



Modelling of a wind power turbine

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Modelling of a Wind Power Turbine

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Abstract—Due to the predicted scarcity of the fossil fuels and their adverse effects to the environment, currently renewable energy generation is a major focus of the power and energy sector. Wind energy is one of the potential and rapidly growing sources of green energy. This is particularly due to the cost of the wind energy production has reduced by a factor of more than five over the last two decades. Moreover, wind turbines can cover a wide range of power outputs from 50 W to 5 MW and beyond compared to other green energy sources. This study is aimed to model a horizontal axis wind power turbine theoretically and computationally. Initially, theoretical calculations were carried out by considering a few specific case studies with different power outputs. Then, the same case studies were considered for a computational fluid dynamics (CFD) analysis. Theoretical results show that the modelled wind turbine reaches a power output of 4.4 MW. Moreover, the theoretically calculated thrust and torque show a good agreement with the values obtained from CFD with a deviation of 2.9% only which confirms the accuracy of results. Therefore, the findings of this work should be useful in investigating ways to improve the performance of horizontal axis wind turbines.

Keywords—Wind power generation; Horizontal axis turbines; Power coefficient; Tip speed ratio; Modelling; CFD.

I. INTRODUCTION

Wind is a natural and renewable source of energy. The greatest potential of wind energy is that it is readily available throughout the year and almost all over the world. The UK's average mean wind speed map is shown in Figure 1.

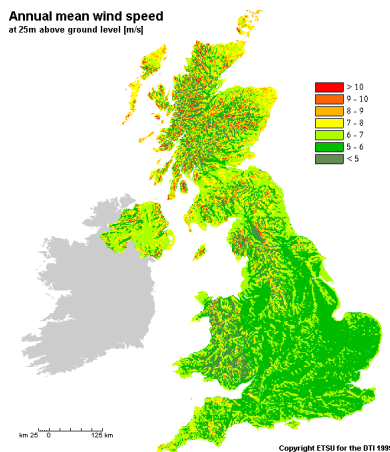


Fig.1: Annual mean wind speed in the UK [1]

In contrast, solar energy can be used efficiently only in the summer for many of the countries. Wind energy is competing with other energy sources such as solar, nuclear, tidal current, wave, geothermal, etc. Over the last 15 years, the use of wind energy has increased rapidly as shown in Figure 2 and only during the period from 2003 to 2007, it is an increment of 25%. [2]. Currently, the Asia is leading the wind energy generation followed by the Europe and the North America. Moreover, the predicted future wind power capacity in the globe is presented in Figure 3.

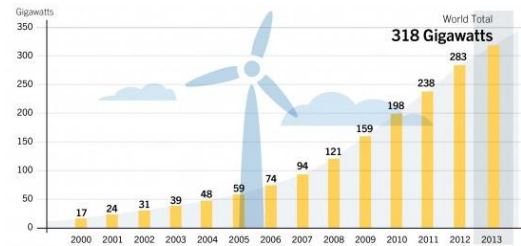


Fig. 2: Increase of global wind power capacity from year 2000-2013 [2]

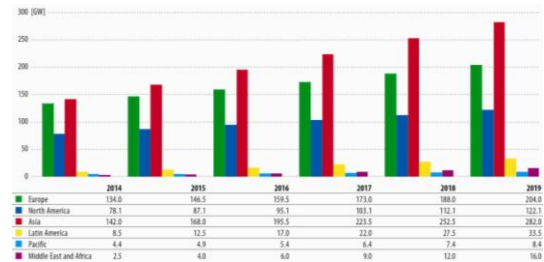


Fig. 3: Cumulative market forecast by region 2014-2019 [3]

As shown in Figure 4, the Europe's total wind power share of the total installed power capacity has increased dramatically from 2.4 % to 14.5 % over the period of 2000 to 2014 [3].

