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Design Of A 2 MW wind turbine for a proposed wind farm project in Nigeria using WT-PERF

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Abstract

This paper presents the results of a 2 MW wind turbine design carried out for the Langtang wind Farm project in Plateau State, Nigeria using the WT_PERF software.

Selection of turbine rotor parameters is done in line with recommendations from the National Renewable Energy Lab (NREL) as well as available data from commercial turbine manufacturers.

Due to availability of large wind resource in the proposed farm location, a turbine rotor radius of 22 m at a hub height of 40 m is chosen.

Airfoils based on design by Dan Somers are selected for the design and an optimum blade planform is selected.

The variation of rotor power generation with wind speeds as well as the application of varying blade pitch on power generation are discussed.

Keywords: Wind Turbine; WT_Perf; Blade Planform; Airfoil; Tower Height; Blade Radius

1. Introduction

The region under evaluation for siting of a wind power generation project is Langtang, Plateau State, Nigeria with a 4 MW daily grid electricity consumption and a 14 MW electricity gap [1].

The proposed wind power generation project aims to provide a healthy amount of steady electric power to Langtang. Considering the current energy gap in the area, as well as projected increase in energy demand in the next few years, a 20 MW project was considered logical and thus selected.

A large amount of wind resource is available in Langtang with mean wind speed of 12.38 m/s, mean power density of 1756 W/m^2 and capacity factor of 0.6 at a height of 100 m as obtained from the global wind atlas [1].

A total of 10 units of 2 MW wind turbines is proposed to meet the 20 MW capacity requirement for this project.

In the wind power generation industry, wind turbine rotor performance is a key determining factor in power generation and system durability. Thus, special attention must be paid to its design.

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2. Rotor modelling and design data

The following shall be specified for the proposed 2 MW wind turbine rotor:

- Number of Blades, B
- Blade Radius, R
- Tower Height, H
- Blade RPM
- Blade Pitch Angle
- Airfoil Type(s)
- Chord as function of Radial Location, r/R
- Twist as function of Radial Location, r/R

2.1. Number of blades

Considering that the proposed wind turbine unit is 2 MW, a 3-bladed rotor is selected based on available historical data. Generally, large rotors (1 MW or higher) use 3-bladed rotors [2].

Thus, B = 3 is selected

2.2. Blade radius and tower height

In the design of Wind Turbines, the tower is selected to be tall enough so that enough clearance is there between the blade tip and the ground, for safety reasons. In the industry, a hub height to rotor diameter ratio of 2 is typical [2].

$$\frac{H}{R} = 2$$

We shall adopt an iterative process in determining the tower height and rotor diameter.

The formula below is used to estimate the blade radius:

$$P = \frac{1}{2}\rho C_P \pi R^2 V^3$$

The blade radius is then given by:

$$R = \sqrt{\frac{P}{\frac{1}{2}\rho C_P \pi V^3}}$$

Where;
P = Rated Power of Wind Turbine (W)
ρ = Air Density at Site (1.225 kg/m^3)
C_P = Power Coefficient
V = Rated Velocity of Wind at Hub Height (m/s)
R = Blade Radius (m)

The rated wind velocity is usually taken to be 1.5 times the mean wind speed measured at the hub location [2].

For large rotors, a power coefficient, C_P of 0.5 is assumed.

We shall assume an initial rotor diameter of 50 m, which is typical for commercial turbines of similar size [3]: Hub height is 100 m.

Mean Wind Speed at 100 m hub height = 12.38 m/s

Rated velocity of wind at 100 m hub height is given as;

$$V = 1.5 \times 12.38 = 18.57\ m/s$$

The Blade Radius becomes;

$$R = \sqrt{\frac{2 \times 10^6}{\frac{1}{2} \times 1.225 \times 0.5 \times \pi \times 18.57^3}}$$

$$R = 18.02\ m$$

Next, assume a rotor diameter of 30 m: Hub height is 60 m.

Rated velocity of wind at 60 m hub height is given as;

$$\frac{V}{18.57} = \left[\frac{60}{100}\right]^{\frac{1}{7}}$$

$$V = 17.26$$

The Blade Radius becomes;

$$R = \sqrt{\frac{2 \times 10^6}{\frac{1}{2} \times 1.225 \times 0.5 \times \pi \times 17.26^3}}$$

$$R = 20.11\ m$$

Next, assume a rotor diameter of 20 m: Hub height is 40 m.

Rated velocity of wind at 40 m hub height is given as;

$$\frac{V}{18.57} = \left[\frac{40}{100}\right]^{\frac{1}{7}}$$

$$V = 16.29$$

The Blade Radius becomes;

$$R = \sqrt{\frac{2 \times 10^6}{\frac{1}{2} \times 1.225 \times 0.5 \times \pi \times 16.29^3}}$$

$$R = 21.9\ m$$

Since there is convergence, we define the rotor diameter, hub height and rated wind velocity as follows:

Rotor Diameter, R = 22 m

Tower Height, H = 40 m

Rated Wind Velocity, V = 16.29 m/s

2.3. Blade rpm

The Tip Speed Ratio (TSR) is given by the formula;

$$TSR = \frac{\Omega R}{V}$$

We shall assume a TSR of 7 for this design. Typically, Tip Speed Ratios around 7 to 10 give good C_P values [2].

