Project Exercise 1
Design And Testing of a Wind Turbine Rotor

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ENE416-G 23H Wind Energy

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Introduction

In aerodynamics, the design of a rotor refers to the process of constructing and optimizing the shape, size, and characteristics of the rotor blades for optimal performance in applications such as wind turbines, helicopters, and other rotating machinery. In the context of wind turbines, rotor design involves determining the optimal blade length, shape, airfoil profiles, and twist distribution along the blade length. These parameters are essential for maximizing wind energy capture and conversion[1].

Designing an efficient rotor is essential for maximizing energy conversion, minimizing losses, enhancing performance, assuring safety, and achieving environmental objectives. It enables optimal energy extraction, minimizes energy waste, enhances system performance, reduces noise and vibrations, ensures dependability, and contributes to environmentally conscious practices.

Various methods and models are utilized in rotor design to optimize performance and accomplish desired characteristics[2]. Here are some common methodologies and models used in the design of rotors:

Analytical Models: Analytical models depict the rotor system and its aerodynamic performance in a simplified manner. These models use mathematical equations and formulas to estimate critical parameters such as lift, drag, and power output.

Computational Fluid Dynamics (CFD): CFD is a powerful instrument used in rotor design to simulate and analyze the airflow around the rotor blades.

Wind Tunnel Testing: Wind tunnel testing is the physical examination of scaled-down replicas of rotor systems in controlled wind tunnel environments.

Blade Element Momentum (BEM): BEM theory is a widely used method in the design of wind turbine rotors. It calculates the aerodynamic forces acting on each section based on local wind conditions, airfoil characteristics, and blade geometry. The BEM theory offers a straightforward yet effective method for estimating rotor performance and optimizing blade design.

Structural Analysis and Finite Element Method (FEM): Rotor design also includes structural analysis to guarantee that the blades can withstand the mechanical loads and stresses they will encounter during operation.

To analyze the aerodynamics of wind turbines, various theories, including the axial momentum theory, blade element theory, strip theory, etc., have been proposed . These hypotheses shed light on the behavior of wind turbine rotors under different operating conditions. However, the conventional analysis of horizontal axis wind turbines (HAWT) based on axial momentum theory assumes ideal flow conditions, an infinite number of blades, and equal static pressures in front of and behind the rotor[3]. In reality, wind turbines have a finite number of blades, and it is impossible to disregard aerodynamic drag and tip losses. In addition, the flow around the rotor is not axial as assumed under optimal conditions due to the rotational wake generated behind the rotor, resulting in energy loss and a decreased power coefficient.

Blade element theory (BEM) is extensively used to eliminate the limitations of axial momentum theory. Among the aforementioned methods, the BEM technique is the most popular due to its simplicity and relatively precise results. The AH 93-W-145 and SG6051 airfoils will be analyzed using the BEM theory and QBlade software in this report.

Methodology

The required methodology for this project has been described in this section.

Step 1: Download The Geometry of Airfoil

Get the Geometry of the airfoils from UIUC Airfoils Coordinates Database for blades[4].

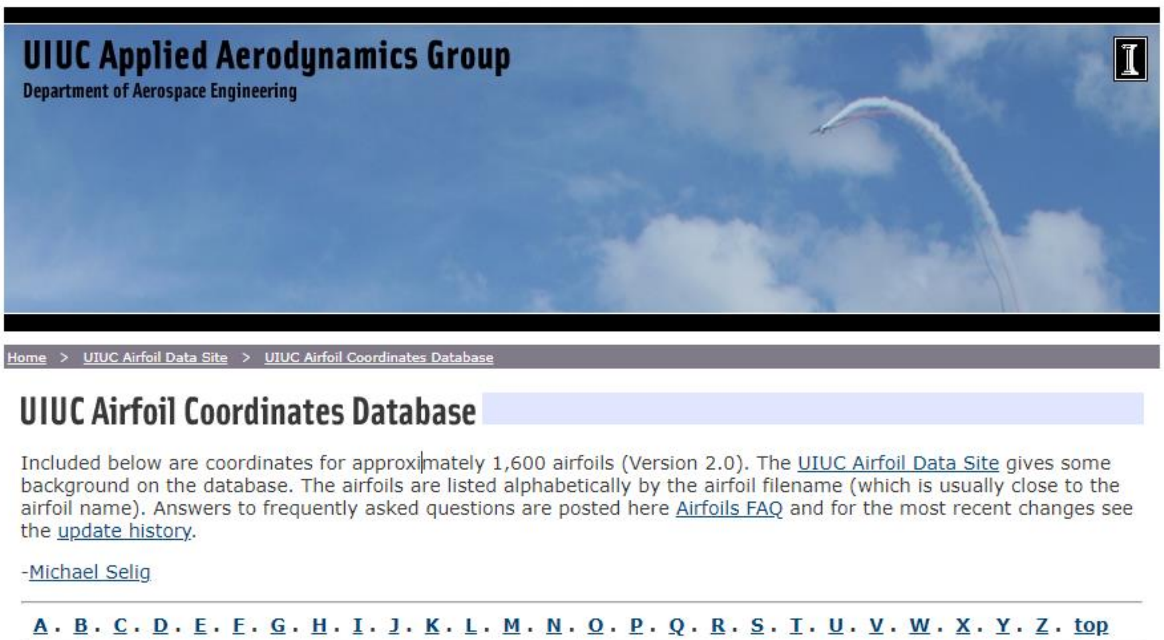


Fig.1. Interface of UIUC Airfoils Coordinates Database

Step 2: Start the project at Qblade

1)Import the Airfoil Geometry at Qblade.

Qblade: QBlade is an advanced Multiphysics software designed to aid in the aero-servo-hydro elastic design, prototyping, simulation, and certification of wind turbines. This potent tool facilitates simulations of wind turbine designs with physics models that are over 30 times faster than in real life. All these features are accessible via an intuitive and user-friendly graphical user interface. QBlade is platform-independent software that can be deployed on workstations or clusters operating under Windows, Unix, or MacOS. The software features an intuitive graphical user interface that assists the user throughout the entire wind turbine design procedure[5].

The Community Edition of QBlade (QBlade-CE) is available for free under the Academic Public License, while the Enterprise Edition (QBlade-EE) is available for purchase under a Commercial License. We will use the community edition here.

