Design and analysis of upstream air deflectors for increasing wind-turbine efficiency

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Abstract. The objective of the present work is to increase the effectiveness of the wind turbine explicitly without changing the design parameters of the existing wind turbines. Deflectors which will deflect the air from outer region into the region where wind turbines harness energy are employed. By doing so the flow gets accelerated and this in turn increases the mass flow rate. This reduces the cut in speed for the wind turbine setup. The present work focuses on simulation for flow over the deflector to study the nature of this setup. The simulation was performed for different angle of deflector and at different velocities and the results are presented. Results highlight the significance of such deflectors in improving entire efficiency of the system.

1. Introduction

Mankind has relied up on nature for all these years to build civilizations from scraps. The most important aid, mankind took from nature is its energy resources. In the advent of new technologies, the requirement for energy, namely electrical energy has increased. The non-renewable energy resources such as petroleum and coal cannot last longer, which brings the need for development in technologies of renewable energy resources. Thus, it is very important to improve the effectiveness as well as the efficiency of the technologies which take energy from renewable energy resources.

The idea of augmenting the wind turbines by controlling the upstream flow has originated as soon as the invention of wind turbine itself. The following are some research which focused on increasing wind turbine efficiency using upstream structures like ducts. Phillips et al. [1] did CFD modelling and developed diffuser augmented wind turbine and studied effects of geometric modification of the diffuser duct. Ohya et al. [2] have studied about a shrouded horizontal axis wind turbine with a flange diffuser which leads to increase the power output with a factor around 4-5 compared to the standard horizontal axis wind turbine. Wang et al. [3] improved the reliability in the large utility horizontal axis wind turbine with digital hydrostatic train drive. But this technique failed to improve the reliability of the wind turbine at very low speeds. Riyanto et al. [4] discussed on increasing the power output by increasing the wind's speed which is made by adding the diffuser to the wind turbine. Khaled et al. [5] have described the improved performance of the wind turbine by using the winglets. The effect of the
boundary layer on the wake of a horizontal axis wind turbine was studied by Sedaghatizadeh et al. [6] and it shows that the presence of boundary layer lowers the power output. Lipian et al. [7] conducted experimental investigations of shrouded and twin-rotor wind turbine systems. They concluded that shrouding increases performance along with aerodynamic loading of rotor whereas twin rotor helps to distribute the loads. Kheirabadi and Nagamune [8] reviewed wind farm control with objective of wind farm power maximization. They stated notable concepts for maximizing power production within wind farms like, power de-rating, yaw-based wake redirection and turbine repositioning. The wind turbine’s power output gets affected because of the vortices generated in the flow. Ozono [9] studied the vortex generated in the wake of a cylinder. He used deflectors in the wake of the cylinder to suppress the vorticity. Banks [10] studied about the vortices generated in the corners of a tilted flat solar panels mounted on flat roofs. He investigated the uplift wind loads on the plate due to the corner vortices. Capone and Romano [11] studied the effects of horizontal and vertical deflector near the wake of a square back car model. They used particle image velocimetry to study the flow around the deflectors.

In the recent years, non-conventional designs of wind turbines are studied. One such design is vertical axis wind turbines. There are many studies done on the effects of deflectors for vertical axis wind turbines. Kim and Gharib [12] effect of an upstream flat deflector on the power output of two counter-rotating straight bladed vertical-axis wind turbines. Yang et al. [13] studied vertical axis turbine consisting of deflectable blades. The research was done both theoretically and practically. Water current was used to study the practical results. It was reported that the performance was improved by 41.1 %. Wong et al. [14] did 3D simulation and parametric study of flat plate deflector for vertical axis wind turbine. Jin et al. [15] investigated the parametric influence of upstream deflector on vertical axis wind turbine’s output power using CFD simulation. Chong et al. [16] studied the performance of deflector integrated with cross axis wind turbine. It focused on low wind speed and high turbulent skewed wind flow similar to an urban environment.