The blade Angular speed is then given as;

$$\Omega = \frac{TSR \times V}{R}$$

$$\Omega = \frac{7 \times 16.29}{22}$$

$$\Omega = 5.2\, rad/s$$

Blade RPM is then obtained as follows:

$$RPM = \frac{60\Omega}{2\pi}$$

$$RPM = \frac{60 \times 5.2}{2\pi}$$

$$RPM = 49.5 \approx 50$$

2.4. Airfoil selection

Due to their operating environments and mode of operation, Wind turbine airfoils are designed with decreasing thickness from root to tip to accommodate both structural and aerodynamic needs. In general, large airfoil thicknesses are required for Wind turbines as compared to aircrafts.

Valuable airfoil resources are available in Dan Somers' website [4]. Different airfoil families are available for different wind turbine sizes and rotor rigidity. The airfoils to be used for this design shall be selected from the family of airfoils available in this repository.

The following airfoil selection criteria are used:

- Moderate to high thickness ratio t/c (Rigid rotor: 16%–26% t/c, Flexible rotor: 11%–21% t/c)
- High lift-to-drag ratio.
- Minimal roughness sensitivity.
- Weak laminar separation bubbles.

Based on the foregoing, the following airfoils are selected for this design.

Table 1 Airfoil Selection for Wind Turbine

Blade Length (m)	**Generator Size (kW)**	**Thickness Category**	**AIRFOIL FAMILY (Root ------------------------------ Tip)**		
22	2,000	Thick	S818	S825	S826

2.5. Chord and twist variation with radial location

The hub radius for this design is chosen as 5%. The remaining 95% is divided into 19 equal parts with the mid-point locations shown below:

Table 2 Chord and Twist Variation with Radial Location

Location	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
r/R	0.075	0.125	0.175	0.225	0.275	0.325	0.375	0.425	0.475
10	11	12	13	14	15	16	17	18	19
0.525	0.575	0.625	0.675	0.725	0.775	0.825	0.875	0.925	0.975

Next, we obtain values of the local inflow angle, Φ i.e., the angle relating the lift and drag of the airfoil element to the thrust and torque forces.

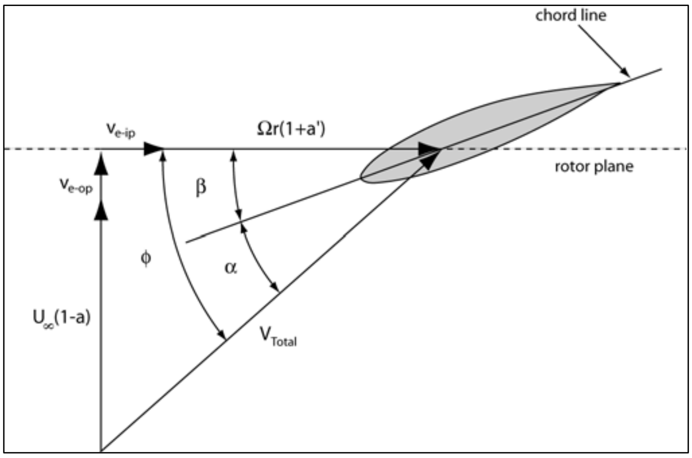

Figure 1 Local element velocities and flow angles

From the above velocity diagram,

$$\tan\Phi = \frac{U_\infty(1-a)}{\Omega r(1+a')}$$

From Rankine's model, largest power production occurs when the axial induction factor, a = 1/3. The swirl factor is negligible; thus, we have.

$$\tan\Phi = \frac{2U_\infty}{3\Omega r}$$

Using this relation, we obtain values of Φ for the radial locations.

The lift and drag forces acting on the rotor blade are summarized in the figure below.

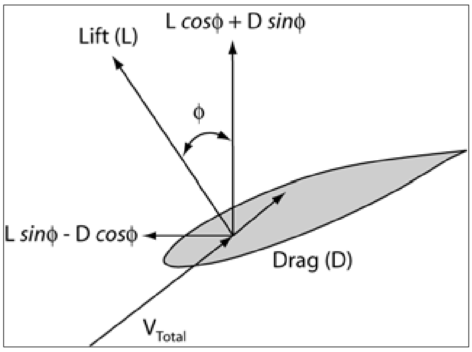

Figure 2 Local elemental forces

For optimum power production, the lift to drag ratio, L/D = C_L/C_D must be maximized.

From the airfoil tables for our selected airfoils obtained from WT_PERF, we determine the optimum angle of attack for maximum C_L/C_D. The results are presented in the table below.

