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CFD-Based In-Depth Investigation of the Effects of the Shape and Layout of a Vortex Generator on the Aerodynamic Performance of a Multi-MW Wind Turbine

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Abstract: Thick airfoils are conventionally adopted in the blade root region of a wind turbine to ensure structural safety under extreme conditions, despite the resulting power loss. To prevent this loss, a passive flow control device known as a vortex generator (VG) is installed at the starting point of the stall to control the flow field near the wall of the suction surface. In this study, we used computational fluid dynamics (CFD) to investigate the aerodynamic characteristics induced as a result of the shape and layout of the VG on a multi-MW wind turbine blade. The separated and vortical flow behavior on the suction surface of the wind turbine blade equipped with VGs was captured by the Reynolds-averaged Navier–Stokes (RANS) steady-flow simulation. The parametric sensitivity study of the VG shape parameters such as the chord-wise length, height, and interval of the fair of VGs was conducted using thick DU airfoil on the blade inboard area. Based on these results, the response surface method (RSM) was used to investigate the influence of the design parameters of the VG. Based on the CFD results, the VG design parameters were selected by considering the lift coefficient and vorticity above the trailing edge. The maximum vorticity from the trailing edge of the selected VG and the lift coefficient were 55.7% and 0.42% higher, respectively, than the average. The selected VG design and layout were adopted for a multi-MW wind turbine and reduced stall occurrence in the blade root area, as predicted by the simulation results. The VG improved the aerodynamic performance of the multi-MW wind turbine by 2.8% at the rated wind speed.

Keywords: vortex generator; computational fluid dynamics; wind turbine blade; stall

1. Introduction

Interest in improving the performance of wind turbines by optimizing the methods used for blade design and flow control devices has grown in the last few decades. In particular, several research efforts have focused on refining these methods to increase the efficiency of wind turbines [1–5]. Wind turbine manufacturers have attempted to increase the blade length not only to improve the annual energy production (AEP), but also to lower the cost of energy [6]. Traditionally, the wind industry has performed aerodynamic blade design and performance analysis based on Blade Element Momentum Theory (BEMT). Aerodynamic blade design methods for wind turbines were reviewed previously [7–10]. The design method based on BEMT applies various types of loss-correction models [11–13] to the tip and hub of the blade, where the three-dimensional flow field is dominant. However, the problem of aerodynamic reliability with high accuracy persists in the various loss-correction models based on BEMT, owing to the enlargement of the blade length and the taper of the blade tip. To overcome the reliability problem, a 3D steady-flow simulation using CFD was performed after preliminarily performing a blade design based on BEMT.

The aerodynamic performance and load of the blade, and the complex 3D viscous flow field around the blade tip and hub were evaluated using the previous simulation results [14,15].

In this study, the use of a vortex generator (VG) as a passive performance-enhancing device for a large wind turbine was studied. A VG is a passive flow control device in the form of a small vane and is mainly used to delay the stall occurrence of an airplane blade [16–18] or even to improve the heat transfer performance by forming longitudinal vortices [19]. In the wind energy industry, the VG has been studied to improve the aerodynamic performance of wind turbines installed on flat terrain, as well as to extend their lifespan through the wind–kinetic energy conversion of wind turbines installed on complex terrain [20]. The effectiveness of the VG has been proven through academia–industry joint research, and it has been installed and operated in thousands of wind turbines since 2013 [21]. VGs are installed toward the root and suction surface of the blade of a wind turbine to mitigate airflow separation. Many CFD analyses and wind tunnel tests have been carried out to assess the feasibility of VG adoption with wind turbine blades. However, few CFD studies focused on full-scale wind turbines equipped with Gurney flap VGs other than airfoil base simulation and wind tunnel testing or CFD using virtual porous models [22–27]. There was a CFD analysis study of the VG-mounted wind turbine blade by RANS, SST k- ω equation, but the blade length was as short as 35 m, and a cuboid VG was investigated for the convenience of lattice formation [28]. Although there have been studies that calculate power increase via BEM using the lift and drag coefficient, calculations using BEM are less accurate than RANS CFD analysis results [29]. The aerodynamic characteristics of multi-MW horizontal-axis wind turbine blades have been analyzed using the commercial CFD software ANSYS CFX [30]. The results of the CFD analysis were validated with GH-Bladed design data [31]. These researchers optimized the shape and layout of the VG to maximize the performance of the wind turbine in terms of power generation.

