Over Speed Protection of Horizontal Axis Wind Turbine Using Slot in the Turbine Blade

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Abstract. The wind energy is more reliable, clear, and easily exploitable form of renewable energy source. Wind turbines are being stationed to capture the wind’s power and convert it to electricity. The wind turbines are operated at rated speed to ensure smooth operation. When the wind turbine faces the higher wind speed, wind force impacts the tower head causing immediate damage the turbine blade. Wind turbines are equipped with various Aerodynamic braking systems and mechanical braking system to control the over speeding of the wind turbine rotor at extreme wind velocity. In this novel methodology, it is attended to reduce the rotational speed of the wind turbine aerodynamically by providing the chord wise slot (opening). The slot modifies the pressure distribution over the upper side and lower side of the turbine blade that slows down the rotational speed of the wind turbine within the safe limit. In this present attempt, the over speeding of the wind turbine rotor is effectively controlled without disturbing the power generation. The different parameters of the slot such as the position of the slot, inclination of the slot, and width of the slot are studied and the slot parameters are computationally optimized.

Keywords: Aerodynamic braking system, CFD, over speed protection, Wind Turbine.

1. Introduction

Wind energy is one of the most mature and growing renewable energy technology. Wind turbine harnesses the wind power. When the wind turbine is exposed to the wind, the turbine's blades spin clockwise direction, capturing energy which rotates the shaft of the wind turbine in turn generate the electricity. The modern wind turbine blades are designed aerodynamically to extract maximum power from the wind. 

The power contained in the wind P, calculated from the expression

\[ P = \frac{1}{2} C_p \rho A V^3 \] (1)

Where \( \rho \) is the air density (1.225 kg/m³), \( C_p \) is the power coefficient, \( A \) is the swept area,
and V is the free stream velocity.

which shows importance of velocity of windin the power generation. The wind power is proportional to cubic power of wind velocity. The wind turbines installation requires lot of investment. The expected life period of the commercial wind turbineis twenty years. The Control system of the wind turbine is one of the vital aspects of the wind turbine to ensure the safe operation of the wind turbine. When the wind turbines face the wind velocity beyond the range i.e. above Beaufort number Six, turbine blades rotate at very high speed that causes blade failure, affects the structural stability and the thrust of the wind may topple the wind turbine. So, it is necessary to provide an effective braking system to slowdown the rotor speed during the Extreme wind velocity. There are several mechanisms available to control the rotor speed. There are Pitchable tips, Tip vanes, Spoilers, Ailerons are used to reduce the wind turbine speed. For 50-750 KW range wind turbines the effective speed control system is pitch control, the most common means of over speed control are either full-span pitch control or pitchable tips. Wind turbines with full-span pitch controls both over-speed protection and power modulation. Pitchable tips may be used for power modulation, over-speed protection and braking. For stall-regulated wind turbines, the common form of over-speed protection is pitchable tips.

Riyadh Belamadi et al. optimized the performance of wind turbine rotors by using different geometries of slotted airfoils. In their work. The NREL S809 airfoil was selected and developed various configurations based on the S809 airfoil. They performed extensive two-dimensional numerical analysis in order to find out the effects of slot's location, width, and slope. They determined the best configuration of the slot's location, width, and slope. And they finally had chosen four turbulence models i.e. standard k-ε, SpalartAllmaras, k-ω and k-ω SST. The two-dimensional simulation was conducted of the airfoil S809. They studied the Different slot locations, slot slope angles, and slot widths to find out the optimum one. The results show that the control system improves aerodynamic performance only over a specific range of angles of attack. The results show that the coefficient of drag value is high for the modified airfoil at the low angle of attack. It was concluded that at moderate and high angles of attack, from 10° to 20°, the slot configuration outperforms the baseline configuration.

Wei Zhang et al analyzed numerical simulations of incompressible flow over two airfoils NACA4412 and NACA0012-64, to investigate the effects of the airfoil geometry on the flow separation and transition patterns at Reynolds number of 1.0x104 and angle of attack 100 degrees. The selected two airfoils are geometrically similar except for maximum camber. They focused on flow separation at the airfoil leading edge, transition of the separated shear layer to three-dimensional flow and subsequently to turbulence.