Table 3 Variation of Drag and Lift Coefficients with Angle of Attack for Selected Airfoils

Airfoil	**S818**			**S825**			**S826**		
α (deg)	C_L	C_D	C_L/C_D	C_L	C_D	C_L/C_D	C_L	C_D	C_L/C_D
0	0.57	0.0087	65.5172	0.66	0.0084	78.5714	0.71	0.0072	98.6111

1	0.67	0.0088	76.1364	0.77	0.0086	89.5349	0.82	0.0074	110.8108
2	0.78	0.0090	86.6667	0.88	0.0089	98.8764	0.93	0.0076	122.3684
3	0.89	0.0093	95.6989	0.98	0.0091	107.6923	1.04	0.0078	133.3333
4	0.99	0.0096	103.1250	1.09	0.0095	114.7368	1.14	0.0082	139.0244
5	1.10	0.0099	111.1111	1.20	0.0098	122.4490	1.25	0.0087	143.6782
6	1.20	0.0103	116.5049	1.30	0.0102	127.4510	1.35	0.0104	129.8077
7	1.31	0.0108	121.2963	1.41	0.0107	131.7757	1.44	0.0146	98.6301
8	1.41	0.0113	124.7788	1.49	0.0155	96.1290	1.53	0.0184	83.1522
9	1.51	0.0118	127.9661	1.58	0.0179	88.2682	1.63	0.0200	81.5000
10	1.56	0.0194	80.4124	1.66	0.0203	81.7734	1.65	0.0219	75.3425
11	1.61	0.0221	72.8507	1.68	0.0250	67.2000	1.67	0.0239	69.8745
12	1.65	0.0245	67.3469	1.70	0.0273	62.2711	1.68	0.0262	64.1221
13	1.65	0.0269	61.3383	1.70	0.0297	57.2391	1.67	0.0288	57.9861
14	1.63	0.0296	55.0676	1.68	0.0324	51.8519	1.65	0.0316	52.2152
15	1.62	0.0520	31.1538	1.66	0.0520	31.9231	1.63	0.0520	31.3462
30	1.08	0.6200	1.7419	1.08	0.6200	1.7419	1.08	0.6200	1.7419
40	1.15	0.9600	1.1979	1.15	0.9600	1.1979	1.15	0.9600	1.1979
50	1.09	1.3000	0.8385	1.09	1.3000	0.8385	1.09	1.3000	0.8385
α_{opt}	9			7			5		

These optimum angles of attack are then used for the three airfoils in calculating the twist angle (β) for each blade element.

Considering that there are three families of airfoils to be spread across the radial locations, we shall use a 26/48/26 percentage spread ratio: the S818 airfoil for the first 5 radial locations, the S825 for the next 9 locations and the S826 for the final 5 locations. This spread has been optimized for twist distribution.

Next, we determine the variation of chord "c" with radial location, r by setting the axial induction factor to be equal to 1/3 – equal to the Betz limit from root to tip.

This value of induction factor yields the highest possible power from actuator disk model studies.

The chord can then be obtained from the following relation [5]:

$$4\pi r U_\infty^2 (1-a)a = \frac{B}{2}[(\Omega r)^2 + U_\infty^2(1-a)^2][C_L\, cos\Phi + C_D\, sin\Phi]c$$

Substituting a = 1/3, the expression becomes.

$$\frac{8}{9}\pi r U_\infty^2 = \frac{B}{2}\left[(\Omega r)^2 + \frac{4}{9}U_\infty^2\right][C_L\, cos\Phi + C_D\, sin\Phi]c$$

Solving for c,

$$c = \frac{16\pi r U_\infty^2}{B[9\Omega^2 r^2 + 4U_\infty^2][C_L\, cos\Phi + C_D\, sin\Phi]}$$

Using the above equation, we solve for chord, c at the various r locations at the centre of each blade element.

The c/R data obtained from the above process is non-linear, hence, we use a linear regression model to obtain a line of best fit using MS Excel as shown below.

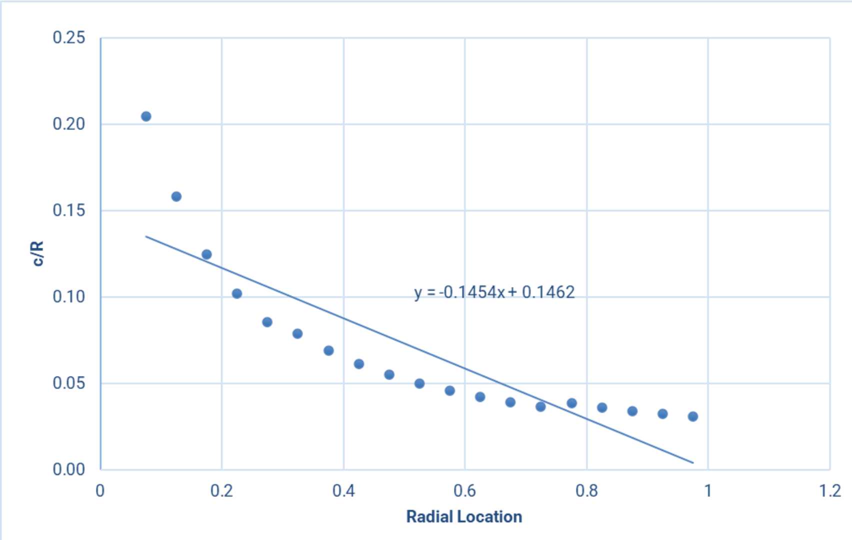

Figure 3 Linear regression fit for chord variation with radial location**.**

Summary of design data is presented in the table below:

Table 4 Summary of Design Data for Selected Airfoils

Location	r/R	r (m)	Φ (rad)	Φ (deg)	Airfoil	C_L	C_D	α (deg)	β (deg)	c (m)	c/R	c/R (Fit)
1	0.075	1.65	0.9021	51.69	S818	1.51	0.0118	9	42.689	4.5020	0.2046	0.1353
2	0.125	2.75	0.6495	37.21		1.51	0.0118	9	28.215	3.4837	0.1583	0.1280
3	0.175	3.85	0.4970	28.48		1.51	0.0118	9	19.478	2.7511	0.1251	0.1208
4	0.225	4.95	0.3993	22.88		1.51	0.0118	9	13.875	2.2450	0.1020	0.1135
5	0.275	6.05	0.3324	19.04		1.51	0.0118	9	10.045	1.8856	0.0857	0.1062
6	0.325	7.15	0.2842	16.28	S825	1.41	0.0107	7	9.283	1.7359	0.0789	0.0989
7	0.375	8.25	0.2479	14.21		1.41	0.0107	7	7.206	1.5199	0.0691	0.0917
8	0.425	9.35	0.2198	12.59		1.41	0.0107	7	5.591	1.3504	0.0614	0.0844
9	0.475	10.45	0.1973	11.30		1.41	0.0107	7	4.302	1.2142	0.0552	0.0771
10	0.525	11.55	0.1789	10.25		1.41	0.0107	7	3.249	1.1026	0.0501	0.0699
11	0.575	12.65	0.1636	9.37		1.41	0.0107	7	2.375	1.0095	0.0459	0.0626
12	0.625	13.75	0.1507	8.64		1.41	0.0107	7	1.637	0.9307	0.0423	0.0553
13	0.675	14.85	0.1397	8.01		1.41	0.0107	7	1.005	0.8632	0.0392	0.0481
14	0.725	15.95	0.1302	7.46		1.41	0.0107	7	0.460	0.8048	0.0366	0.0408
15	0.775	17.05	0.1219	6.98	S826	1.25	0.0087	5	1.983	0.8503	0.0386	0.0335
16	0.825	18.15	0.1146	6.56		1.25	0.0087	5	1.564	0.7995	0.0363	0.0262
17	0.875	19.25	0.1081	6.19		1.25	0.0087	5	1.192	0.7544	0.0343	0.0190

18	0.925	20.35	0.1023	5.86		1.25	0.0087	5	0.860	0.7141	0.0325	0.0117
19	0.975	21.45	0.0971	5.56		1.25	0.0087	5	0.561	0.6778	0.0308	0.0044

Also, we obtained the following parameters:

Table 5 Wind Turbine Rotor Design Parameters

Parameter	Magnitude
Number of Blade, B	3
Blade Radius, R (m)	22
Tower Height, H (m)	40
Hub Height/Radius Ratio	1.82
Rated Wind Speed, V (m/s)	16.29
Rotor Angular Speed, Ω (rad/s)	5.2
RPM	50
Tip Speed Ratio, TSR	7
Hub Radius	0.05

3. Rotor analysis using Wt_Perf

Analysis of the wind turbine rotor is carried out based on the design data obtained using WT_PERF software to predict the variation of wind power generation with Tip Speed Ratio (TSR) at various pitch angles.

In addition to the data obtained from the preceding section, the following parameters are used for the performance prediction:

- Prandtl tip loss model
- Number of circumferential sectors = 1
- Maximum number of iterations for induction factor = 20,000
- Hub height = 1.82m
- Yaw error = 0 deg
- Precone angle = 0 deg
- Shaft Tilt = 0 deg
- Wind shear exponent = 0 (no BL present)
- Density of Air = 1.225 kg/m^3
- Kinematic viscosity of Air = 1.48 x 10^{-5} m^2/s
- Pitch range: 0 – 10
- Tip Speed Ratio (TSR) range: 3 – 12.5

The above data are fed into the WT_PERF input file (.wtp) and the program is executed. Corresponding performance prediction (.oup) and blade element data (.bed) output files are obtained.

The Power generation and Power Coefficient (CP) for the range of Tip Speed Ratios (TSR) provided are obtained for various pitch angle settings in the output (.oup) file.

The wind speed is calculated from the TSR using the following relation:

$$\Omega = \frac{TSR \times V}{R}$$

Thus;

$$V = \frac{\Omega \times R}{TSR}$$

Values of power generation with wind speeds as well as power coefficient with TSR at various pitch settings are obtained and tabulated.

The values obtained for power generation versus wind speed for the various pitch settings are provided in the table below.