2. Materials and Methods

Considering the aerodynamics and structural aspects of the blade, the airfoils shown in Figure 1 are extended in the span direction as shown in Figure 2. Figure 3 schematically shows the main parameters and layout of the VG. The distance between the VG pairs (λ) and the angle of attack (α) of the VG were specified as 6° and 11° for efficiency. The recommended λ/h investigated through a flat-plane CFD analysis study is 5 [32]. The VGs are installed on the suction surface and at the root of the blade to enhance the aerodynamic performance. Table 1 presents the wind turbine specification and Table 2 the shape parameters of the VG normalized by the chord length.

Figure 1. Airfoil series.

Figure 2. Three-dimensional form of the blade of the wind turbine.

Figure 3. Schematic diagram of VG and the design variables.

Table 1. Wind turbine specification.

Category	Value
Simulation region	Volume
Number of blades	3
Rotor diameter	113 m
Rotational speed	variable
Rated wind speed	10 m/s
Rated wind power	2.3 MW
Rotational direction	clockwise (viewed from upwind)
Blade profile	DU airfoils
Target wind class	Class II

Table 2. VG specification normalized by the chord length.

Category	Value
Number of VGs per blade	45
Mounting position	10~30% of blade length from blade root, 20% of chord length from leading edge
Layout	1.5%
Length	1.5%
Height	1%
Angle to the direction of the chord	11°

2.1. Numerical Analysis Methodology

Three major numerical analysis techniques, namely, direct numerical simulation (DNS) [33], large eddy simulation (LES) [34], and RANS simulation, can be used to analyze turbulent flow fields. To analyze the general vortex behavior precisely in a turbulent flow field containing vortices of various scales, the calculation grid size must be smaller than the minimum space scale of the vortex structure and the time interval should be less than the minimum time scale of the vortex variation. LES uses the spatially averaged Navier–Stokes equations, which directly calculate vortices greater than the grid scale and indirectly refer to the subgrid-scale model for vortices smaller than the grid scale. DNS and LES require extensive resources for their calculations, making them unfeasible in practical engineering applications. In comparison, RANS uses the time-based ensemble-averaged Navier–Stokes equations and models all of the effects caused by turbulence. Although RANS yields a lower resolution analysis than DNS or LES, it is widely used in engineering applications because it does not require high-resolution calculation grids. RANS uses the following equations:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho U_j) = 0, \quad (1)$$

$$\frac{\partial(\rho U_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho U_i U_j) = -\frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j}(\tau_{ij} - \rho \overline{u_i u_j}) + S_M \quad (2)$$

Turbulence models that are widely used for RANS numerical analysis in engineering include k - ε , k - ω , and SST. The k - ε turbulence model [35] precisely analyzes the turbulence behavior in free-stream regions with small pressure gradients; however, it inaccurately estimates the boundary layer separation in viscous sub-layer regions. Although the k - ω turbulence model, which was developed by Wilcox [36], accurately analyzes the separation caused by adverse pressure gradients, it is sensitive to the free-stream region. Menter [37] combined the advantages of the k - ε and k - ω models and proposed the SST turbulence model. Simulation of the wind turbine flow generally involves the use of CFD to analyze the performance of the cross-sectional airfoil of the blade, and the numerical analysis and experimental results are often in agreement [38,39]. The complete formulation of the SST model is given by:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho U_i k)}{\partial x_i} = \tilde{P}_k - \beta^* \rho k \omega + \frac{\partial}{\partial x_i} \left[(\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_i} \right] \quad (3)$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho U_i \omega)}{\partial x_i} = \alpha \rho S^2 - \beta \rho \omega^2 + \frac{\partial}{\partial x_i} \left[(\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_i} \right] + 2(1 - F_1) \rho \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i} \quad (4)$$

