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Design of Horizontal Axis Wind Turbine

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Abstract— The objective of this study is to design a wind turbine. The design process includes the selection of the wind turbine type and the determination of the blade airfoil, pitch angle distribution along the radius, and chord length distribution along the radius. The pitch angle and chord length distributions are optimized based on conservation of angular momentum and theory of aerodynamic forces on an airfoil. Blade Element Momentum (BEM) theory is first derived then used to conduct a parametric study that will determine if the optimized values of blade pitch and chord length create the most efficient blade geometry. This work includes a discussion of the most important parameters in wind turbine blade design to maximize efficiency. QBlade V0.8, an integration of different versatile software like xfoil, XLR5, 360 extrapolation using Montgomerie and Viterna theory, has been used for simulation.

Key words: Wind Turbine, HAWT, BEM Theory, Parametric Study, Maximization of efficiency and QBlade V0.8.

I. INTRODUCTION

Wind energy is one of the clean renewable forms of energy that can handle the existing global fossil fuel crisis. Although it contributes to 2.5% of the global electricity demand, with diminishing fossil fuel sources, it is important that wind energy is harnessed to a greater extent to meet the energy crisis and problem of pollution.

According to the Global Wind Energy Council (GWEC) the global installed power capacity of wind energy at the end of 2013 is 318105 MW [1]. Wind Energy has very high potential in tropical climatic conditions where the wind speed is relatively steady.

The Gujarat government, which is banking heavily on wind power, has identified Samana as an ideal location for installation of 450 turbines that can generate a total of 360 MW. To encourage investment in wind energy development in the state, the government has introduced a raft of incentives including a higher wind energy tariff. Samana has a high tension transmission grid and electricity generated by wind turbines can be fed into it. For this purpose, a substation at Sadodar has been installed. Both projects are being executed by Enercon Ltd, a joint venture between Enercon of Germany and Mumbai-based Mehra group.

In order to successfully design an efficient wind turbine, the blade contour must take advantage of aerodynamic considerations while the material it is made from provides the necessary strength and stiffness. By investigating the aerodynamic characteristics of a wind turbine blade, the parameters that make up the blade contour are optimized, and the loads that test its structural adequacy are calculated. Only aerodynamic principles are being analyzed in this study.

In order to define the power extracted from the wind by the wind turbine, conservation of linear momentum and Bernoulli's principle were used to arrive at the Betz limit. Schmitz developed a more comprehensive model of the flow in the rotor plane based on conservation of angular momentum.

A. *Basic Terms related to Design*

1) *Chord Length and Blade Pitch*

Chord refers to the imaginary straight line joining the leading and trailing edges of an aerofoil. The chord length is the distance between the trailing edge and the point on the leading edge where the chord intersects the leading edge. Blade pitch refers to turning the angle of attack of the blades of rotor into or out of the wind to control the production or absorption of power. It is used to adjust the rotation speed and the generated power for wind turbine.

The pitch of the blade is distributed along its radius to ensure the relative wind direction is intercepting the blade at the desired angle of attack. And the chord length is optimized to provide maximum lift along the blade's radius.

2) *Efficiency of Wind Turbine*

Wind turbine efficiency is quantified by a non-dimensional value called the coefficient of power C_P, which is the ratio of power extracted from the wind, P, to the total power in wind crossing the turbine area.

$$C_P = 4a(1-a)^2$$

B. *Blade Element Momentum (BEM) Theory [2]*

BEM theory is a compilation of both momentum theory and blade element theory. Momentum theory, which is useful in predicted ideal efficiency and flow velocity, is the determination of forces acting on the rotor to produce the motion of the fluid. Blade element theory determines the forces on the blade as a result of the motion of the fluid in terms of the blade geometry. By combining the two theories, BEM theory, relates rotor performance to rotor geometry. Two relationships required for BEM theory are given below.

$$\frac{a}{a-1} = \frac{\sigma C_y}{4\sin^2(\phi)}$$

$$\frac{a'}{a'+1} = \frac{\sigma C_x}{4\sin(\phi)\cos(\phi)}$$

Including the Prandtl tip loss correction factor, above two parameter results as follow,

$$a = \frac{1}{\left(\frac{4F_P\sin^2(\phi)}{\sigma C_y}+1\right)}$$

$$a' = \frac{1}{\left(\frac{4F_P\sin(\phi)\cos(\phi)}{\sigma C_y}-1\right)}$$

These equations are only accurate in computing axial interference factors for values less than 0.2, above which simple momentum theory starts to break down. When a > 0.2, the correction factor will be used that was formulated by Glauert [3] and redefined in terms of the average axial interference factor [4] as below.