In this approach, a chordwise slot (opening) is provided on the blade as shown in the figure 1 which reduces the wind turbine rotational speed when it is faces to high wind velocity. This approach is based
on the difference of static pressure between the upper side and lower side of the airfoil. This slot between the pressure side and suction side alters the pressure distribution over the blade. The change in pressure distribution reduces the lift generation that keeps the wind turbine speed within the limits, even when the turbine is exposed to extreme wind velocities. When wind velocity exceeds the described limit, the other aerodynamic braking systems bring the machine to a halt. But this recommended braking system keeps the wind turbine speed within the rated revolutions per minute (rpm) and generate the power continuously. The advantages of this system are that there are no complex electronic circuits, no mechanical links, no moving parts, less maintenance, reduced noise generation and decreased weight of the braking system. The performance of the braking system could be experimentally calculated with the help of wind tunnel experiments

2. Computational Study
The slot on the wind turbine blade modifies the pressure variation that keeps the lift force generated under control. If the slot is very small, it could not effectively alter the pressure distribution and the improper or over slot affects the power generation. It is important to select the proper position for slot. The various parameters such as position, width, shape and length of the slot are optimized by computational method. In this work, the widely used National Renewable Energy Laboratory airfoil (NREL) S809 is selected for simulation. The S809 is a twenty-one-percentage thick, laminar flow airfoil designed specifically for horizontal axis wind turbine applications. The correct turbulence model is chosen from various turbulence model. The turbulence model results are equated with experimental results. The various turbulent models Spalart-Allmaras, Standard K-ε and standard K-ω are used to calculate the aerodynamic coefficients. The derived results for different turbulent models are compared with reliable experimental results[4](Figure 2 &Figure 3). The turbulence model standard K-ω results exactly coincides with the experimental results. Hence The Standard K-ω turbulence model based on the Wilcox (1988) K-ω model is followed for the further computational technique. It has two separate equations to solve the transport equation for turbulent viscosity. The turbulence model equation for the K-ω is given by:

![Figure 2. NREL 809 airfoil lift Co-efficient co-efficient for various turbulence models with experimental data](image1)

![Figure 3. NREL 809 airfoil drag for various turbulence models with experimental data](image2)
The turbulent eddy viscosity is
\[ v_T = \frac{a_1 k}{\max(a_1, SF_2)} \]  
(2)

\[ \frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \tau_{ij} \frac{\partial U_i}{\partial x_j} - \beta^* k w + \frac{\partial}{\partial x_j} \left[ (v + \sigma^* v_T) \frac{\partial k}{\partial x_j} \right] \]  
(3)

\[ \frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \alpha S^2 - \beta \omega^2 + \frac{\partial}{\partial x_j} \left[ (v + \sigma_\omega v_T) \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_1) \sigma_{\omega^2} \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i} \]  
(4)

Equation (3) determines the turbulent kinetic energy (k)
Equation (4) determines the specific rate of dissipation turbulent kinetic energy (\epsilon)

\[ F_1 = \tan h \left\{ \min \left[ \max \left( \sqrt[4]{\frac{500 \nu}{\beta^* \omega y^2}}, \frac{4 \sigma_\omega^2 k}{CD_{K\omega y^2}} \right) \right] \right\} \]  
(5)

\[ F_2 = \tan h \left[ \max \left( \frac{2 \sqrt{\nu}}{\beta^* \omega y^2} \right) \right] \]  
(6)

\[ P_k = \min \left( \tau_{ij} \frac{\partial U_i}{\partial x_j} 10 \beta^* k \right) \]  
(7)

\[ CD_{K\omega} = \max \left( 2 \rho \omega^2 \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i} 10^{-10} \right) \]  
(8)

\[ \emptyset = \emptyset_1 F_1 + \emptyset_2 (1 - F_1) \]  
(9)

The empirical constants
\[ \alpha_1 = 0.555 \quad \alpha_2 = 0.44 \quad \beta^* = 0.09 \]
\[ \beta_1 = 0.075 \quad \beta_2 = 0.0828 \]
\[ \sigma_{K1} = 0.85 \quad \sigma_{K2} = 1 \quad \sigma_{\omega1} = 0.5 \quad \sigma_{\omega2} = 0.85 \]

In this work, S809 is modeled with chord length of 1m. The airfoil profile is modeled in Pro-E. Boundary conditions and mesh is created in ICEM in the figure 4 and 5. The ICEM is a pre-processer used to create the structured meshes with quadrilateral elements. From the study of various papers, C-type grid topology is the best method to obtain the accurate results. Calculations are done for various angles of attack from -5° to 20° degrees.
2.1. Effect of Position of The Slot