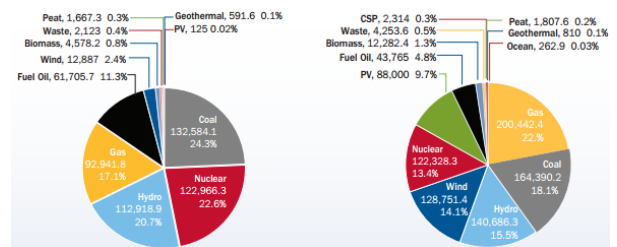


Fig. 4: Installed power capacity within the Europe in MW – Left in year 2000, Right in year 2014 [3]

Thanks to the numerous research and development, the typical size of wind power turbines has been increased by a factor of 100 over last two decades. Therefore, wind power plants with huge capacities are currently available (in rural areas and also in offshore) and also this sector is expecting further improvements to cater the future energy demand. In the initial stage of this work, an investigation was made on the basic principles of harnessing wind energy. The major focus of this work was made on horizontal axis wind turbines with three blades due to their wider availability. In the second stage, theoretical calculations were performed to determine the power output of wind turbines with different rotor radii, blade angles and also over different wind speeds. Then, an efficient design was selected based on the theoretical results and the selected design was modelled with CFD as well. Eventually, a comparison was made between theoretical and CFD results.

A. Wind Turbine Types

The technology of fabricating wind turbines and harvesting wind energy has been achieved a vast improvement over the last few decades. The important facts and milestones of this development process have been presented by European Wind Energy Association (EWEA) [2] and Kaldellis *et al.* [4].

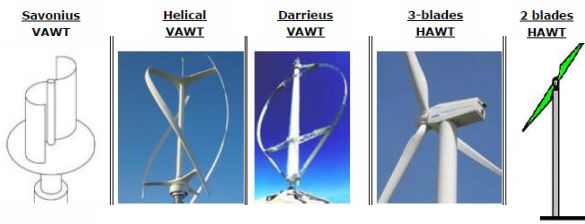


Fig. 5: Wind turbine types [4]

Typical wind turbines (WT) can be categorized into two major groups as horizontal axis (HA) and vertical axis turbines (VA) as shown in Figure 5. Of these two types, horizontal axis is the most commonly used type and they are available with two or three blades. Wind turbines with three blades are high in efficiency and also they are less in noise compared to two blade turbines [2]. Turbines with two blades run at a higher tip speed than three blades and this causes in high noise levels. Work carried out by Yang *et al.* [6] explored on the structure and the common faults of wind turbines. More information on wind power generation can be found in the literature [2, 6-8].

B. A Typical Horizontal Axis Wind Power Plant – Components and Operations

A wind turbine consists of a rotor, a nacelle and tower which are built on a foundation as shown in Figure 6. The rotor is composed of a hub and blades, which are pitch controlled. The rotor catches the wind energy which rotates the main shaft (i.e., the low speed shaft). The low speed shaft is connected with a generator shaft (i.e., direct drive) or with a high speed shaft through a gear box. The main task of the gearbox is to transform the energy with the desired speed of the generator which then transforms the mechanical energy into the electrical energy. Currently, different types of generators are available in the market (e.g., squirrel cage or doubly-fed induction generators, double-fed asynchronous

generators, wound field or permanent magnet synchronous generators). The most commonly used in wind turbines is the double-fed asynchronous generator due to its power electronic converter.

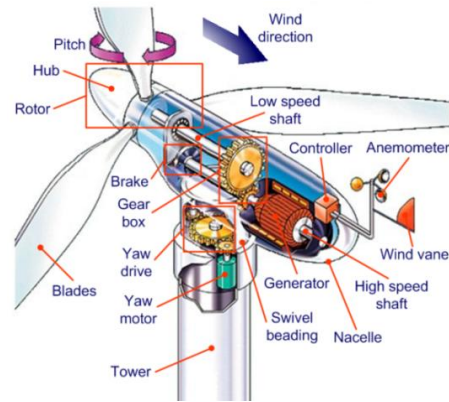


Fig. 6: Components of a horizontal axis wind turbine [5]