$$a = \frac{1}{2}\left(2 + K(1-2a_c) - \sqrt{(K(1-2a_c)+2)^2 + 4(Ka_c^2 - 1)}\right)$$

Torque(T) and Thrust (T_h) for each blade segment is calculated by,

$$T(r) = \frac{1}{2}\rho w^2 c C_x r$$

$$T_h(r) = \frac{1}{2}\rho w^2 c C_y r$$

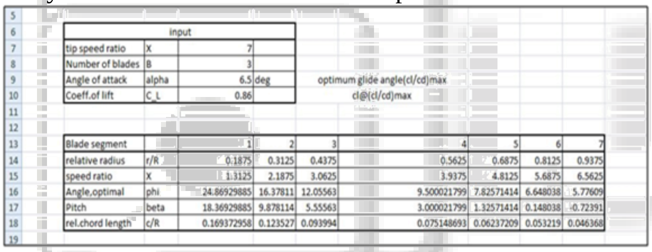
The total axial force and power are

$$T_h = B\int_0^R T_h(r)dr$$

$$P = \omega B\int_0^R T(r)dr$$

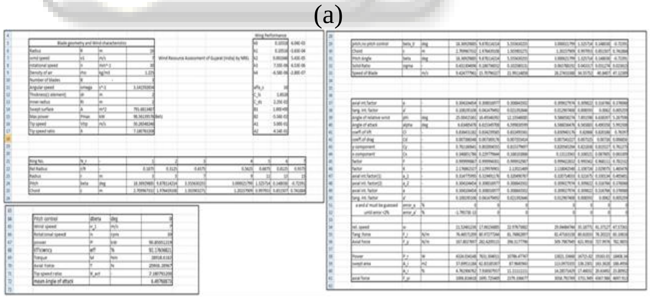
II. DESIGN OF BLADES AND TURBINE

The geometry of the blades is determined by the task to transform as much energy as possible from the incoming air flow into mechanical, respectively electric power. Thus the aerodynamic design of the windmill should fulfill the minimum induced loss principle. During the preliminary design of the blades, the operating conditions for the local airfoil sections were defined in terms of Reynolds and Mach numbers as well as lift coefficient range. These conditions were used for the design of new airfoils, which were then used in the windmill design method to find the optimum blade shapes. Later additions to the code make it possible to account for the boundary layer of the ground by performing several analysis at different azimuthal blade positions.



input									
tip speed ratio	X	7							
Number of blades	B	3							
Angle of attack	alpha	6.5	deg	optimum glide angle(cl/cd)max					
Coeff.of lift	C_L	0.86		cl@(cl/cd)max					
Blade segment		1	2	3	4	5	6	7	
relative radius	r/R	0.1875	0.3125	0.4375	0.5625	0.6875	0.8125	0.9375	
speed ratio	X	1.3125	2.1875	3.0625	3.9375	4.8125	5.6875	6.5625	
Angle,optimal	phi	24.86929885	16.37811	12.05563	9.500021799	7.82571414	6.648038	5.77609	
Pitch	beta	18.36929885	9.878114	5.55563	3.000021799	1.32571414	0.148038	-0.72391	
rel.chord length	c/R	0.169372958	0.123527	0.093994	0.075148693	0.06237209	0.053219	0.046368	

(a)



(b)

Fig. 1: Design of blades in Excel Sheet for airfoil NACA 23012

The size of the wind turbine is the first constraint in designing a wind turbine. Data shows that the higher a wind turbine sits off the ground, the greater the wind speeds are, and the available power for a turbine increases with the cube of the wind velocity. Another parameter of the wind turbine design that is constrained by the allowable height of the structure is the size of the blades. Since the maximum theoretical power output of a wind turbine is proportional to the square of the blade length, it is also important to maximize the blade length as much as the zoning regulations allow. So that we have selected R = 16m, v = 7m/s (average at 50m) and hub height = 50m based on the weather data available on IRENA.

A. Selection of Airfoil

There are many airfoils available from UIUC [5]. We have selected few from them which can be used in wind turbine blades (at low Reynolds number) which are FX84W97, FX84W127, FX84W140, FX84W150, FX84W150, FX84W175, FX84W218, AH93W145, AH93174, AH93215, AH93257, AH93300, AH93480b. Selection of airfoil for blade design is done by considering maximum and gradual values of CL/CD for given angle of attack.