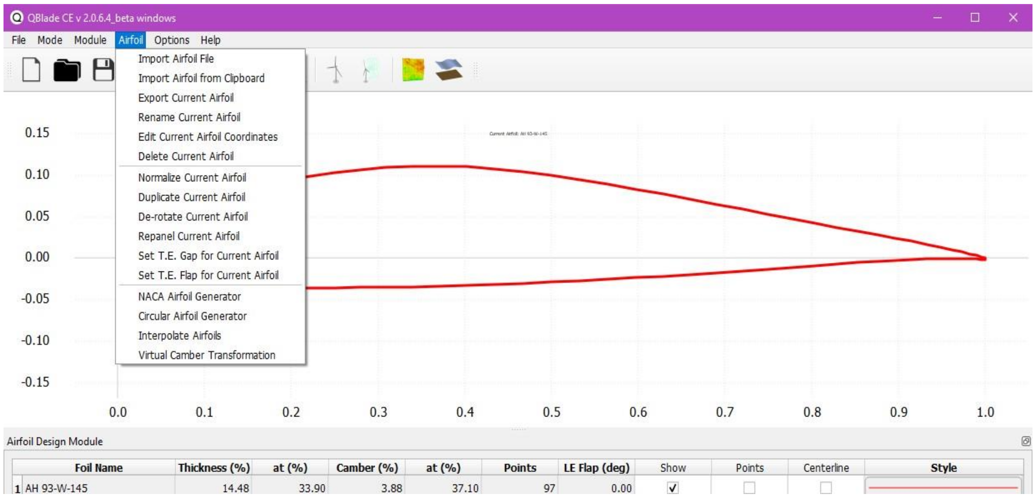


Fig.2. Import the Airfoil Geometry at Qblade

Step 3: Construct the Airfoils

1) Open Airfoil Analysis Module.
2) Create Polar Definition

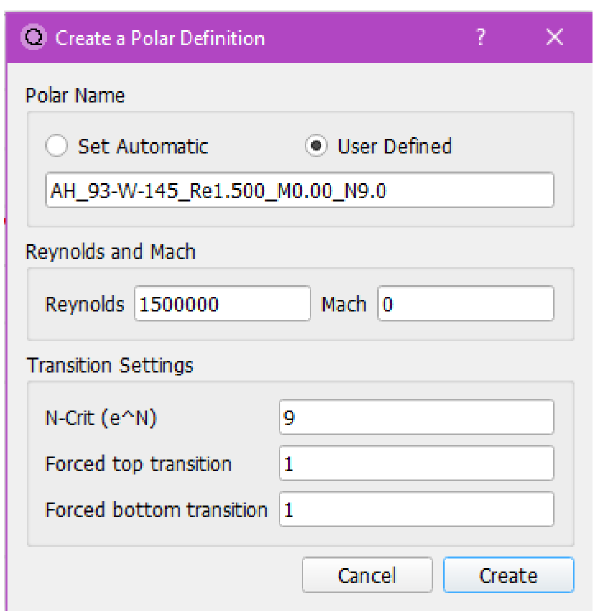


Fig.3. Creation of Polar Definition

3) Start Airfoil Analysis

From this analysis we will find lift coefficient and Drag Coefficient at different angle of attack.

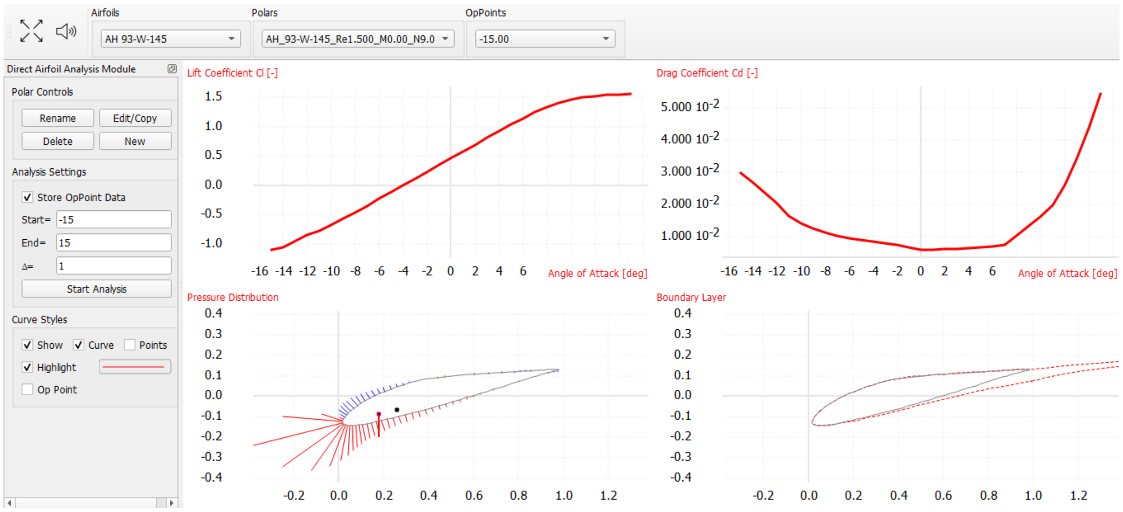


Fig.4. Airfoil Analysis

Step 4: Design the blade.

1)Lift to Drag Ratio

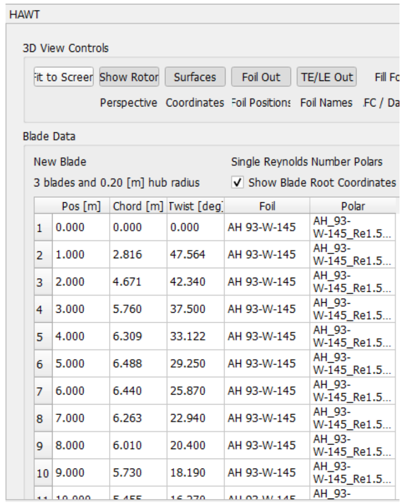
- In this step we have to export the data of lift coefficient and drag coefficient in another software like Excel or Matlab. We have used Matlab here. Then from there we must plot Lift to Drag Ratio at different angle of Attack. Then we finally determined the optimum angle of Attack.