Even though there are many research works done on wind turbines but very less work has been done for horizontal axis wind turbine with deflector in the upstream. In this research, the deflector is designed and analysed for horizontal axis wind turbine. The deflector used to increase the effectiveness is shown in Fig. 1. The dimensions of deflector may vary according to the wind turbine dimensions. The deflectors mentioned in the present work are self-reliable i.e., they get power from solar panels placed on the top of them. Also, they can supply excess power (if any) from their solar panels for the user requirements. Since these deflectors are self-reliable in terms of energy requirements, they can work for a very long time. Many such deflectors can be placed around a single wind turbine as shown in Fig. 2 to account for the fact that flow direction may vary with time. These deflectors will be connected to the wind turbine to get the airflow data at every instant and use the airflow data for maximizing the effectiveness of the whole system. The objective of the present work is to analyse the effect of such a deflector in the upstream of wind turbines.

2. Design methodology
Deflectors contain 3 major components, the top body which deflects the air, the lever which raises or drops the deflector and the base which holds the deflector components in place. The lever is operated by a servo motor which deploys the lever when required. Also solar panels can be placed on the top body, and the solar energy can be converted and stored in batteries, and the same energy can be used to operate the levers. Apart from these mechanical fittings, the components like battery and controllers are placed in the notches provided in the deflector base. For an isolated wind turbine, the number of deflectors to be placed around can be decided based on the annual wind report of that area. If there is a frequent change in wind direction, multiple deflectors can be placed as in Fig. 2 so as to have increased effectiveness, whereas in the region where the wind direction is predominantly bidirectional or unidirectional, the number of deflectors around a turbine can be reduced.
2.1 Working of the deflector
The deflector in deployed and active state is shown in Fig. 3. The deflector in closed state is presented in Fig. 4. The state of the deflector is decided by the direction of wind. When the wind is not in the direction of deflector, there is no need for it to be in active state, thus it gets back to its closed state where the settling angle is as per the most efficient angle for solar energy absorption. And also, when the wind speed is approaching cut off velocity, the defectors are dropped so as to avoid damage of the wind turbines.

2.2 Basic equations
Let density, velocity and area of cross section at inlet and exit of deflector region (as represented in Fig. 5) be $\rho_1$, $V_1$, $A_1$ and $\rho_2$, $V_2$, $A_2$ respectively.

By assuming laminar, inviscid flow
Mass flow at 1 = Mass flow at 2
$$\rho_1 V_1 A_1 = \rho_2 V_2 A_2$$ (1)

For incompressible flow, ($\rho_1 = \rho_2$) So, equation (1) becomes,
$$V_1 A_1 = V_2 A_2$$
$$V_2 = V_1 \times (A_1/A_2)$$ (2)
And, as in Fig. 5, the effective area of flow decreases downstream, thus the term \((A_1/A_2)\) has value more than 1. It conveys that there is an increase in flow velocity at region 2 than region 1. This basic equation does not include various factors such as upstream velocity profile, flow suction because of wake and so on. This gives the basic idea behind the purpose of deflector in a very simple manner.

2.3 Domain
For performing computational fluid dynamics, there is a need to define the domain over which the flow of air is analysed. The current analysis is done by using a cuboidal domain with dimensions as shown in Fig. 6, and the deflector with the dimensions as shown in Fig. 7 is placed on the bottom surface of the domain at 20 m from inlet to include boundary layer effect due to land ahead of the deflector.

3. Results and discussions
The results were simulated through CFD analysis, for which ANSYS was used as a simulation platform. Five simplified solid models were made with different angles for simulation. They were tested at 4 different velocities, 5 m/s, 10 m/s, 15 m/s and 20 m/s, which are the usual air velocities at which wind turbines operate. The solid models are as shown in Fig. 8. The 5 models vary based on the deflection angle, where, model D1, D2, D3, D4, D5 corresponds to the 10°, 20°, 30°, 40°, 50° angle of deflection, respectively. These 5 models were made separately and Analysis was done separately with different free stream velocity. The effect of earth surface boundary layer is also included in this simulation. Thus, a viscous laminar model was used to simulate the boundary layer effectively. The present work focuses on the downstream velocity profile and the volume of wake region formed. The flow profile is visualised as contour plot in the mid plane of the deflector. The profiles shown in Figs. 9-12 are or model D1, D2, D3 and D4 respectively with 5 m/s free stream velocity.
The velocity profile viewed from the side view with respect to the mid plane varies with the deflector angle, the velocity reached at downstream increases and at the same time the wake region formed at downstream becomes larger with increase in angle of deflection. The velocity profile for model D5 with different angles of attacks are as shown in Figs. 13-16. The profiles show very large wake regions along with a high increment of airflow in certain regions. The force acting on the deflector is directly proportional to the volume of wake formed downstream. Fig.17 shows the pressure distribution over the model D5 deflector, which has 50 degrees angle of deflection with freestream velocity of 15 m/s.