The blending function F_1 is defined by:

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

where $CD_{k\omega} = \max \left(2\rho \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i}, 10^{-10} \right)$ and y is the distance to the nearest wall. The turbulent eddy viscosity is defined as follows:

$$\nu_t = \frac{\alpha_1 k}{\max(\alpha_1 \omega, SF_2)} \quad (6)$$

The second blending function F_2 is defined by:

$$F_2 = \tanh \left[\left[\max \left(\frac{2\sqrt{k}}{\beta^* \omega y}, \frac{500\nu}{y^2 \omega} \right) \right]^2 \right] \quad (7)$$

A production limiter is used in the SST model to prevent the build-up of turbulence in stagnation regions:

$$P_k = \mu_t \frac{\partial U_i}{\partial x_j} \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \rightarrow \tilde{P}_k = \min(P_k, 10 \cdot \beta^* \rho k \omega) \quad (8)$$

2.2. Implementation of Vortex Generators on a Wind Turbine Blade

To accurately calculate ω (specific dissipation) in the viscous sub-layer region using RANS simulation with the SST turbulence model, the minimum grid size must satisfy $y^+ < 1$ in the viscous sub-layer simulation [40]. Figure 4 shows the blade calculation area. In the calculation domain, a spatial resolution of 7 times the rotor radius in the inflow direction, 10 times the wake direction, and 10 times the radial direction was configured. A no-slip condition was applied to the blade surface equipped with the VG, and a freestream condition was applied to the inlet. The flow field of the wind turbine blade was simulated by applying a 120° periodic boundary condition in the direction of rotation. The interface between the rotating and fixed parts was analyzed by applying the frozen interface condition.

Figure 4. Grid for the simulation of a VG mounted blade.

3. Results and Discussion

3.1. Validation of CFD Model

The results of the CFD analysis of the wind turbine blade without a VG were compared with experimental BEMT data. The BEMT-based analysis was carried out using GH Bladed, which is commercial code used for wind turbine design. Figures 4 and 5 shows the computational grid system of the blades in the simulation, and Table 3 provides the number of elements in the computational grid system used for the simulation. Figure 6 and Table 4 present the results of the CFD analysis of the blade and the GH Bladed design values. These results are confirmed to be consistent within a margin of error of 0.24% at a wind speed of 7.5 m/s and 2.36% at a rated speed of 10 m/s.

Figure 5. Surface mesh of plain blade.

Table 3. Number of elements of blade for numerical analysis.

Simulation Area	Volume (-)	Number of Elements (EA)
Blade	Rotationary	4,060,800
	Stationary	576,000
	Total	4,636,800

Figure 6. Comparison of the results of the angular velocity and axis output computed using GH Bladed design data and CFD. (a) Angular velocity. (b) Shaft power.

Table 4. BEMT design data and CFD results.

Case	Wind Speed (m/s)	Angular Velocity (rad/s)	GH-Bladed Power (kW)	CFD Power (kW)	Note
1	7.5	1.41372	1232.18	1235.7	0.24%
2	10.0	1.41372	2491.71	2432.4	2.36%

3.2. Flow Behavior on the Wind Turbine Blade

The simulation was performed by specifying many grids in the wake direction of the blade tip to accurately simulate the tip vortex, and these results are shown in Figure 7. Vortex core 1 is generated in the boundary layer of the suction surface, and vortex core 2 is combined with vortex core 1 in the boundary layer of the pressure surface. Vortex core 3 is a boundary layer generated at the blade trailing edge and is swept into the tip

vortex structure. As shown in Figure 8, large-scale flow separation occurred at a distance of approximately 20% of the chord length from the leading edge. The airflow characteristics on the suction surface of the blade were affected by the thickness ratio of the airfoil and the angle of attack depending on the wind speed. The flow-separated low-energy air was confirmed to flow secondarily in the tip direction along the suction surface owing to forces such as the centrifugal force, Coriolis force, and pressure difference in the radial direction of the rotor.