2) HAWT Blade Design:

- In this step we have to calculate all the necessary blade design parameters[6]. The common parameters are:

✓ Radius of the rotor (R)
✓ Number of blades (B)
✓ Tip speed ratio of the rotor at the design point (λ_D)
✓ Cord Length
✓ Blade Setting Angle (β)

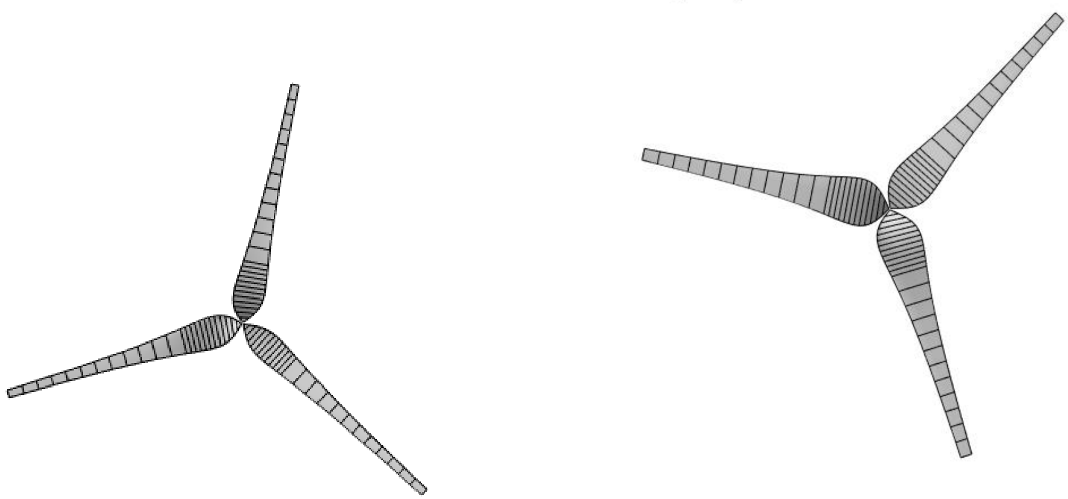
- Then we have to put the necessary values at 3D view control of blade to construct the blades at proper dimensions. At figure the tables for making AH-93-W-145 blade has been shown.



	Pos [m]	Chord [m]	Twist [deg]	Foil	Polar
1	0.000	0.000	0.000	AH 93-W-145	AH_93-W-145_Re1.5...
2	1.000	2.816	47.564	AH 93-W-145	AH_93-W-145_Re1.5...
3	2.000	4.671	42.340	AH 93-W-145	AH_93-W-145_Re1.5...
4	3.000	5.760	37.500	AH 93-W-145	AH_93-W-145_Re1.5...
5	4.000	6.309	33.122	AH 93-W-145	AH_93-W-145_Re1.5...
6	5.000	6.488	29.250	AH 93-W-145	AH_93-W-145_Re1.5...
7	6.000	6.440	25.870	AH 93-W-145	AH_93-W-145_Re1.5...
8	7.000	6.263	22.940	AH 93-W-145	AH_93-W-145_Re1.5...
9	8.000	6.010	20.400	AH 93-W-145	AH_93-W-145_Re1.5...
10	9.000	5.730	18.190	AH 93-W-145	AH_93-W-145_Re1.5...

Fig.5. Blade dimensions

At the figure 6 the designed AH-93-W-145 and SG6051 blades are presented.



(a) (b)

Fig.6. (a) AH-93-W-145 blade and (b) SG6051 blade

Step 5: Blade Element Momentum (BEM) analysis of the rotor

- At this step we will use Rotor BEM analysis to understand the different rotor characteristics and performance.
- We have to put all the necessary turbine data here.

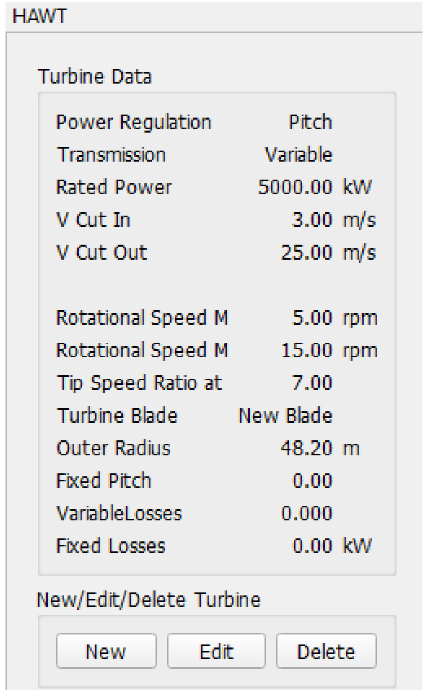


Fig.7. Turbine Data

- We can plot different performances curve of turbine using BEM analysis.

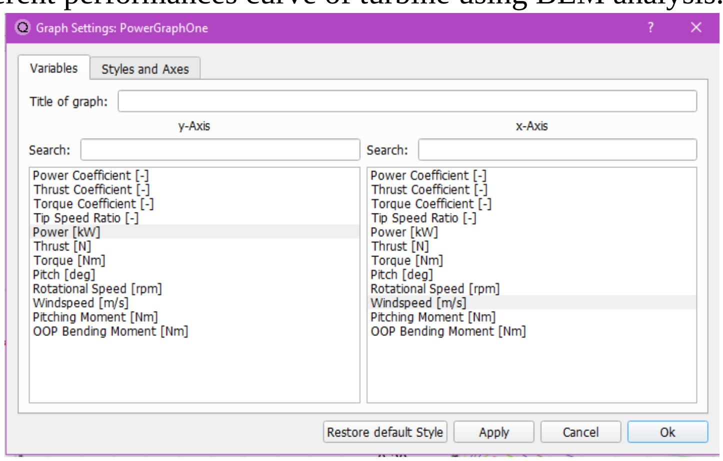


Fig.8. Graph settings

- For comparing the performances of two different blades we will use Matlab for better understanding.

Flow Chart:

The whole process of designing the rotor is presented by a flow chart in figure 9.

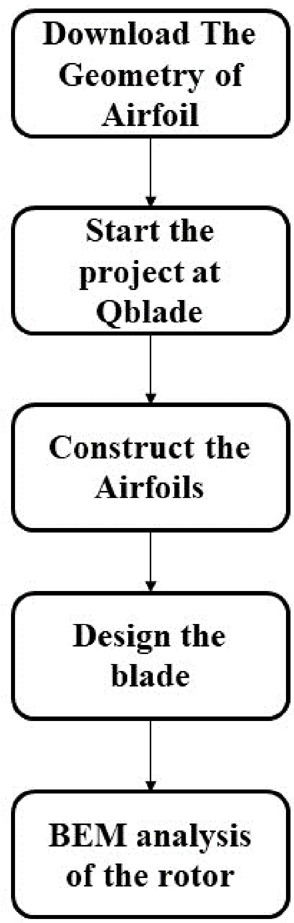


Fig.9. Flow chart of Methodology

Result and Analysis

Lift Force: When wind travels across the rotor blades of a wind turbine, an aerodynamic lift force is generated. It is responsible for generating electricity by causing the rotor to rotate. The lift force is generated by the difference in air pressure between the blade's two surfaces. Due to the blade's typical curvature, air traveling over the upper side must cover a greater distance per unit of time than air traveling through the lower side. Therefore, the air particles in the upper layer travel more quickly. This, according to Bernoulli's theorem, should produce a low-pressure region at the airfoil's tip. This pressure difference between the upper and lower surfaces of the airfoil will result in a force F. The component of this force perpendicular to the direction of the undisturbed flow is called the lift force L[1].