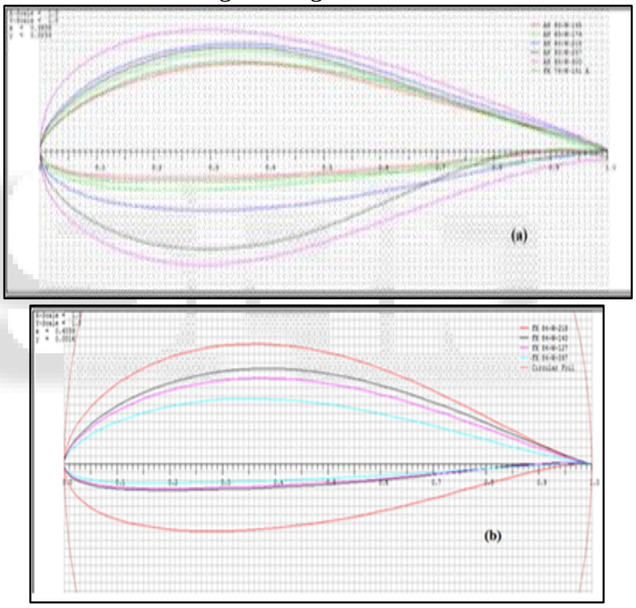


Fig.2: Airfoils (a) FX84 series (b) AH93 series

Tip Speed Ratio(Assumed)	X	6
No. of Blades	B	3
Angle of attack (@ max C_L/C_D)	Alpha	8.5
Coefficient of Lift (@ max C_L/C_D)	C_L	1.33

Table 1: Designated parameters

Blade Segment	-	1	2	3	4	5	6	7
Relative radius	r/R	0.187	0.312	0.437	0.562	0.687	0.8125	0.937
Speed ratio	X	1.125	1.875	2.625	3.375	4.125	4.875	5.625
Angle, optimal	phi	27.755	18.714	13.902	11.002	9.084	7.728	6.720
Pitch	beta	19.255	10.214	5.402	2.502	0.584	-0.771	-1.779
Rel. chord length	c/R	0.135	0.104	0.080	0.0651	0.0543	0.046	0.040

Table: 2: Optimized Dimensionless Wind Turbine Blade Geometry

Table: 2 contain the pitch angle and relative chord length for each of the 7 blade segments (8 segments minus the inner-most segment for the hub). The values in the table are dimensionless so that the distributions of pitch and chord length can be applied to a blade of any size. Each segment is assumed to have constant aerodynamic properties, pitch, and chord length, so having more blade segments creates a more accurate analysis. Using a constant wind velocity of 7m/s, which was determined to be the average wind speed for the Samana village, Gujarat at a height of 50 meters, the rotational velocity of the turbine was changed until it created a tip speed ratio of about 6. Since the blade was optimized for a tip speed ratio of 6, it should be the ratio that most efficiently extracts power from the wind.

B. *Design of Turbine*

Power Regulation	Pitch control
Transmission	Variable
Power	150kW
V cut in	2 m/s
V cut out	20 m/s
Rotational min speed	10 rpm
Rotational max speed	40 rpm
Tip speed ratio at design	6.7
Outer Radius	16 m
Orientation	Upwind

Table: 3: Design specification for Turbine

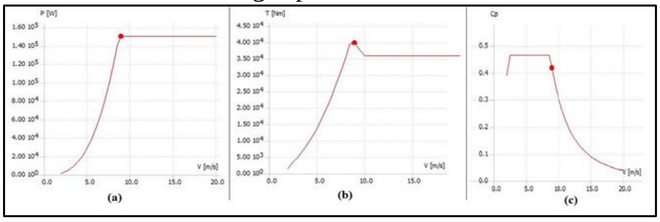


Fig.3: Characteristics Curves of turbine (a) Power vs Wind speed (b) Torque vs Wind speed (c) CP vs Wind speed