Table 6 Power Generation Versus Wind Speed for the Various Pitch Settings

	Pitch (deg)	0	2	4	6	8	10
TSR	Wind Speed (m/s)						
3.00	38.13	3,332.04	4,617.28	5,927.57	7,037.28	7,992.72	8,722.07
3.25	35.20	3,782.24	5,061.43	6,166.73	7,123.01	7,820.28	8,131.51
3.50	32.69	4,200.73	5,344.72	6,300.01	7,030.95	7,370.56	7,420.46
3.75	30.51	4,536.79	5,510.85	6,292.74	6,705.84	6,776.13	6,576.65
4.00	28.60	4,748.23	5,593.30	6,083.84	6,206.73	6,089.07	5,778.51
4.25	26.92	4,891.57	5,484.58	5,697.21	5,636.75	5,409.85	5,022.69
4.50	25.42	4,905.74	5,201.14	5,211.62	5,061.54	4,757.00	4,341.16
4.75	24.08	4,706.49	4,798.02	4,716.43	4,496.14	4,164.15	3,759.92
5.00	22.88	4,353.77	4,371.00	4,213.06	3,984.53	3,656.63	3,263.39
5.25	21.79	3,986.39	3,910.33	3,766.80	3,526.51	3,214.39	2,843.61
5.50	20.80	3,579.68	3,493.91	3,373.21	3,133.36	2,834.62	2,489.79
5.75	19.90	3,183.33	3,144.48	3,011.17	2,791.79	2,509.45	2,187.49
6.00	19.07	2,840.85	2,827.61	2,695.07	2,492.86	2,231.79	1,927.25
6.25	18.30	2,540.37	2,536.64	2,420.29	2,233.90	1,993.03	1,703.47
6.50	17.60	2,274.47	2,278.43	2,179.77	2,008.85	1,783.60	1,509.61
6.75	16.95	2,038.25	2,049.57	1,968.79	1,812.86	1,600.07	1,339.94
7.00	16.34	1,829.40	1,846.02	1,782.12	1,640.54	1,438.99	1,190.12
7.25	15.78	1,645.24	1,665.48	1,616.39	1,487.67	1,296.93	1,058.43
7.50	15.25	1,482.73	1,505.31	1,468.88	1,351.91	1,172.13	942.18
7.75	14.76	1,338.87	1,362.60	1,337.45	1,231.01	1,061.50	839.36
8.00	14.30	1,210.63	1,235.87	1,219.88	1,123.14	962.90	748.02
8.25	13.87	1,095.60	1,123.09	1,114.23	1,026.52	874.67	667.40
8.50	13.46	992.39	1,022.62	1,019.08	939.79	795.19	595.81
8.75	13.07	899.89	932.80	933.17	861.83	723.56	530.75
9.00	12.71	816.82	852.27	855.45	791.66	658.85	471.63
9.25	12.37	741.90	779.71	785.04	728.20	600.62	417.28
9.50	12.04	673.88	714.16	721.29	670.61	548.09	367.72
9.75	11.73	612.42	654.66	663.50	618.28	500.50	322.72

10.00	11.44	556.90	600.50	611.04	570.61	457.22	281.77
10.25	11.16	506.47	551.11	563.33	527.04	417.61	244.59
10.50	10.90	460.56	506.10	519.91	487.13	381.25	210.69
10.75	10.64	418.61	464.99	480.28	450.52	347.84	179.64
11.00	10.40	375.57	427.31	444.03	416.83	316.94	151.16
11.25	10.17	340.38	392.72	410.77	385.78	288.28	124.96
11.50	9.95	308.17	360.88	380.18	357.11	261.72	100.82
11.75	9.74	278.63	331.64	351.98	330.58	236.95	78.52
12.00	9.53	251.48	304.72	325.94	306.00	213.99	57.76
12.25	9.34	226.52	279.84	301.87	283.20	192.65	37.33
12.50	9.15	203.51	256.84	279.56	262.01	172.82	17.34

The values obtained for Power Coefficient versus TSR for the various pitch settings are provided in the table below.

Table 7 Power Coefficient versus TSR for the Various Pitch Settings

Pitch (deg) / TSR	0	2	4	6	8	10
3.00	0.0632	0.0876	0.1124	0.1335	0.1516	0.1654
3.25	0.0912	0.1221	0.1487	0.1718	0.1886	0.1961
3.50	0.1265	0.1610	0.1897	0.2118	0.2220	0.2235
3.75	0.1681	0.2041	0.2331	0.2484	0.2510	0.2436
4.00	0.2135	0.2515	0.2735	0.2790	0.2738	0.2598
4.25	0.2638	0.2958	0.3072	0.3040	0.2917	0.2709
4.50	0.3140	0.3329	0.3336	0.3240	0.3045	0.2779
4.75	0.3543	0.3612	0.3551	0.3385	0.3135	0.2831
5.00	0.3823	0.3838	0.3699	0.3499	0.3211	0.2866
5.25	0.4052	0.3975	0.3829	0.3585	0.3267	0.2891
5.50	0.4184	0.4084	0.3942	0.3662	0.3313	0.2910
5.75	0.4251	0.4199	0.4021	0.3728	0.3351	0.2921
6.00	0.4311	0.4290	0.4089	0.3783	0.3386	0.2924
6.25	0.4357	0.4350	0.4151	0.3831	0.3418	0.2922
6.50	0.4388	0.4396	0.4205	0.3875	0.3441	0.2912
6.75	0.4404	0.4428	0.4253	0.3917	0.3457	0.2895
7.00	0.4408	0.4448	0.4294	0.3953	0.3467	0.2868
7.25	0.4404	0.4458	0.4327	0.3983	0.3472	0.2833
7.50	0.4394	0.4461	0.4353	0.4006	0.3474	0.2792
7.75	0.4378	0.4456	0.4373	0.4025	0.3471	0.2745
8.00	0.4354	0.4445	0.4388	0.4040	0.3463	0.2690