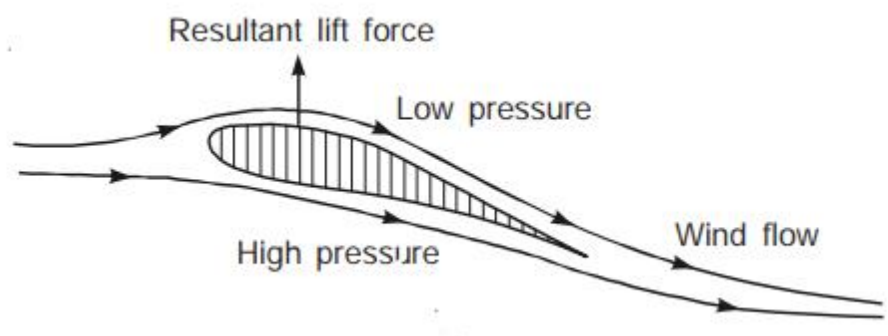


Fig.10. Lift Force

Drag Force: A wind turbine's drag force is an aerodynamic force that operates parallel to the direction of the wind that is blowing. It is one of the main aerodynamic forces that has an impact on how well a wind turbine works. The pressure differential between the turbine blade's front and back as the wind passes over it is what generates the drag force. This force tends to slow down the blade's speed because it acts in the opposite direction. The force in the direction of the undisturbed flow is called the drag force D.

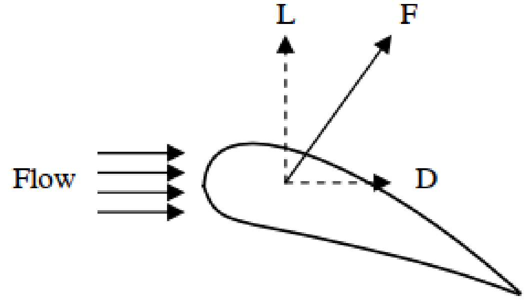


Fig.11. Drag Force

The lift force is given by,

$$L = \frac{1}{2} C_L p_a AV^2 \quad ......(1)$$

The Drag force is given by,

$$D = \frac{1}{2} C_D p_a AV^2 ......(2)$$

Where,

$C_L = Lift\ Coefficient$

$C_D = Drag\ Coefficient$

$p_a = Air\ Density$

$A = Area\ of\ Wind\ Turbine$

$V = wind\ Velocity$

Angle of Attack: The angle between the chord line of the turbine blade and the direction of the incoming wind is known as the angle of attack (α) in wind turbines. It is a significant factor that influences the wind turbine's overall effectiveness and the blade's aerodynamic performance[6].

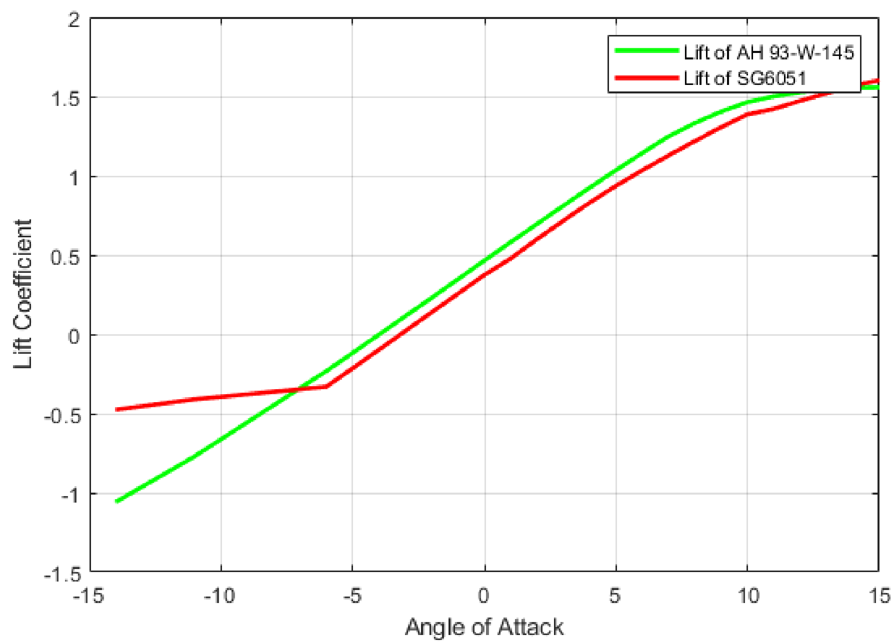


Fig.12. Lift Coefficient of **AH 93-W-145 and SG6051** blade

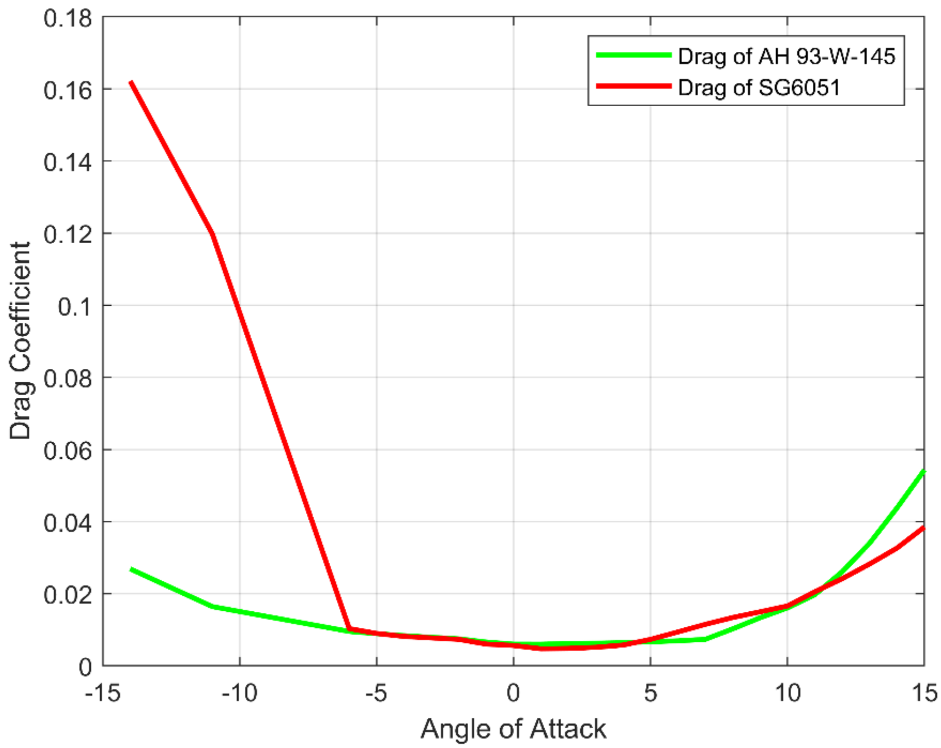


Fig.13. Drag Coefficient of **AH 93-W-145 and SG6051** blade

The effect of angle of attack on the lift coefficient and Drag of an airfoil is depicted in Figure 3 and 4. At smaller assault angles, the lift force increases with D. The lift of an airfoil reaches its optimum at a specific D angle (8 degree in AH 93-W-145 blade) and then decreases rapidly as D increases further. At high attack angles, the airflow enters a region of excessively turbulent flow, and the boundary layers separate from the airfoil. In this region, lift force decreases and drag force swiftly increases, causing the blade to stall.