**Figure 8.** Different models of deflectors used for simulation.

**Figure 9.** Velocity contour for model D1 with 5 m/s freestream velocity
Figure 10. Velocity contour for model D2 with 5 m/s freestream velocity

Figure 11. Velocity contour for model D3 with 5 m/s freestream velocity

Figure 12. Velocity contour for model D4 with 5 m/s freestream velocity
Figure 13. Velocity contour for model D5 with 5 m/s freestream velocity

Figure 14. Velocity contour for model D5 with 10 m/s freestream velocity

Figure 15. Velocity contour for model D5 with 15 m/s freestream velocity
Figure 16. Velocity contour for model D5 with 20 m/s freestream velocity

Figure 17. Pressure contour of model D5 with 15 m/s freestream velocity

Figure 18. Velocity profiles of deflectors in downstream at 5 m/s freestream velocity.
To understand the effectiveness of the deflectors better, velocities at the downstream is measured at 2.5 meters from the leading edge of the deflector at 2 meters height to the height at which the velocities of the downstream match the freestream velocities. The velocity profile in wake region is not plotted in the graph. The velocity variation with height behind the deflector for 5 m/s and 20 m/s for different deflector angles are shown in Figs. 18 and 19 respectively. From the graphs in Fig.18 and 19, the average incremental velocity over an area can be calculated. Thereby the percentage velocity increment in the upstream of the wind turbine can be calculated. The contour plots show that the velocity profiles for a constant deflector angle does not vary with velocity for the range of 5 to 20 m/s. This is due to very less change in Reynolds number. Thus, the analysis done in these velocities can be easily deduced to intermediate velocities. As the deflector characteristic dimension is 2 m, the velocity just after the deflector will be very less for height less than 2 m. This puts the limit to the minimum height at which the wind turbine blade tip can be placed. Also, the effect of deflector fades away slowly with height and at some height the downstream velocity becomes equal to the freestream velocity. This gives the idea for optimal height of the wind turbine blade for which the deflector influence is at the maximum. The deflector analysed in this present work can be used to augment any existing mini wind turbines. The optimal dimension of such wind turbine is a tower of 5 meters and the blade diameter of 5 meters approximately. The wind turbine with such dimension will experience a maximum average upstream velocity of 5.7 % more than the freestream velocity for 50° deflector deflection. Apart from the positive effects, there are some negative effects of the deflectors which are not desirable for some situations.

The negative effects include the flow circulation due to wake region which exerts a twisting force at the wind turbine tower which can affect the local load distribution of the tower. The deflector setup can also affect the wind turbine blades as the velocity profile of downstream of deflector are parabolic curves which means the rotating blade experience different air speed at different positions, this causes periodically fluctuating load which may lead to accelerated fatigue. Due to the deflection of air, there is a vertical component of air generated for the downstream of the deflector. The vertical component of air speed is relatively very low compared to the axial component. But the vertical velocity exerts a twisting force on the turbine blades, thus the turbine blades should be stronger to withstand the forces. The mentioned excessive loads at region of cut-in velocities will be negligible and thus the deflector will be highly effective with a cut in speed reduction of 5.4 %. And the average velocity during moderate wind speed can be increased to 5 % thus the power output is expected to increase to a good value as the power of the flow is directly proportional to the third power of velocity.

Figure 19. Velocity profiles of deflectors in downstream at 20 m/s freestream velocity.
4. Conclusion

An upstream air deflector for increasing wind turbine efficiency has been designed and analysed in present work. The deflector proposed in this work is a simple model which does not require changes in wind turbine design, and the deflector helps in increasing the effective upstream velocity of mini-wind turbines with the expense of non-uniform. For the wind turbine with tower height of 5 m and blade diameter 5 m, the upstream flow power is increased by 18.2% with average incremental velocity of 5.7% as seen in the case of deflection angle of 50 degrees and freestream velocity of 20 m/s. The future works related to this work may include the behaviour of wind turbine blades to non-uniform velocity profiles.

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