Wind turbines operate in variable speeds or with a fixed speed. Hence, the wind turbine generator systems (WTGS) are available in two types: fixed speed WTGS and variable speed WTGS. Fixed speed WTGS is directly coupled to the grid and those bring some good properties such as rugged construction, low cost, less maintenance and the simple operation. The rotor speed has just a variation of 1- 2% of the rated speed. Usually, constant speed wind turbines are mechanically more robust than variable speed turbines. Since the rotor speed is constant, wind speed fluctuations can create heavy vibrations on the rotors. This results in higher structural loads than with variable speed systems. Usually, the fixed speed is achieved by braking the system until the desired speed is achieved. If strong wind turbulences emerge or the wind speed increases, these can be easily regulated by stall or pitch control. It is just a connection between the grid and rotor when the rotor runs at a fixed speed. Variable speed system has one main advantage as they can generate more energy for a specific wind speed range compared to a fixed speed turbine. The mechanical stress that the components may be subjected to is less because the rotor acts like a flywheel. Therefore, it is possible to store the energy temporarily as a buffer. Moreover, the noise level is much lower in variable speed systems. The rotational speed is low as the wind turbine can work at lower wind speeds as well. To achieve variable speed operation, the mechanical rotor speed and the electrical frequency of the grid must be decoupled. For this purpose, a special generator should be employed. Hence, doubly fed induction generators with a power electronic converter are used in variable speed wind turbines [6-8].

The variable speed technology brings better output power quality to the grid. The rotor is connected with the grid as to deliver the power only at a specific speed range. The architecture of a typical three blade wind turbine is that a low speed shaft is connected between the blade shaft and a gearbox. The gearbox is connected to the generator through a high speed shaft. To get high quality power output the electrical control system regulates the generator. The converter and transformer transform the power to the grid. The

control system is called the command centre, because it measures the direction of the wind for the yaw system. The yaw system turns the nacelle into the direction of the wind to use the wind energy by maximum efficiency. As shown in Figure 6, it is divided into yaw drive and yaw motor. Also, the control system controls the electric power output by stabilizing it with the pitch system. The controller is connected to an anemometer and a wind vane. While an anemometer gives the wind speed, a wind vane provides the wind direction. Based on this information, the braking system can stop the whole wind turbine system as required. The brake should also be used in maintenance work. The tower and foundation carry the wind turbine and the tower should have a certain height to gain the highest possible wind energy.

C. Downwind and Upwind Rotor

A wind turbine can be designed with a downwind or an upwind rotor [8]. A turbine with a downwind rotor does not need a yaw system hence it has a free yaw. It turns the rotor automatically in the direction of the wind. However, if the wind changes abruptly or suddenly, the system may perform badly. Downwind rotor does make more noise than upwind rotor. Yaw controlled upwind rotors with three blades have no this problems. That is the reason why upwind rotors dominate in wind power plants when an active pitch control is used.

D. Stall and Pitch Control

In general, two options are available to regulate the rotor power in high wind cycles: stall regulation and pitch regulation. The stall regulated turbines absorb the wind power with their aerodynamic design. The most of the modern wind turbines use active pitch control; and it can be separated into hydraulic and electrical pitch. Electrical pitch is much used because it is more flexible and is easy to control. If a wind turbine uses pitch regulation (or known as pitching the blades), their blades can turn electrically around the axis of the blades. The pitch control has the task to use the best angle for the right wind speed to get the optimum power output. In other words, the pitch angle helps the blades to maximize the energy. Only a small change of the pitch angle can have a huge effect on the power output of the wind turbine [2, 8]. The main objective of both control options is the same, to control the output power in high wind speeds. The pitch control system has four tasks: (i) to minimize the dynamic and static loads on the blades by changing the angle, (ii) when the wind speed is more than the rated speed it has to steady the output power of the generator, (iii) use the blade back as an aerodynamic brake to stop the rotor if required, (iv) damping out the rotor vibrations to minimize the mechanical load.

II. DESIGN OF THE WIND POWER PLANT

A. Power Output

The information provided in the previous work [4- 10] was used in calculating the power output of horizontal axis wind turbines with three blades. An upwind rotor is considered in

the design since downwind rotors may perform badly in high wind speeds. Usually, wind turbines are controlled with a pitch control mechanism over variable wind speeds and directions. Thus, a variable speed turbine which allows a good energy intake was chosen in this work. For this case study, diameter (d) of the rotor was chosen as 100 m and also air density (ρ) as 1.225 kg/m³. Then, the wind tower height and the rotor swept area are given by eq. (1) and (2), respectively.