Lift to Drag Ratio: Lift-to-Drag ratio is the ratio of the lift force to the drag force operating on the turbine blades. It is a measurement of the equilibrium between the drag and lift forces and can shed information on the turbine's aerodynamic performance.

Wind turbines are typically designed to have a higher lift-to-drag ratio, as a greater lift force enables more efficient power generation. A greater lift-to-drag ratio indicates that the lift force is greater than the drag force, which results in a more efficient conversion of wind energy into rotational energy. In a given flow, it is crucial to place the airfoil at the optimal angle of attack so that the CL-CD ratio is maximized. At figure 5 and 5 the Lift to Drag ratio for both the blades are presented[7].

The optimal angles of attack for AH 93-W-145 and SG6051 are **7^o and 4^o** respectively where the lift to drag ratio is maximized.

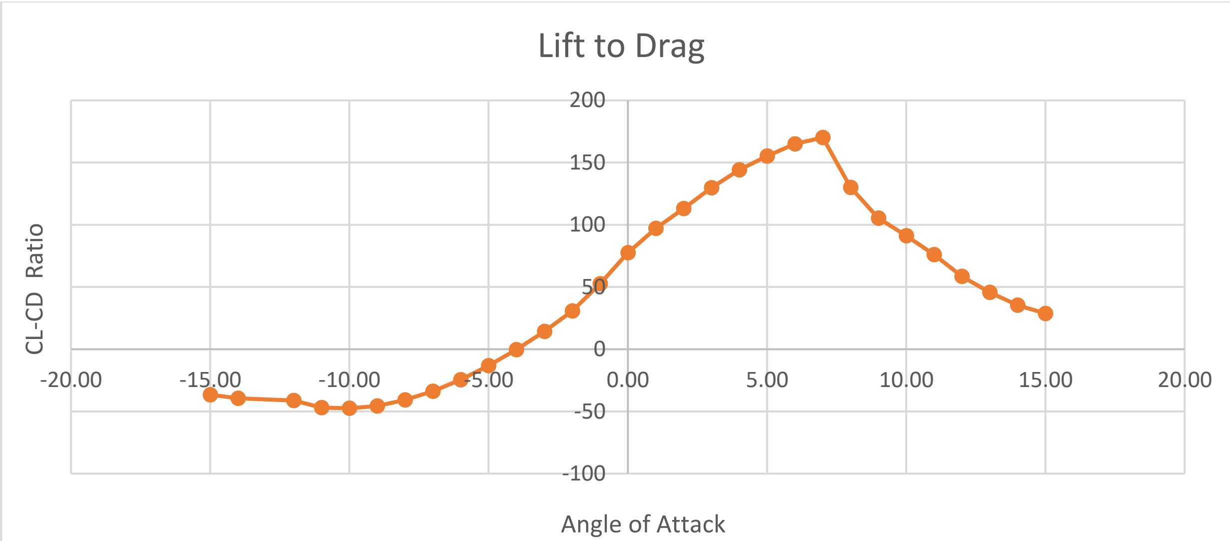


Fig.14. Optimal Angle of Attack for AH-93-W-145 blade(7°)

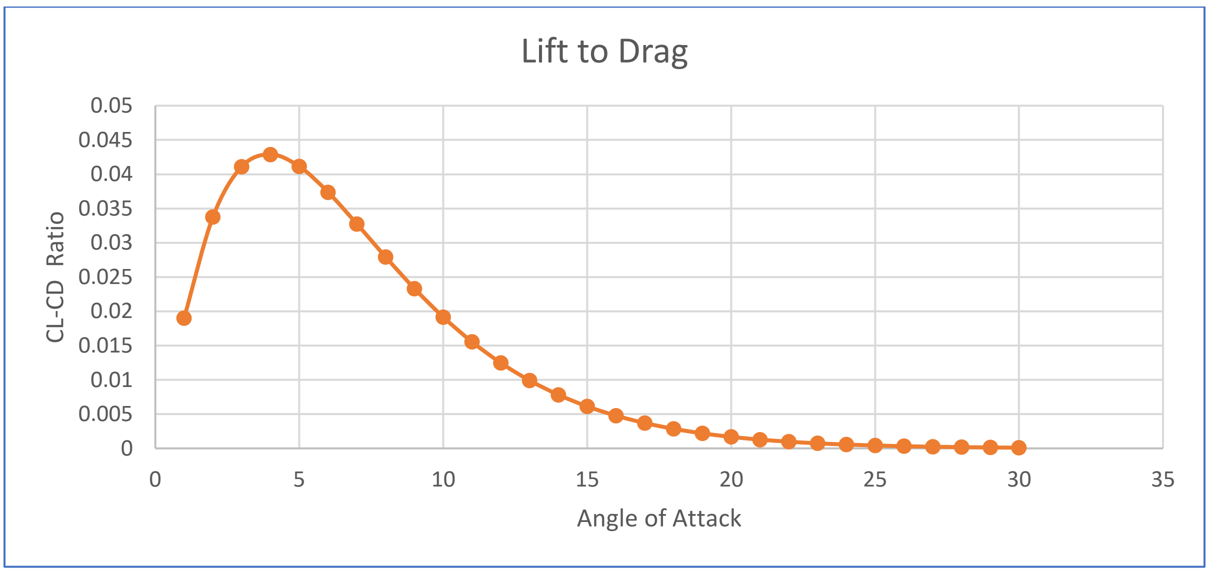


Fig.15. Optimal Angle of Attack for SG6051 blade(4°)

Designing of Turbine Rotor:

Design Parameters:

1. Radius of Rotor(R): The rotor's diameter is mainly determined by the expected output of the turbine and the wind conditions in which it operates. Various losses associated with the energy conversion process must also be considered[6].