8.25	0.4322	0.4430	0.4395	0.4049	0.3450	0.2633
8.50	0.4281	0.4412	0.4396	0.4054	0.3431	0.2570
8.75	0.4235	0.4390	0.4392	0.4056	0.3405	0.2498
9.00	0.4183	0.4365	0.4381	0.4054	0.3374	0.2415
9.25	0.4125	0.4335	0.4365	0.4049	0.3339	0.2320
9.50	0.4059	0.4301	0.4344	0.4039	0.3301	0.2215
9.75	0.3987	0.4262	0.4320	0.4026	0.3259	0.2101
10.00	0.3912	0.4218	0.4292	0.4008	0.3212	0.1979
10.25	0.3831	0.4169	0.4262	0.3987	0.3159	0.1850
10.50	0.3745	0.4116	0.4228	0.3961	0.3100	0.1713
10.75	0.3653	0.4058	0.4191	0.3932	0.3036	0.1568
11.00	0.3512	0.3995	0.4152	0.3897	0.2963	0.1413
11.25	0.3404	0.3928	0.4109	0.3859	0.2883	0.1250
11.50	0.3292	0.3856	0.4062	0.3815	0.2796	0.1077
11.75	0.3175	0.3779	0.4011	0.3767	0.2700	0.0895
12.00	0.3053	0.3699	0.3956	0.3714	0.2598	0.0701
12.25	0.2925	0.3614	0.3898	0.3657	0.2488	0.0482
12.50	0.2792	0.3524	0.3836	0.3595	0.2371	0.0238

4. Results and discussions

4.1. Design parameters

Based on the turbine rotor modelling and design calculations, we obtain the following parameters for design of the turbine rotor.

Table 8 Optimized Blade Design Parameters

Parameter	**Magnitude**
Number of Blades, B	3
Blade Radius, R (m)	22
Tower Height, H (m)	40
Hub Height/Radius Ratio	1.82
Rated Wind Speed, V (m/s)	16.29
Rotor Angular Speed, Ω (rad/s)	5.2
RPM	50
Hub Radius	0.05
Airfoil Families	S818, S825, S826

The number of blades has been chosen to be 3 based on historical trends. In general, most turbines sized at 1 MW and above use 3-bladed rotors [2]. This provides more surface for contact by wind.

The blade radius of 22 m was chosen following an iterative process to optimize the tower height and blade radius. The blade radius of most commercial wind turbines of similar size usually ranges from 50 m and above [3]. The smaller blade radius obtained is due to the higher mean wind speed available at the chosen location. The rated wind speed used for the design (16.25 m/s) is quite high and uncommon for most wind sites. Commercial wind turbines usually design with wind speeds of 8 – 12 m/s.

The tower height of 40 m has been optimized for the blade radius. This height also provides sufficient clearance from the ground for safety reasons.

The tower height to blade radius ratio was initially set to 2. However, following an iterative process to optimize the blade radius and tower height, it is adjusted to 1.82. This ratio is consistent with data for most commercial turbines. For instance, The GE 1.5 MW turbine has a tower height to radius ratio of 1.827, The Vestas V90 from Denmark has a ratio of 1.7703 while the 2 MW Gamesa G87 from Spain has a ratio of 1.79.

The rated wind speed of 16.25 m/s was obtained by multiplying the mean wind speed at the specified tower height of 40 m by a factor of 1.5 [2]. This is because the wind speeds at various locations are not constant but vary across a range of values. The wind speed values obtained by measurements or from literature are usually the average speeds over a specified period. Designing for higher wind speeds ensures that the turbine rotor does not begin to stall beyond the mean wind speed.

By careful selection of a Tip Speed Ratio (TSR) of 7, the obtained angular speed of the rotor is 5.2 rad/s or 50 RPM. Generally, lower values of RPM minimize noise and vibrations.

A hub radius of 5% is chosen for the design in line with NREL recommendations [2]. This portion of the rotor blade is usually considered as part of the hub and not accounted for in the twist and chord design calculations.

Finally, the airfoil selection has been done to optimize lift-to-drag ratio, minimize roughness sensitivity and prevent laminar separation bubbles. The selected airfoils are based on the work by Dan Somers [4].

4.2. Chord and twist vs radial location

We optimized the rotor blade planform by optimizing the twist angles using the optimum angles of attack for the three selected airfoils and linearizing the chord variation with radial location for optimum power generation using regression analysis.

The variation of twist and chord with radial location is presented in the table and plots below.