The position of the slot at the wind turbine blade plays a crucial role in the braking system. The improper position of slot affects the overall efficiency and power generation. The proper position is found by creating slot at various locations from the leading edge. The positions at 0.2C(200 mm), 0.25C(250 mm), 0.3C(300 mm), 0.35C(350 mm), 0.4C (400 mm) from the leading edge are considered as the key positions. Where C-Chord length and chord length is considered as one metre. The 0.01 C(10 mm), 0.15C(15 mm), 0.20C(20 mm) are taken as width of the slot. The aerodynamic coefficients are calculated and the results are related with airfoil without slot for various wind velocity.
Figure 6. Comparative view of pressure and velocity contours for different positions of slot.
The figure 6 shows the comparative view of pressure contours over the airfoil for α=5°. The figure clearly distinguishes the high pressure region at the bottom of the airfoil and low pressure region at the top of the airfoil. The successive figures show that there is alteration in pressure distribution due to the slot. These velocity contours illustrate the high velocity region on the upper side of the airfoil and low velocity region in the lower side of the airfoil. The flow separation advances in the upper part of the airfoil because of the slot. The earlier flow separation affects the lift generation that results in rotation of the airfoil under control. The above Fig 7, 8 & 9 explains aerodynamic co-efficient for different widths 10 mm, 15 mm and 20 mm.

**Figure 7.** Lift co-efficient Vs varying position keeping 0.01C width

**Figure 8.** Lift co-efficient Vs varying position keeping 0.01C width

It is observed that airfoil without slot generates maximum coefficient of lift and airfoil slot at 0.35C effectively alters the pressure distribution without affecting the CL value. Even though the wind velocity increases, the co-efficient of CL value remains constant at high wind velocity that ensure the lift force and the speed of the wind turbine under control. The other models underperform when compared to the airfoil model slot at 0.35 of chord.

**Figure 9.** Lift co-efficient Vs varying position keeping 0.01C width
2.2. Inclination of the Slot

The velocity vector of the S809 airfoil with slot at 0.35C is shown in Figure 10. It is observed that if the slot is perpendicular to the direction of the free stream, the flow rate is minimum from the pressure side to the suction side.

![Figure 10. Velocity vector of the S809 airfoil with slot at 0.35C](image)

The flow volume declines inside the slot and fluid velocity inside the slot is very low when compared to the near-by region. The fluid loses its momentum inside the slot and velocity of flow inside the slot drastically declines.

![Figure 11. Closer view of Outlet](image)

![Figure 12. Closer view of Inlet](image)

![Figure 13. Pressure contour for inclined Slot](image)

![Figure 14. Velocity contour for inclined slot](image)
The Figure shows the pressure contours of the airfoil with inclined slot. Figure 14 shows the velocity contours of the airfoil with inclined slot. It is clearly noticed that inclined slot effectively alters the pressure distribution and increases the velocity of the fluid inside the slot when compared with vertical slot.

Figure 15 shows the path lines of the exit of the slot of the airfoil with inclined slot. It is observed that fluid flow rate surges and velocity of the fluid inside the slot surges due to the inclination.

Figure 15. Path lines of upside of the opening

Figure 16. Inclination of the airfoil

The slot is considered at an inclination to rise the flow rate. The suitable inclination angle and the effect of inclination is analysed. In order to rise the flow rate from the upper side to the lower side of the airfoil, the slot is kept inclined at various angles and effects is analyzed. The 30°, 45°, and 60° have been taken as an inclination angle of the slot for the study. The effective inclination angle is studied through two-dimensional flow analysis. The slot is kept as 0.35C from the chord and the aerodynamic performance is calculated for inclination angle 300, 450, and 600. The pressure contour, velocity vector and path lines for the different configuration studied.

In Figure 17, the first row represents the pressure contours for the airfoil with inclined slot at an angle of 30° on 0.35 C on the chord of the airfoil for the angle of attack 0°, 5°, 10°, and 15°. It is noticed that pressure difference increases with the angle of attack increases. Similarly, the second row and third row represent the pressure contours for the airfoil with inclined slot at an angle of 45° and 60° on 0.35 C on the chord of the airfoil for the angle of attack 0°, 5°, 10°, and 15°. It is observed that pressure difference increases with the angle of attack increases.