$$\text{Height: } h = 2.7936 \times d^{0.7663} = 95.23 \text{ m} \quad (1)$$

$$\text{Rotor swept area: } A = r^2 \times \pi = 7853.98 \text{ m}^2 \quad (2)$$

Every part that moves has a kinetic energy. The formula for the kinetic energy U of is given by:

$$U = \frac{1}{2} \times m \times v_w^2 \quad (3)$$

where m is the mass [kg] and v_w is the wind speed [m/s]. It is directly proportional to the square of the velocity v and mass m of the body. This also applies to a body of air when the wind flowing through an area A . If the surface is normal to the wind direction, the energy flux P_W which is transported by the wind through the surface is calculated by:

$$P_W = \frac{1}{2} \times \rho \times A \times v_w^3 \quad (4)$$

Since the power of the wind increases with a cubic power of the wind speed, a small increase in speed causes a large capacity gain. The theoretically maximum available wind power is:

$$P_T = \frac{1}{2} \times c_p \times \rho \times A \times v_w^3 \quad (5)$$

Wind turbines cannot harness the full amount of energy gathered in a flowing wind. The fraction of the power that can be extracted from wind through a wind turbine is usually given by the symbol c_p (known as the power coefficient) and this describes the efficiency of a wind turbine. The power coefficient is different for each wind turbine type and also this depends on the parameters such as tip speed ratio, wind speed/pattern.

$$c_p = \frac{P_T}{P_W} \quad (6)$$

The wind has to pass the blades to rotate the rotor and hence the speed of the wind cannot be zero behind the turbine blades. The incoming wind speed v_1 is larger than the wind speed v_2 behind the turbine. The reported maximum for all types wind turbines is that only 59.3% of the kinetic energy of the wind can be converted into mechanical energy. Well-designed wind turbines generally fall in the range of 35% - 45% [7].

$$\text{Betz coefficient: } v_2 = \frac{1}{3} \times v_1 \quad (7)$$

$$c_p = \frac{P_T}{P_W} = \frac{(v_1 + v_2) \times (v_1^2 - v_2^2)}{2 \times v_1^3} = \frac{16}{27} = 0.5926 = 59.3\% \quad (8)$$

That is the reason why the maximum power coefficient is defined as: $c_{pmax} = 0.59$. The tip speed ratio λ indicates how fast the blade tips are relative to the wind speed.

$$\lambda = \frac{v_{tip}}{v_w} \quad (9) \quad v_{tip} = \frac{f \times \pi \times d}{60} \quad (10)$$

$$\lambda = \frac{\omega_r \times r}{v_w} \quad (11) \quad \omega_r = \frac{2 \times \pi \times f}{60} \quad (12)$$

where, v_{tip} is the blade tip speed [m/s], ω_r is the angular velocity [radians/sec], and f is the revolutions per minute [rpm]. To calculate the c_p for a variable speed wind turbine, the values of pitch angle β and the tip speed ratio λ are required [10].

$$\lambda_i = \frac{1}{\lambda + 0.008 \times \beta \frac{0.0085}{\beta^{2.5} + 1}} \quad (13)$$

$$c_p(\lambda, \beta) = 0.73 \times \left[\frac{151}{\lambda_i} - 0.58\beta - 0.002\beta^{2.14} - 13.2 \right] \times e^{-\frac{124}{\lambda_i}} \quad (14)$$

Figure 7 shows the power coefficient as a function of pitch angle and tip speed ratio. The highest c_p is 0.44 with a tip speed ratio of 8 and a zero pitch angle. The diagram shows that the power coefficient decreases as the pitch angle increases. Hence, it possible to achieve a high power by maintaining the pitch angle and hence some wind turbines use a braking system to control the blade angle.