III. RESULTS

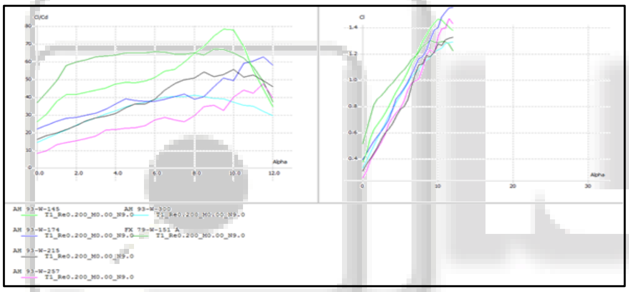


Fig. 4: C_L/C_D vs. Alpha and C_L vs. Alpha for FX84 series airfoils

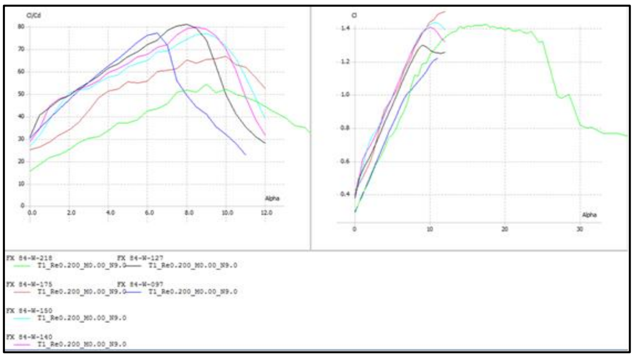
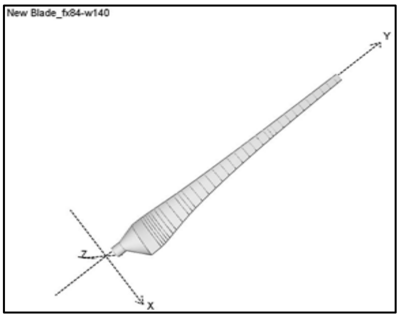


Fig. 5: C_L/C_D vs. Alpha and C_L vs Alpha for AH93 series airfoils



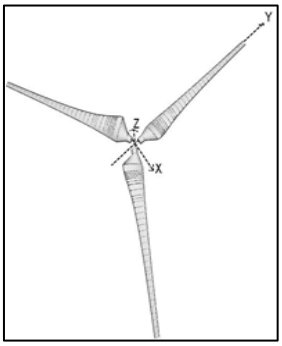


Fig. 6: 3D Model of blade and rotor FX84-W140

By observing above graphs in Fig.4 & Fig.5 carefully one can decide that FX84W140 airfoil have high C_L/C_D value of 79.8 at Alpha 8.5. At this Alpha = 8.5, co-efficient of lift C_P=1.33.

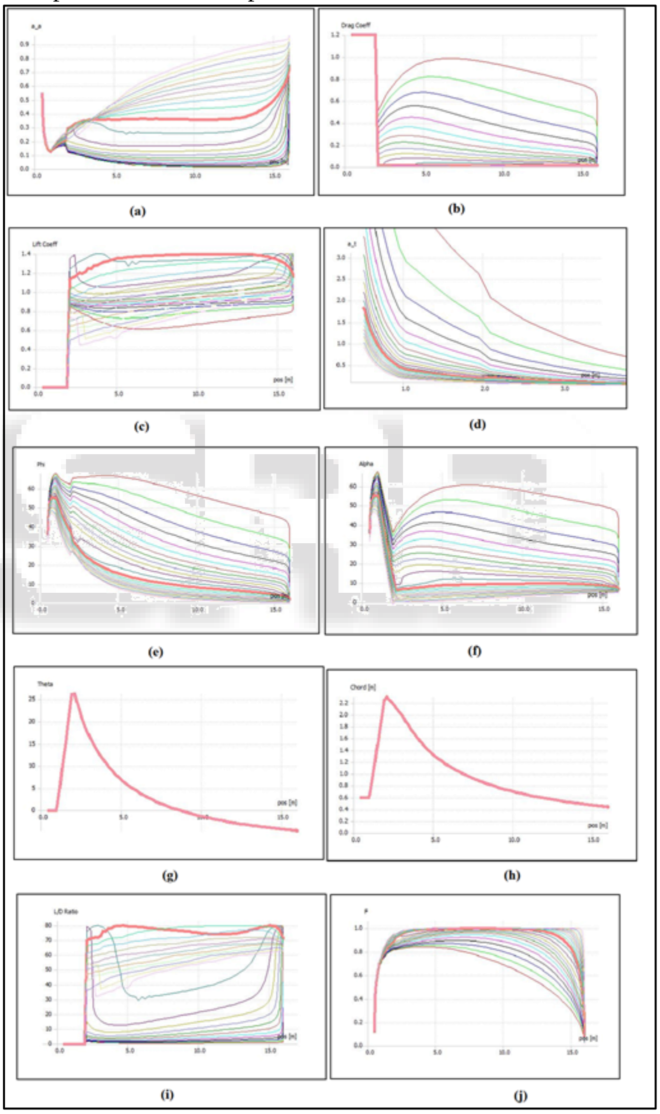


Fig. 7: Various Parameters Vs Radial Position Graphs (a) Axial induction factor (b) Drag Coefficient (c) Lift Coefficient (d) tangential induction factor (e) Angle of incidence/Relative wind Angle (f) Angle of Attack (g) Blade Twist Angle (h) Chord Length (i) Lift to Drag Ratio (j) prandlt Tip loss factor