The aerodynamic performance has been calculated based on the aerodynamic coefficients co-efficient of lift and co-efficient of drag. Figure 18(a), (c)&(e) show the lift coefficient and drag coefficient for
the angle of attack 0° to 20°. The black colour curve indicates the lift coefficient value and the red
colour curve indicates the drag coefficient curve. In each diagram, the performance of the modified
airfoil performance is compared with the baseline airfoil. The lift coefficient of the baseline airfoil is
high compared with modified airfoils. The coefficient of lift is the baseline airfoil is 0.017 for AOA=0°
and 0.965 for AOA=20°.

The co-efficient of drag of the baseline airfoil is minimum compared with modified airfoils (from AOA
0° to 20°). The co-efficient of drag of the base line airfoil is 0.013 for AOA=0° and 0.105 for
AOA=20°. The glide ratio (lift-over-drag ratio) of the baseline airfoil and airfoil with slot is shown in
Figure 18(b),(d)&(f). Based on the glide ratio it is concluded that the inclination angle 60° is found as
an optimum inclination angle to alter the pressure distribution. The glide ratio of the baseline airfoil is
35.16 and the closest glide ratio (29.63, 29.07 and 28.75) is achieved for inclination angle 60° in all
cases except 60° inclination from the chord. Based on the aerodynamic performance the 600is
recommended.

![Graphs showing aerodynamic performance](image)

**Figure 17.** Aerodynamic co-efficient and Glide ratio of various configurations
Figure 18. Pressure contours of S809 airfoil with inclined slot at 30°, 45°, 60° from the chord.
### Width of the Slot

The width of the slot shown in figure 19 is an important parameter which has profound influence in the effectiveness of the braking system. The too small width is not sufficient to develop the pressure difference and the excess width affects the lift generation. Hence the optimum width is calculated. The various width 0.01C, 0.015C, 0.02C, are considered and based on this, the aerodynamic coefficients are calculated by varying the slot positions at 0.35C.

![Figure 19. Width of the Slot](image)

| Pressure contours | Velocity contours | Streamlines |
|-------------------|-------------------|-------------|
| ![Pressure contours](image) | ![Velocity contours](image) | ![Streamlines](image) |

1. **Pressure contours**
   - 1(a): Pressure distribution
   - 1(b): Velocity contours
   - 1(c): Streamlines

2. **Velocity contours**
   - 2(a): Pressure distribution
   - 2(b): Velocity contours
   - 2(c): Streamlines

3. **Streamlines**
   - 3(a): Pressure distribution
   - 3(b): Velocity contours
   - 3(c): Streamlines
Figure 20. Pressure contours, velocity contours, and streamlines of different width of slot

The figure 20 shows velocity contours, pressure contours, and streamlines for the airfoil with different width slot for the angle of attack 100. The first row shows the pressure contours of various configurations. It indicates that slot alters the pressure distribution. If the width of the slot increases, it correspondingly alters the pressure distribution over the airfoil. Figure 21 shows the pressure coefficient for the different configurations. Figure 21 (a) shows the pressure coefficients of baseline airfoil i.e. without slot. Figure 21 (b), 21(c) and, 21(d) shows the pressure coefficients of the airfoil with slot width 0.005C, 0.01C and 0.02C respectively.

Figure 21. Pressure coefficients for the different configurations
The aerodynamic coefficients have been calculated for different wind speed is shown in figure 22. The baseline airfoil performs better compared to other configurations. The 0.01C width at 0.35C from the leading edge is found as the optimum slot as the performance of the slot width 0.01C is closer with base line airfoil. The coefficient of lift of baseline airfoil is 0.94 at 5 m/s and1.09 at 20 m/s. The coefficient of lift of the airfoil with slot 0.01C is 0.744 at 5 m/s and 0.79 at 20 m/s for the angle of attack 100. The drag coefficient of baseline airfoil is 0.013 at 5 m/s and 0.01 at 20 m/s. The drag coefficient of the airfoil with slot 0.01C is 0.074 at 5 m/s and 0.06 at 20 m/s. Based on the two-dimensional computational studies 0.01C is an effective width to alter the pressure distribution.