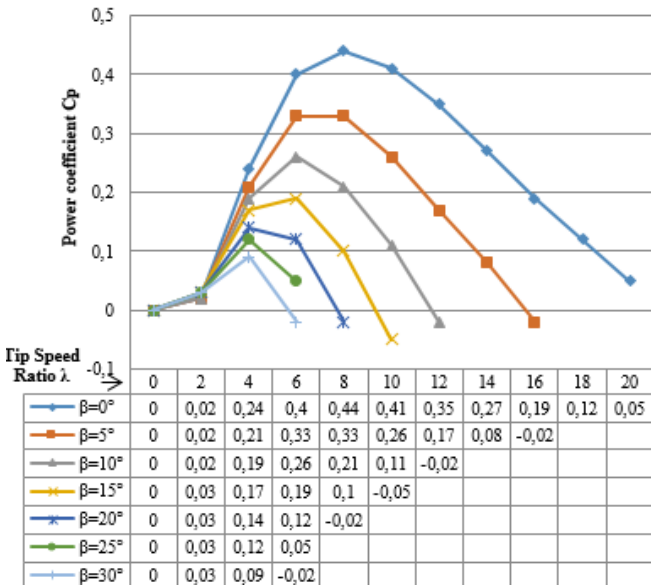


Fig. 7: Power coefficient C_p at different pitch angles β and tip speed ratios λ

After choosing the best parameters to generate the maximum possible power, the power outputs with different wind speeds from 0 to 30 m/s were calculated in Mathcad 15. It was assumed that the generator attached to the wind turbine has its cut-in speed at 4 m/s and its cut-out speed at 24 m/s. The calculated power output for the different wind speeds with the used pitch angle and the resulting power coefficient is given in Table 1.

The actual power output (P_O) of the wind turbine is:

$$P_O = \eta_{gb} \times \eta_{ge} \times P_T \quad (15)$$

where η_{gb} is the gearbox efficiency (depends on the gearbox type and could be as high as 95%) and η_{ge} is the generator efficiency (80% or possible more for a grid-connected induction generator).

The cut-in speed is the wind speed at which the generator starts to produce electricity. In this case, it is at 4 m/s with a power of 0.1 MW. Afterwards, the power output is increasing gradually with the wind speed until the wind speed reaches 14 m/s (at this speed the power output is 4.4 MW). Also at this wind speed the generator reaches its maximum power production. As the wind speed go above 14 m/s, the wind turbine has to pitch its blade angle to control the power output. Therefore, the wind turbine can hold this maximum power until the wind speed reaches its cut-out speed (24 m/s). At the cut-out wind speed the blade pitch angle reaches its maximum of 30° and there will be no power generation at the wind speeds above the cut-out speed as shown in Figure 8. Table 1 and Figure 7 show that the power coefficient is decreasing as pitch angle is increasing.

TABLE I: POWER OUTPUT WITH VARIOUS WIND SPPEED AND PTICH ANGLES

	Wind Speed [m/s]	Power Output [MW]	Pitch Angle [°]	Power coefficient	Tip Speed Ratio
	0	0	0	0	0
	2	0	0	0,44	8
Cut-in speed	4	0,1	0	0,44	8
	6	0,35	0	0,44	8
	8	0,83	0	0,44	8
	10	1,6	0	0,44	8
	12	2,77	0	0,44	8
Rated output speed	14	4,4	0	0,44	8
	16	4,4	7,6	0,31	7
	18	4,4	14	0,21	6
	20	4,4	18,5	0,15	6
	22	4,4	26	0,11	4
Cut-out speed	24	4,4	30	0,09	4
	26	0	30	0	0
	28	0	30	0	0
	30	0	30	0	0

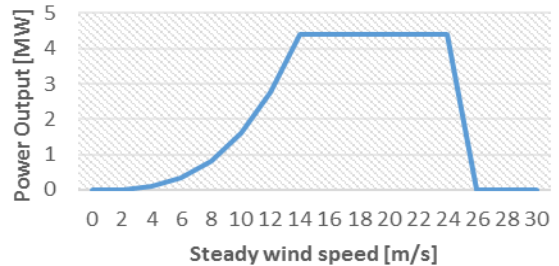


Fig. 8: Power output with steady wind speed

As shown in Figure 8, the wind turbine produces energy only within the wind speed range of 4-24 m/s only. Also, it reaches the best power output in the speed range of 14-24 m/s.

B. Wind Turbine Blades

Previous studies [12-14] provide valuable information on the design of wind turbine blades. The key parameters of a wind turbine design are the number of blades, the aerofoil shape, the chord distribution and the twist distribution. The design process should start with determining the rotor diameter based on the conditions of site and $P = \frac{1}{2} \times c_p \times \eta \times \rho \times A \times v_w^3$. The chosen diameter in this work is 100 m. Then, a tip speed ratio should be chosen where it should be in the range of

$4 < \lambda < 10$ for the wind turbines in electrical power generation. Hence, the tip speed ratio (λ) was chosen as 8.