Table 9 Variation of Twist and Chord with Radial Location

r/R	Airfoil Family	Twist (deg)	Chord (c/R)
0.075	S818	42.689	0.1353
0.125	S818	28.215	0.1280
0.175	S818	19.478	0.1208
0.225	S818	13.875	0.1135
0.275	S818	10.045	0.1062
0.325	S825	9.283	0.0989
0.375	S825	7.206	0.0917
0.425	S825	5.591	0.0844
0.475	S825	4.302	0.0771
0.525	S825	3.249	0.0699
0.575	S825	2.375	0.0626
0.625	S825	1.637	0.0553
0.675	S825	1.005	0.0481

0.725	S825	0.460	0.0408
0.775	S826	1.983	0.0335
0.825	S826	1.564	0.0262
0.875	S826	1.192	0.0190
0.925	S826	0.860	0.0117
0.975	S826	0.561	0.0044

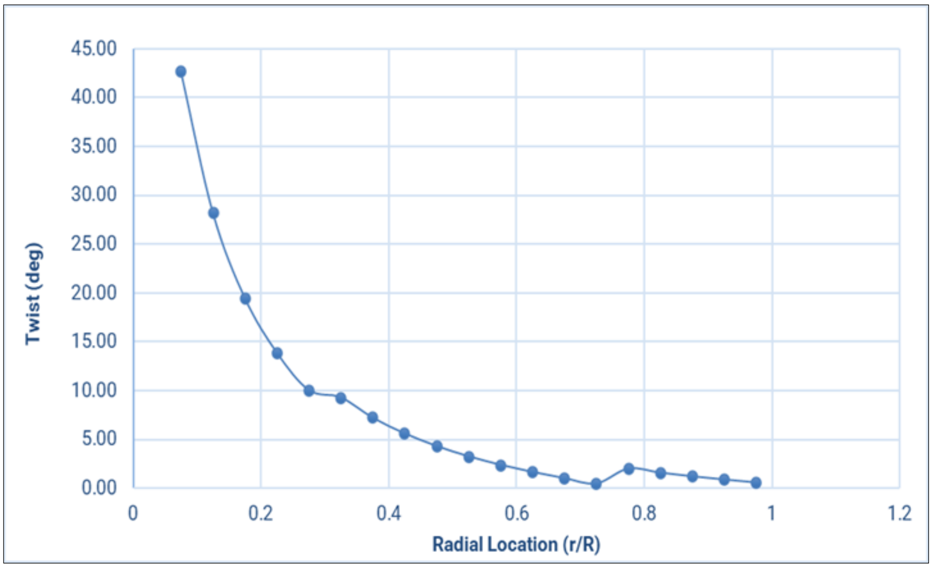

Figure 4 Twist variation with radial location

From fig. 4, we observe that the twist profile with radial location is not a smooth curve. This is due to changes in airfoil selection along the planform, with each airfoil family having different characteristics. This variation was also optimized by careful selection of the airfoil transition locations.

In the manufacture of rotor blades, it is possible to manipulate this uneven twist across the planform, however, it will result in higher manufacture cost.

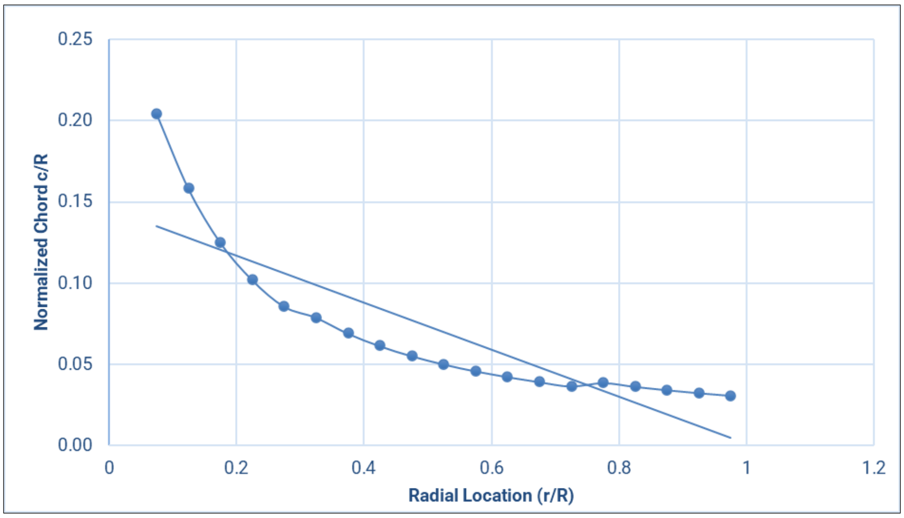

Figure 5 Chord variation with radial location

In fig. 5, we also observe a similar non-smooth variation of the calculated normalized chord with radial location. This non-linear, non-smooth chord profile results in the maximum power generation.

In reality, it is extremely difficult and capital intensive to manufacture rotors with varying chord. Generally, chord profiles are chosen to be linear, hence the need to linearize the calculated profile.

We have used a linear regression model in MS Excel to obtain a line of best fit for the chord profile that also optimizes power generation. Data obtained from this linearized profile is then used for the rotor design analysis.

4.3. Power generation vs wind speed and pitch

Based on data obtained from WT_PERF performance prediction simulation, plot of power generation with wind speed at various pitch angles is made.