$$R = \left[\frac{2P_D}{C_{PD}\eta_d\eta_g\rho_a\pi v_d{}^3}\right]^{\frac{1}{2}} \text{......(3)}$$

P_D = Power expected from the turbine at its design point = 5 MW

C_{PD} = Design power coefficient = 0.45

η_d= The drive train efficiency

η_g = The generator efficiency

$\eta_d \eta_g = Combined\ efiiciency = 0.9$

$\rho_a = Air\ Density = 1.224\ kg/m^3$

v_d = Wind velocity= 14 m/s

The radius of the rotor is, R = 48 m approximately

2. Number of blades (B) and Design Tip Speed Ratio (λ_D):
   A wind turbine's tip speed ratio (TSR) is the ratio of the speed of the blade tips to the speed of the wind. The turbine's design tip speed ratio is dependent on the application for which it is being developed. For aero generators λ_D may be higher than 5 where we require a relatively fast running rotor hence high tip speed ratio. In our case we have selected it as 7 as the number of blades are 3 in our case[6].
   The number of rotor blades is directly proportional to the design tip speed ratio. The number of blades would decrease as tip speed ratio increased. A relation between this two has presented in figure 16.

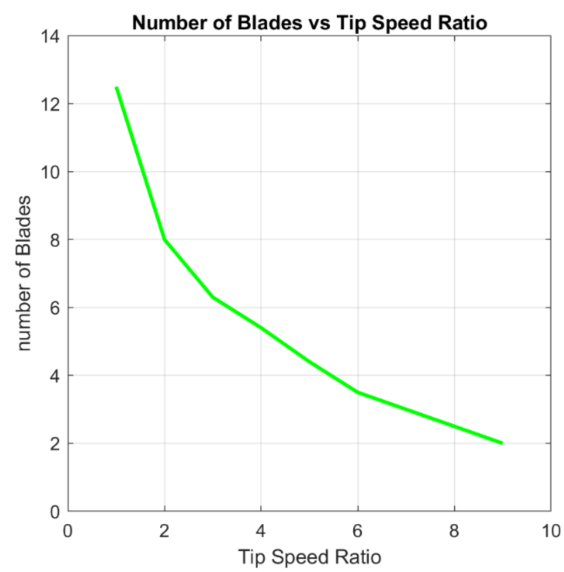


Fig.16. Number of blades and design tip speed ratio.

3. Cord Length (C) and Blade Setting Angle (β): It is the line joining the leading edge and the trailing edge of wind turbine airfoil. The blade setting angle of an airfoil is the angle at which the airfoil is set or positioned with respect to the wind or airflow direction.

C and β of a blade section at a distance "r" from the center can be determined by the following sets of relationships.

Local tip speed ratio $\lambda_r = \frac{\lambda_D \times r}{R}$ ……(4)

The relation between optimum angle of attack and the blade setting angle is presented in figure 17.

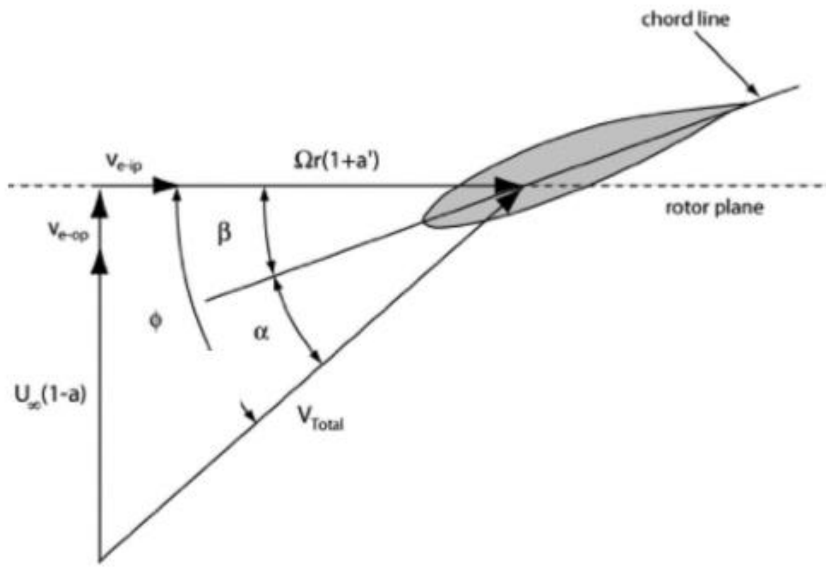


Fig.17. Blade setting angle and angle of attack.

$$\varphi = \frac{2}{3} tan^{-1} \frac{1}{\lambda_r} \text{……(5)}$$

$$\beta = \varphi - \alpha \quad \text{……(6)}$$

$$C = \frac{8\pi r}{BC_{LD}}(1 - cos\varphi) \text{ ……(7)}$$

Here we have divided blades into a few sections to find the roto design values for both blades. At table 1 the design parameters at different r is presented for AH-93-W-45 blade.

Table 1: Design Parameters for AH 93-W-145 blade

Distance	λ_r	$\varphi(Radian)$	φ (degree)	$\beta(Radian)$	β(Degree)	C
0	0	1.046666	59.9694	52.9694	0.916959	0
1	0.143266	0.952332	54.56448	47.56448	0.823394	2.816318
2	0.286533	0.86116	49.34072	42.34072	0.732965	4.670573
3	0.429799	0.776578	44.49456	37.49456	0.649072	5.764143
4	0.573066	0.700278	40.12287	33.12287	0.573394	6.308985
5	0.716332	0.632795	36.25641	29.25641	0.506461	6.488367
6	0.859599	0.573837	32.87838	25.87838	0.447983	6.441072
7	1.002865	0.522645	29.94528	22.94528	0.397208	6.263006