The next step is to choose the number of blades B , which was chosen as three in this work. Then, it is possible to select the shape of the aerofoil. In fact, different aerofoils can be used at different sections of the blade. A thick aerofoil is better for the root of the blade to provide better strength [14]. In this work, four NACA aerofoils from the NACA 4 digit aerofoil database are analysed with the CFD software ANSYS 15 to get the lift and drag values with different angles of attack. According to the published literature on NACA 6412, it can reach a very high lift coefficient as shown in Figure 9.

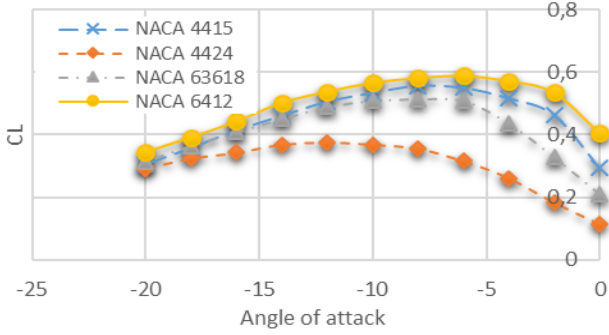


Fig. 9: Lift coefficient vs Angle of Attack for the selected aerofoils

According to the results of this work as well, the NACA 6412 shows the best performance. The NACA 4415, which is thicker, has also good lift coefficients. Hence, the NACA 4415 is used for the root of the blades and the NACA 6412 for the wing and the tip. For the design, blade has to be divided into N elements as shown in Figure 10. Usually 10 to 20 elements would be used. Rough calculations of the relative flow angle in to blades (γ) and the chord length C is shown below: [14]

$$\gamma = 90^\circ - \frac{2}{3} \tan^{-1} \left(\frac{1}{\lambda_r} \right) \quad (16)$$

where λ_r is the tip speed ratio of the local radius.

$$C = \frac{8\pi r \cos \gamma}{3B \lambda_r} \quad (17)$$

The widest chord is usually given by:

$$r = 0.2 \times R \quad (18)$$

where R is the blade radius and r is the local radius of the blade element. The blade in this work has the greatest chord length at 10 m. The complete turbine with blades and the hub were modelled using Solid Works 2014 and shown in Figure 10. In optimizing the blade, the Element Momentum Theory can be used by considering important parameters such as the axial induction factor (a), the annular induction factor (a') and more information on this can be found in the literature [10-12]. The calculation of the optimum blade is an iterative process and the designer has to spend a lot of time to refine the chord and twist distribution to get an acceptable solution.

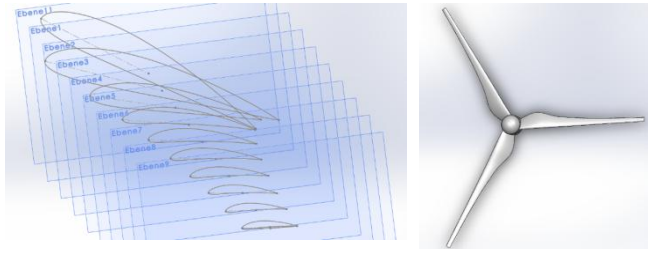


Fig. 10: Left- Blade elements with different chord lengths and inflow angles, Right - Modelled Wind Turbine in Solid Works

