blade can no longer be turbulent so that maximum power can be extracted from the wind. In current research, as shown in Table 3 at a wind velocity of 4.5 m/s, the power coefficient increases up to 0.58 due to very less turbulence at this wind speed. Moreover, the power coefficient decreases when the pitch angle increases. Therefore, the pitch angle is kept less than 0° to obtain the experimental values of C_p at 4.5 m/s wind velocity.

The comparison is made between C_p obtained in current research at given TSR and C_p limit imposed by the Betz's law, as shown in Fig. 6. The percentage error is calculated as 5%. The effects of pitch angle on conversion efficiency and power coeffiecent are analyzed in

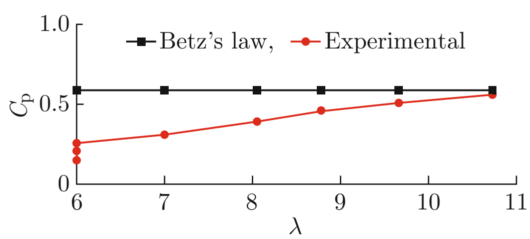

Fig. 6 Error analysis for experimental values of C_p

Figs. 7 and 8. Figure 7 shows that as pitch angle increases, the conversion efficiency ξ first increases and then decreases, and maximum conversion efficiency is at 15°.

Figure 8 illustrates that C_p is maximum for the pitch angle at 15°—17°. As the designed velocity is 6 m/s for this research, it is clear from Fig. 8 that the power coefficient can reach maximum at this designed velocity. Maximum power coefficient is achieved at a designed velocity of 6 m/s. To verify designed wind turbine, Warlock wind turbine design calculator is used. Different values of power are checked by varying designed parameters like wind velocity, TSR and efficiency factor, as shown in Fig. 9.

Analysis is also performed on simulation software ANSYS Fluent to verify designed wind turbine. The results are described in Figs. 10—12, where C_d is the drag coefficient.

In Fig. 12, velocity contours show the velocity variations at turbine blade. The blue color which is the designed velocity parameter of this research is very close to the turbine blade. This means that blade designing is perfect according to wind speed range.

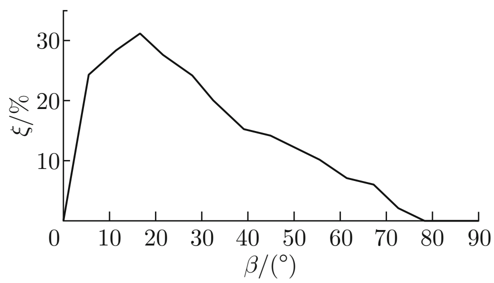

Fig. 7 Relationship between pitch angle and conversion efficiency

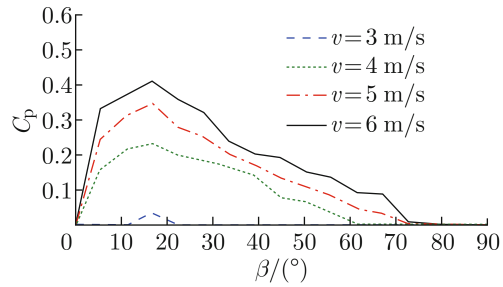

Fig. 8 Relationship between pitch angle and power coefficeint

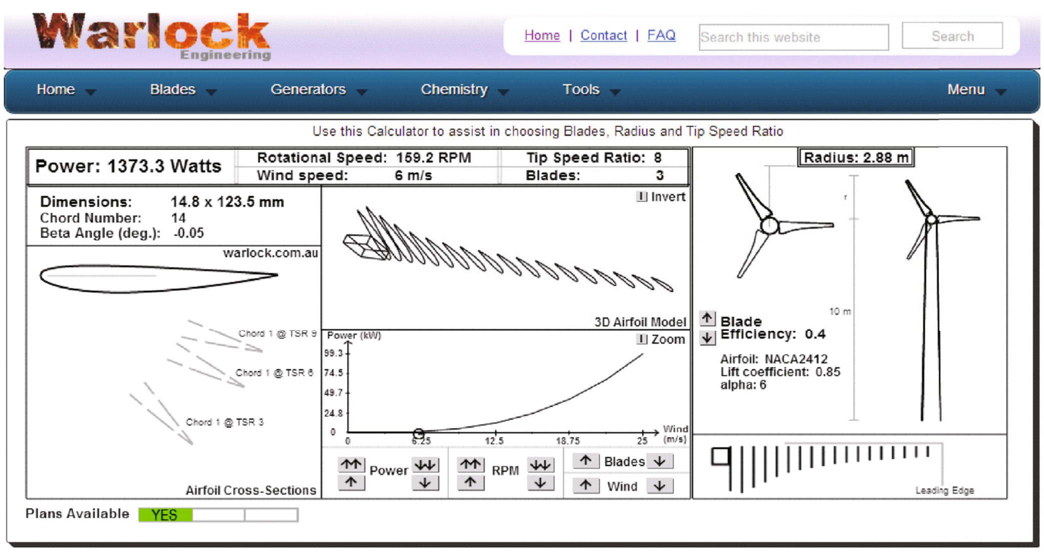

Fig. 9 Snapshot of Warlock wind turbine blade calculator

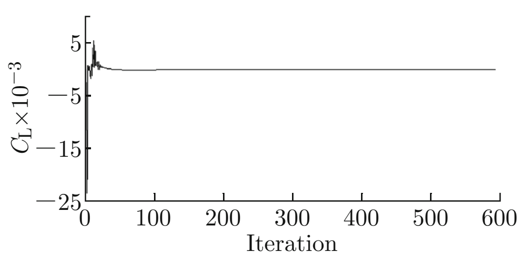

Fig. 10 Lift coefficient graph

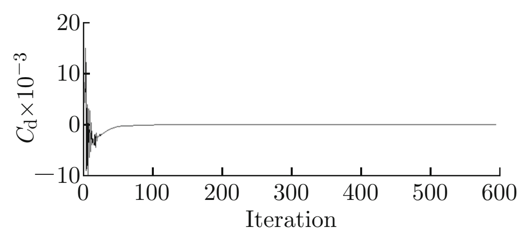

Fig. 11 Drag coefficient graph

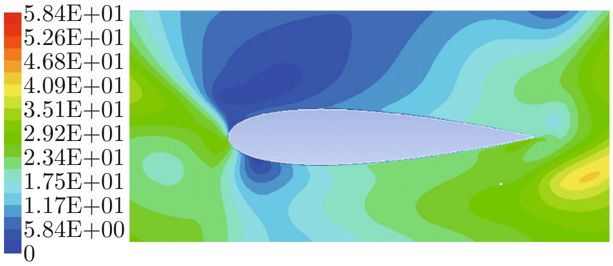

Fig. 12 Velocity contours of NACA 2412 digit airfoil generator (m/s)

3 Conclusion

The fundamental goal of current research is to provide an essential base for further study and improvements in the extraction of wind energy. This research presents the accurate design and calculations for a horizontal axis wind turbine to fulfill energy demands at small scales in Pakistan. From current design and calculations, it can be concluded that the power coefficient varies slightly with wind velocity and its value is higher at lower wind velocities as compared with high wind velocity. At maximum power, TSR and power coefficient both decrease with the increase of the blade pitch angle. Moreover, these calculations and design for extraction of energy from wind are suitable to provide sustainable, pollution free and decentralized energy system.

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