8	1.146132	0.478275	27.40307	20.40307	0.3532	6.016311
9	1.289398	0.439771	25.19698	18.19698	0.31501	5.739385
10	1.432665	0.406255	23.27664	16.27664	0.281767	5.455011
11	1.575931	0.376956	21.59794	14.59794	0.252707	5.176127
12	1.719198	0.35122	20.12338	13.12338	0.22718	4.909648
13	1.862464	0.328499	18.82154	11.82154	0.204644	4.658876
14	2.005731	0.308336	17.66631	10.66631	0.184646	4.424995
15	2.148997	0.290354	16.63605	9.636047	0.166811	4.207989
16	2.292264	0.274241	15.71279	8.712788	0.150828	4.007184
17	2.43553	0.259734	14.88162	7.881616	0.13644	3.821577
18	2.578797	0.246617	14.13009	7.130091	0.12343	3.650031
19	2.722063	0.234709	13.44779	6.447794	0.111618	3.491383
20	2.86533	0.223856	12.82596	5.825962	0.100854	3.344505
21	3.008596	0.213929	12.25719	5.257187	0.091008	3.20834
22	3.151862	0.204818	11.73518	4.735181	0.081971	3.08191
23	3.295129	0.19643	11.25458	4.254576	0.073651	2.964324
24	3.438395	0.188684	10.81077	3.810769	0.065969	2.854776
25	3.581662	0.181511	10.3998	3.399798	0.058854	2.752539
26	3.724928	0.174852	10.01823	3.018233	0.052249	2.656962
27	3.868195	0.168653	9.663097	2.663097	0.046101	2.567457
28	4.011461	0.162871	9.331791	2.331791	0.040366	2.4835
29	4.154728	0.157465	9.022039	2.022039	0.035004	2.404619
30	4.297994	0.1524	8.731841	1.731841	0.02998	2.33039
31	4.441261	0.147645	8.459433	1.459433	0.025264	2.260432
32	4.584527	0.143174	8.203253	1.203253	0.02083	2.194404
33	4.727794	0.138962	7.961914	0.961914	0.016652	2.131996
34	4.87106	0.134987	7.73418	0.73418	0.012709	2.072928
35	5.014327	0.131231	7.518948	0.518948	0.008984	2.01695
36	5.157593	0.127675	7.315227	0.315227	0.005457	1.963833
37	5.30086	0.124305	7.12213	0.12213	0.002114	1.913368
38	5.444126	0.121106	6.938855	-0.06115	-0.00106	1.865369
39	5.587393	0.118066	6.764679	-0.23532	-0.00407	1.819663
40	5.730659	0.115174	6.598949	-0.40105	-0.00694	1.776093
41	5.873926	0.112418	6.441069	-0.55893	-0.00968	1.734518
42	6.017192	0.10979	6.290501	-0.7095	-0.01228	1.694806
43	6.160458	0.107281	6.146752	-0.85325	-0.01477	1.656836
44	6.303725	0.104884	6.009373	-0.99063	-0.01715	1.620501
45	6.446991	0.10259	5.877953	-1.12205	-0.01942	1.585697
46	6.590258	0.100394	5.752115	-1.24788	-0.0216	1.552332
47	6.733524	0.098289	5.631514	-1.36849	-0.02369	1.52032
48	6.876791	0.09627	5.515832	-1.48417	-0.02569	1.489581

The same table can be shown for SG6051 blade. But for maintaining the simplicity it's not presented here.

Analysis:

1) Power Coefficient (C_p) vs Tip Speed Ratio (λ_D): The power coefficient indicates the efficiency with which a wind turbine converts the kinetic energy of the wind into electrical power. A Cp vs _D curve depicts the relationship between the power coefficient and tip speed ratio. This curve illustrates the relationship between the power coefficient and the tip speed ratio for a given wind turbine design. The Cp versus curve typically displays a characteristic peak value. Due to low blade rotational speed, the power coefficient is comparatively low at low tip speed ratios. As the tip speed ratio increases, so does the power coefficient, which reaches its optimum value at the optimal tip speed ratio. Beyond this optimal point, the power coefficient begins to decrease because of increased aerodynamic losses and turbine design limitations. At figure 18 the Cp VS λ_D curve is presented for both blades[8].

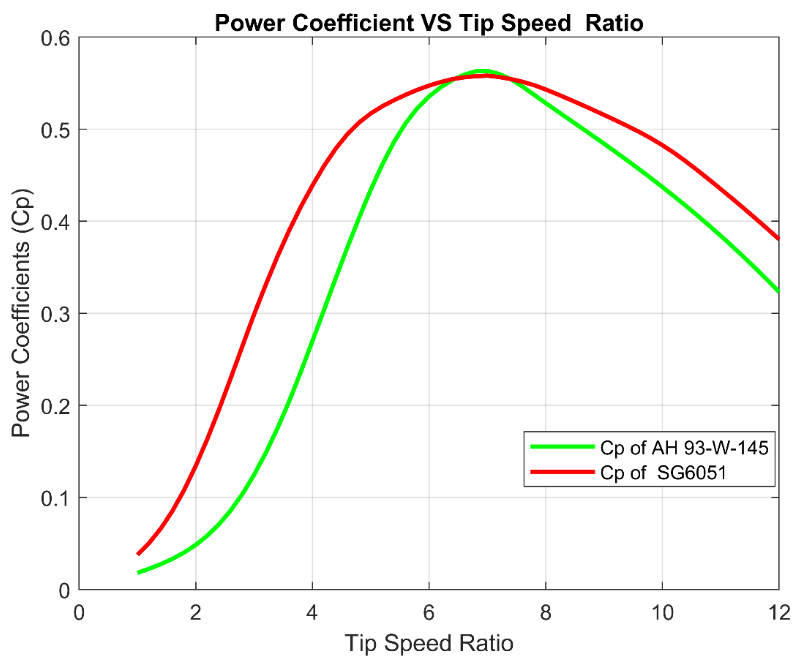


Fig.18. Cp VS λ_D for AH 93-W-145 and SG6051 blade

2) Torque Coefficient (C_m) vs Tip Speed Ratio (λ_D): Similar to the relationship between the power coefficient (Cp) and tip speed ratio, the torque coefficient (CT) and tip speed ratio (D) in wind turbines have a similar relationship. The torque coefficient represents the efficiency with which a wind turbine converts wind kinetic energy to rotational torque. Due to low blade rotational speed, the torque coefficient is

comparatively low at low tip speed ratios. As the ratio of tip speed to rotational speed increases, the torque coefficient also increases, reaching a maximal value at the optimal ratio of tip speed to rotational speed. Beyond this optimal point, the torque coefficient begins to decline due to increased aerodynamic losses and turbine design limitations. At figure 19 the C_m VS λ_D curve is presented for both blades.