In above Fig.7, Dark pink line indicates tip speed Ratio (TSR)=7 and other lines are for varied TSR from 1 to 12.Co-ordinates for all graphs at TSR=7 are provided in appendix section at the end.

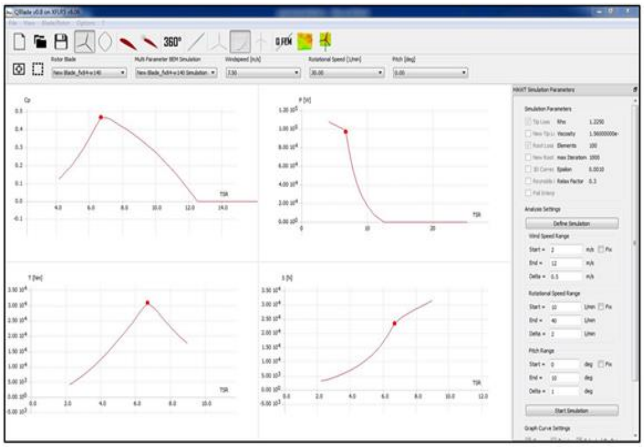


Fig. 8: Simulation of design parameters in QBlade v0.8.

Parametric test for wind speed range 2 to 12 (d = 0.5), Rotational speed range 10 to 40 (d = 2), and pitch angle 0 to 10 (d = 1) display result in form of graph as shown in Fig.8. By keeping wind speed constant and changing rotational speed different result are obtained for coefficient of power, Power, Torque and Thrust force. As shown in Fig.8, in our case we get maximum co-efficient of power = 4.65 for wind speed = 7.5 and rotational speed = 30 which will produce power approximately near 100 kW.

Here one important thing to notice is that we get maximum Cp at TSR = 6.7 which is different from design TSR = 6. This result indicates that value of TSR should be kept low in design than desired value of TSR in actual conditions.

Average wind speed	$v_{average}$	m/s	7
Rotational speed	u	m/s	28
Power	P	kW	78.620
efficiency	eff. (related to betz limit)	%	79.76
Torque	M	Nm	26812.6
Axial Force	T	N	20380
Tip Speed Ratio	X_act	-	6.702
Mean Angle of Attack	Alpha_mean	deg	8.95
Coefficient of power	C_p	-	0.465
Rated wind speed	v_{rated}	m/s	9
Rotational speed	u	m/s	36
Rated Power	P_{rated}	kW	150
efficiency	$Eff._{rated}$(related to betz limit)	%	71.60
Torque	M	Nm	39800
Coefficient of power	C_p	-	0.418

Table: 4: Overall Design

IV. Conclusions

Optimizing the parameters that define a wind turbine blade is a process that requires knowledge of both momentum theory and blade section aerodynamic theory. By equating the thrust force on the rotor with the axial momentum force, one is able to solve for axial interference factor (a) and by equating the torque force with the angular momentum force on the rotor, one is also able to solve for the tangential interference factor (a’). And finally, one is able to calculate the power produced by the wind turbine, by using an iterative process to solve for (a) and (a’). Using this process of determining the efficiency of a wind turbine, one is able to test a range of values for any given parameter in a design and determine which values optimize the output.

Optimizing the pitch angle was accomplished by formulating an equation based on conservation of angular momentum, which gave the pitch angle as a function of blade radius. The most efficient angle of attack was based on the angle of attack corresponding to the greatest ratio of coefficient of lift to coefficient of drag, which is a known value for any given airfoil.

The assumption which was made without much prior knowledge was the value of tip speed ratio. Since the effect that the tip speed ratio would have on the turbine performance was not known, a parametric study was conducted which demonstrated that based on the methods of defining the pitch angle and chord length, the tip speed ratio that is chosen to shape the blade should be less than the expected value that the turbine encounters. Doing so will ensure the turbine operates at peak efficiency.

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