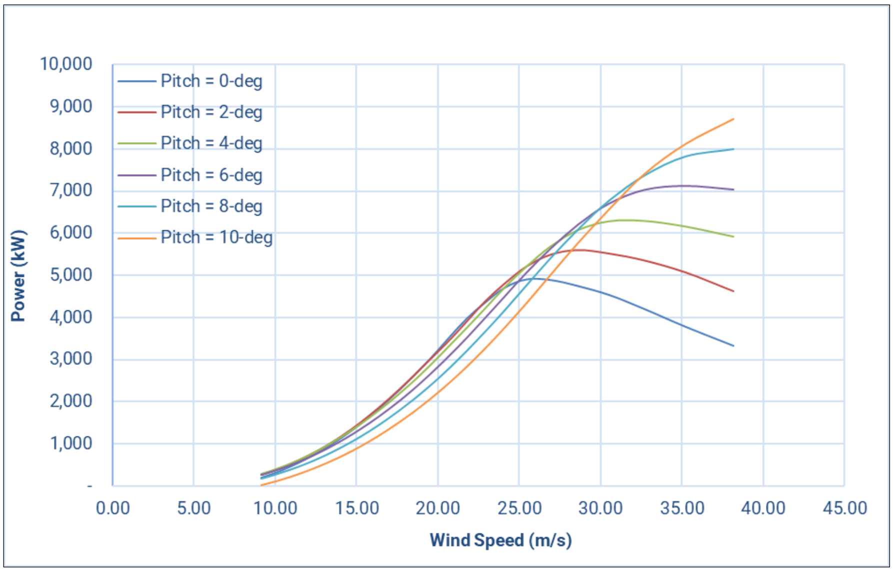

Figure 6 Variation of power generation with wind speeds at various pitch angles

From fig. 6, we observe that at a pitch angle of 0-deg, the desired power generation of 2 MW is obtained at the rated speed of 16.25 m/s. The power generation continues to increase up to a maximum at about 25 m/s after which the rotor begins to stall.

At a higher pitch angle of 10-deg, wind speed of about 19.5 m/s is required to generate the desired 2 MW power.

In general, the power generation reduces with pitch angle at a constant wind speed. To ensure that the turbine generator does not burn out beyond the rated speed, pitch control shall be used to control the power generation at higher wind speeds. A control system that monitors wind speeds and adjusts the pitch accordingly shall be incorporated with the design.

4.4. Power coefficient vs tip speed ratio and pitch

The variation of power coefficient with Tip Speed Ratio (TSR) at various pitch settings is shown in the plot below.

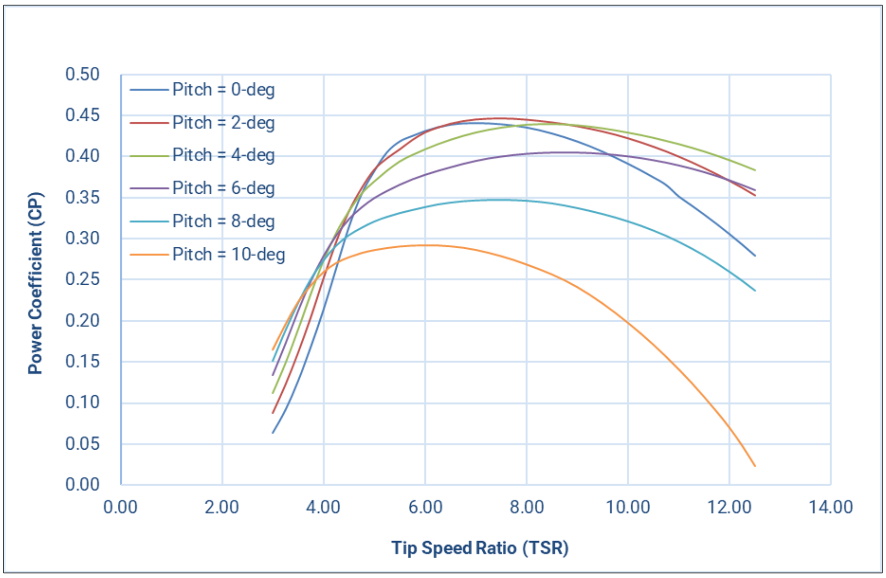

Figure 7 Variation of power coefficient with Tip Speed Ratio at various pitch angles

From fig. 7, we observe that at lower tip speed ratios, the power coefficient attains maximum values. This is consistent with higher power generation.

It can also be observed that the power coefficient declines faster with tip speed ratio after attaining maximum value for higher pitch settings. This is because stall velocities are closer to the wind speeds that generate maximum power at higher pitch settings.

5. Conclusion

Detailed analysis and sizing have been carried out for each turbine unit for the proposed Langtang Power Generation project. A total of ten (10) turbine units are expected to meet the desired 20 MW power generation capacity.

From an initially predicted tower height of 100 m and rotor radius of 50 m, we obtained lower results from deign calculations primarily due to the presence of very good wind resources at the chosen location as compared to average data used for most commercial wind turbine designs.

Our analysis of predicted turbine power generation using WT_PERF has also highlighted the importance of pitch control for our rotor. Pitch control is desired to prevent burn out of turbine generator at higher wind speeds and allows continuous power generation until cut-off speed is attained.

The non-smooth variation of twist with radial location on the rotor poses an additional requirement for special attention during manufacture to ensure optimum performance. The normalized chord profile was optimally linearized for ease of manufacture.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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