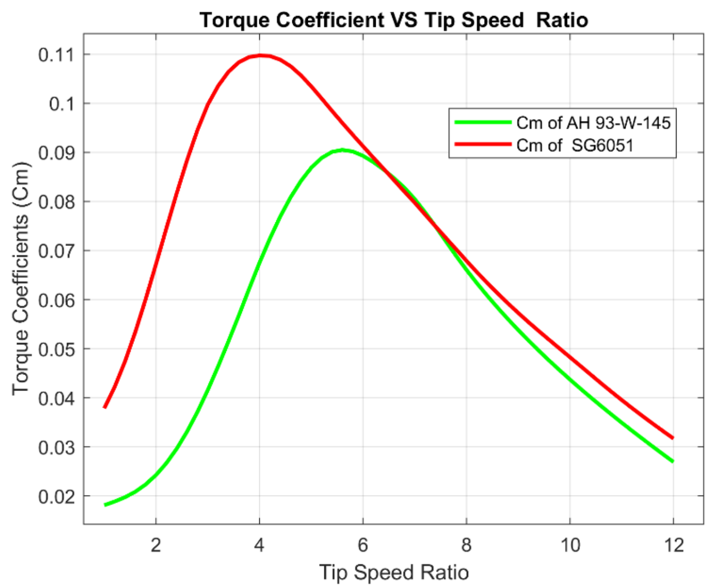


Fig.19. Cm VS λ_D AH 93-W-145 and SG6051 blade

3) <u>Thrust Coefficient (C_T) vs Tip Speed Ratio (λ_D):</u> The thrust force is generated by the pressure difference across the rotor of the wind turbine. The pressure on the front side of the rotor blades is greater than on the rear side. This pressure difference generates a net force in the opposite direction of the wind flow, known as thrust force. At figure 20 the C_T VS λ_D curve is presented for both blades[8].

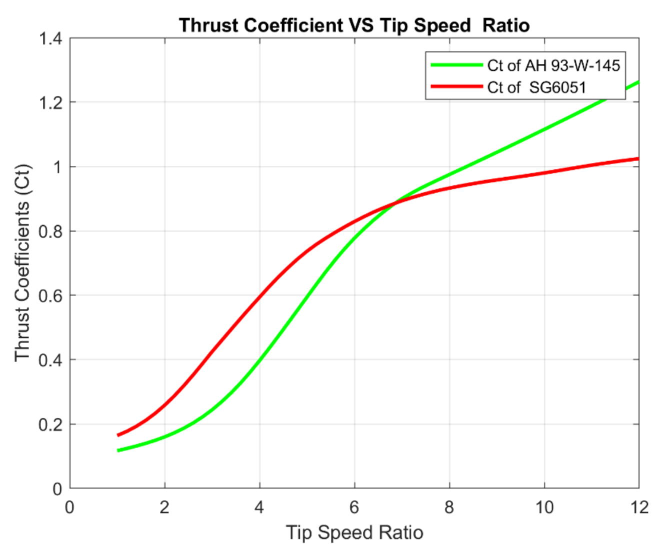


Fig.10. C_T VS λ_D AH 93-W-145 and SG6051 blade

4) <u>Power- Speed Characteristics:</u> The power-speed characteristics of a wind turbine characterize the relationship between the turbine's power output and wind speed. Wind turbines typically have a specific wind speed range within which they can function optimally. This range is referred to as the cut-in and cut-out speeds. Below the cut-in speed, the wind speed is insufficient for the turbine to generate significant electricity. When the wind speed exceeds the cut-out speed, the turbine must close down to prevent damage. Within the operating range, the power output of a wind turbine rises as wind speed increases. At figure 21 the Power VS Wind Speed curve is presented for both blades.

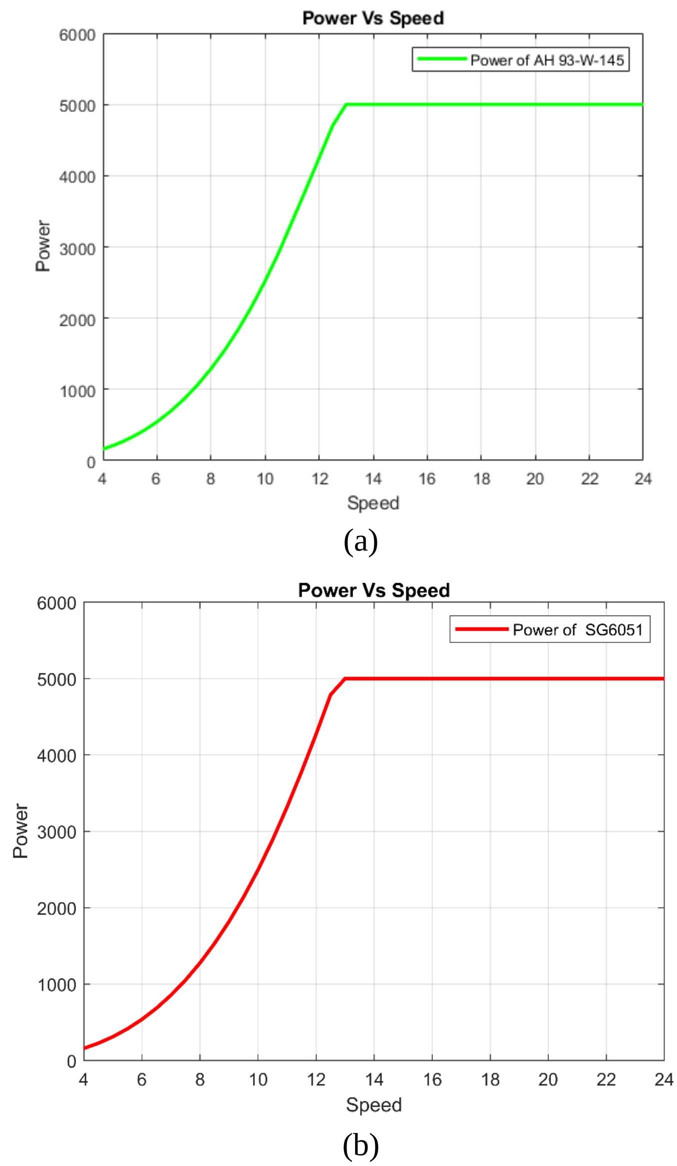


Fig.21. Power VS Speed curve of (a) AH 93-W-145 and(b) SG6051 blade

Conclusion

A comparative analysis of AH 93-W-145 and SG6051 blades is depicted in table 2

Table.2. comparison between AH 93-W-145 and SG6051

Parameters	**Comparison**
Power Coefficient	The power coefficient for both blades follow nearly the same path. However, the SG6051baldes reaches its peak power coefficient a tad earlier than expected. Approximately 0.55 is the maximal power coefficient for both blades.
Torque Coefficient	The torque coefficient of the SG6051 blade is 0.11, which is more than the torque coefficient of the AH 93-W-145 blade (0.09). Furthermore, the SG6051 blade achieves peak torque at lower TSR. This means that the SG6051 blade is more efficient than the AH 93-W-145 blade.
Thrust Coefficient	As the torque coefficient of SG6051 blade is more than AH 93-W-145, hence the thrust coefficient for is more at AH 93-W-145 blade in Hight TSR
Power	The power generated by both blades is nearly identical. At a wind speed of approximately 12.5 m/s, the power output reaches 5 MW. Before this period, both blades pass through a transitory region. After 12 .5 m/s of wind speed, the output reaches a steady-state value.

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