3. Conclusion
In this work, a newer type of wind turbine aerodynamic braking system is numerically analyzed. From this, it is demonstrated that slotchangesthe pressure distribution of the turbine blade at high speed wind. The chordwise position of the slot, inclination position of the slot and the width of the slot are optimized in this work. The slot at 0.35C from the leading edge is found to be the suitable position for the slot. The rate of fluid flow can be increased by providing the slot at an angle 60°. The slot at 60° provides the maximum fluid flow at the high velocity. The 0.01C width slot provides the better results. The experimental and computational results obtained in the wind tunnel matches with the results of computational Analysis. Though the slot provided in the wind turbine blade slightly affects the electrical power generation, it can be prevented by providing simple closing and opening mechanism. This mechanism can be designed in such a way that the slot remains closed at low velocity and the slot opens only at high velocity. This proposed aerodynamic braking system could be effectively implemented to control the over speeding of the wind turbine at extreme high velocity.

4. References
[1] D.A.Griffin,R.Lynetteand associates, “Investigation of aerodynamic braking devices for wind turbine Applications,” National Renewable Energy Laboratory, NREL/SR-440-22253, 1997.
[2] GeneQuandt, “Wind Turbine Trailing Edge Aerodynamic Brake Design,” National Renewable Energy Laboratory, NREL/TP-441-7389, January1996.
[3] Paul Migliore, “Wind Turbine Trailing-Edge Aerodynamic Brake Design” NREL/TP-441-7389 • UC Category: 1213 • DE96000525.
[4] Somers, D.M., “Design and experimental results for the S809 airfoil”, National Renewable Energy Laboratory, NREL/TP-441-7389.
[5] National Renewable Energy Laboratory Information. Available from: <http://www.nrel.gov>.

[6] Cao, H. V., & Wentz Jr, W. H. Performance and aerodynamic braking of a horizontal-axis wind turbine from small-scale wind tunnel tests 1987.

[7] Eleni, D. C., Athanasios, T. I., & Dionissios, M. P. Evaluation of the turbulence models for the simulation of the flow over a National Advisory Committee for Aeronautics (NACA) 0012 airfoil. Journal of Mechanical Engineering Research, 4(3), 100-111 2012.

[8] Rathakrishnan, E. Instrumentation measurements and experiments in fluids. CRC Press 2007.

[9] Hoffmann, M. J., Reuss Ramsay, R., & Gregorek, G. M. Effects of grit roughness and pitch oscillations on the NACA 4415 airfoil (No. NREL/TP--442-7815). National Renewable Energy Lab., Golden, CO (United States); Ohio State Univ., Columbus, OH (United States) 1996.

[10] Houghton, E. L., & Carpenter, P. W. Aerodynamics for engineering students. Elsevier 2003.

[11] Johansen, J., & Sørensen, N. N. Aerodynamic investigation of winglets on wind turbine blades using CFD. Technical Report. RISO 2006.

[12] Anderson Jr, J. D. Fundamentals of aerodynamics. Tata McGraw-Hill Education 2010.

[13] Anderson, D., Tannehill, J. C., & Pletcher, R. H. Computational fluid mechanics and heat transfer. CRC Press 2016.

[14] Hansen, M. O. L. Aerodynamics of Wind Turbines, second edition Earthscan. London, UK 2008.

[15] Abbott, I. H., & Von Doenhoff, A. E. Theory of wing sections, including a summary of airfoil data. Courier Corporation 1959.

[16] Navin Kumar, B., & Parammasivam, K. M. Wind Turbine Aerodynamic Braking System Analysis Using Chord Wise Slot. In Applied Mechanics and Materials (Vol. 787, pp. 217-221). Trans Tech Publications 2015.

[17] Navinkumar B, Parammasivam KM, Rajendran S, Mohanavel V. CFD analysis of horizontal axis wind turbine braking system using chordwise spacing. Materials Today: Proceedings. 2020.

[18] Navinkumar B, Rajendran S, Vasudevan A, Balaji G. Aerodynamic braking system analysis of horizontal axis wind turbine using slotted airfoil. Materials Today: Proceedings

[19] Kumar, B., Navin, K. M., Paramasivam, M., Prasanna, and AZG Mohamet Karis. "Computational Fluid Dynamics Analysis of Aerodynamic Characteristics of NACA 4412 vs S809 Airfoil for Wind Turbine Applications." International Journal of Advanced Engineering Technology 7 (2016): 168-173.

[20] Navin Kumar B, Parammasivam KM. Wind Turbine Aerodynamic Braking System Analysis Using ChordwiseSpacing. In Applied Mechanics and Materials 2015 (Vol. 787, pp. 217-221). Trans Tech Publications Ltd.