The momentum theory gives:

$$\sigma' = \frac{B \times C}{2 \times \pi \times r} \quad (19)$$

$$Q = \frac{2}{\pi} \cos^{-1} \left[\exp \left\{ - \left(\frac{B/2(1-r/R)}{(r/R) \cos \gamma} \right) \right\} \right] \quad (20)$$

$$a = \frac{\sigma' (C_L \sin \gamma + C_D \cos \gamma)}{4Q (\cos \gamma)^2 + \sigma' (C_L \sin \gamma + C_D \cos \gamma)} \quad (21)$$

$$a' = \frac{(1-a) \sigma' (C_L \sin \gamma + C_D \cos \gamma)}{4Q (\cos \gamma)^2 + \sigma' (C_L \sin \gamma + C_D \cos \gamma)} \quad (22)$$

$$F_x = \sigma' \pi \rho \frac{v_w^4 (1-a)^2}{(\cos \gamma)^2} (C_L \sin \gamma + C_D \cos \gamma) r dr \quad (23)$$

$$T = \sigma' \pi \rho \frac{v_w^4 (1-a)^2}{(\cos \gamma)^2} (C_L \cos \gamma + C_D \sin \gamma) r^2 dr \quad (24)$$

where T is the thrust, Q is the torque, dr is the ring section of the rotor disc, σ' is the local solidity and Q is the blade correction factor.

TABLE II: CALCULATED PARAMETERS

Radius r [m]	Thrust F_x [N]	Torque T [Nm]	Lift coefficient C_L	Drag coefficient C_D
10	18909	58720	1.4	0.1
15	28417	102746	1.5	0.04
20	38041	144745	1.59	0.022
25	47478	182416	1.57	0.017
30	56321	217400	1.45	0.013
35	64275	245217	1.3	0.012
40	72010	270776	1.25	0.012
45	74717	279416	1.21	0.011

With the torque values calculated, total power from each annulus can be determined.

$$P_a = w_r \times T \quad (37)$$

Then, the total power from the rotor is given by:

$$P = \int_{r_h}^R P_a \times dr = \int_{r_h}^R w_r T \times dr \quad (38)$$

where r_h is the radius of the hub which is 3.5 m in this work. R is the total radius of the wind turbine blade. Table 3 shows the total power from each annulus and the total power from the rotor for each radius of the blade.

TABLE III: TOTAL POWER OF GENERATED FROM THE TURBINE

Radius r [m]	Total Power from each annulus P_a [kW]	Total Rotor Power P [kW]
10	94	4368
15	164	7644
20	232	10781
25	292	13572
30	348	16175
35	392	18244
40	433	20146
45	477	20789

III. CFD MODELLING

In CFD, an accurate mesh is necessary to achieve acceptable results. The geometry and mesh of the wind turbine is done by considering previous works. After importing the boundary conditions into ANSYS-Fluent, the simulation was performed and the pattern of streamlines across the blades is shown in Figure 11. Then, the mechanical power can be calculated by using the achieved torque value. In this work, the theoretically calculated torque is 279416 Nm where the torque achieved from CFD is 287649 Nm.

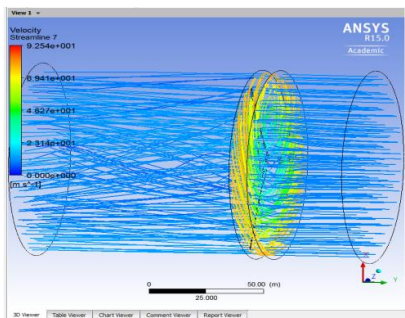


Fig. 11: The pattern of streamlines shown in CFD Results

IV. CONCLUSION AND FUTURE WORKS

A design of a horizontal with turbine was performed theoretically and in CFD. The designed wind power turbine has a rotor diameter of 100 m where its height is 95.23 m. The proposed wind turbine reaches its maximum power output within the wind speed range of 14-24 m/s. Generally, the wind turbine reaches its maximum at 14 m/s and then it can hold its maximum power until the speed reaches to 24 m/s by pitching the blades from 0 to 30°. The maximum possible output power of the proposed design is 4.4 MW. As the wind speed increases the power output increases while the power output decreases as the blade pitch angle increases. According to the theoretical results, the torque generated by the proposed wind turbine is 279416 Nm where the CFD results showed that it is 287649 Nm for the same design. Hence, the theoretical and CFD results are in good agreement with a small deviation of 2.9 %. Generally, this type of models can be used to evaluate the performance of wind turbines at wide range of operating conditions to achieve optimum power generating performance prior to their fabrication. In future work, various sizes of blade diameters will be considered over wide operating conditions to make a better comparison. Moreover, the study will be extended to explore the effects different shape of aerofoils and different types of materials for constructing blades to choose the best possible combination.

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