Figure 7. Vortex flow structure near the tip.

Figure 8. Separated flow structure near the root.

3.3. Aerodynamic Characteristics of DU Airfoil with VG

Based on the results of the CFD analysis, the cross-sectional DU airfoil in the region where flow separation occurs predominantly was selected as the test airfoil for VG application analysis. Figure 9 shows the surface grid of the VG-equipped airfoil used for simulation, and Table 5 contains the number of grids that were used.

The chordwise velocity contours of the airfoil with and without the VG are shown in Figure 10a,b. The results of the CFD analysis confirm that, in the case of the airfoil without the VG, the fluid did not accelerate along the suction surface and flow separation occurred; however, in the case of the airfoil with the VG, the fluid accelerated along the suction surface and flow separation did not occur. When flow separation occurs on the suction side, a low-pressure region is formed in the wake, which lowers the lift coefficient and increases the drag coefficient. As shown in Figure 11a,b, when the VG is attached, the airfoil experienced a high lift force at an angle of attack of 5.9° or higher and a low drag force at an angle of attack of 14.8° or higher.

Figure 9. Surface mesh of VG-mounted airfoil extruded in the span direction.

Table 5. Number of elements for the numerical analysis of the VG-mounted airfoil.

Simulation Area	Volume (-)	Number of Elements (EA)
VG airfoil	VG	1,932,483
	Region surrounding the VG	3,924,000
	Total	5,856,483

Figure 10. Cross-sectional velocity contour of the blade: (a) without VG; (b) with VG.

Figure 11. Lift and drag coefficient vs. angle of attack: (a) lift coefficient; (b) drag coefficient.

3.4. Investigation of the Influence of VG Design Parameters

The design variables and layout of the VG are shown in Figure 3, where the thickness t is fixed at 0.05 and the length of the upper section u is fixed at 0.2. A total of 27 CFD analyses were performed, and the variables used in each of these cases are listed in Table 6. In the analyses, the Reynolds number and angle of attack were set to 3.0×10^6 and 12° , respectively. The results of these case studies are presented in Table 7. Figures 12 and 13 show the vorticity contours for cases 1, 2, 3, 5, 8, 11, and 20 at locations 50% and 100% of the chord length from the leading edge, respectively. In Figure 13, the vorticity contour at the trailing edge can be compared when each parameter is changed based on case 2.

The response surface methodology (RSM) used a LOWESS (Locally Weighted Scatterplot Smoother) second equation to find combinations that could represent the best VG effect using the three independent design parameters, layout (L), length (l), and height (h), as shown in Figure 3 [41]. Four objective variables, C_L , C_D , and the maximum vorticity at the positions 50% and 100% from the leading edge to the trailing edge, were investigated. The correlation between the C_L values is shown for these cases in Figure 14 as 3D surface plots. In this figure, the value calculated for C_L tends to be higher as the length (L) is closer to the median value and the height (h) and layout (l) are lower. The correlation between the maximum vorticity values of the trailing edge is also shown in terms of the three parameters in Figure 15. Unlike C_L , the calculated value of the maximum vorticity of the trailing edge tends to be higher for l , lower for L , and that of h is closer to the median value. The VG design parameter selection criteria, more weight assigned to the maximum vorticity at the trailing edge, and the parameters were selected as shown in Figure 3 in consideration of manufacturability.

Table 6. Values of the analyzed VG design parameters.

Case	Layout (l)	Length (L)	Height (h)
01	1.5%	1.5%	0.75%
02	1.5%	1.5%	1%
03	1.5%	1.5%	1.25%
04	1.5%	1.75%	0.75%
05	1.5%	1.75%	1%
06	1.5%	1.75%	1.25%
07	1.5%	2%	0.75%
08	1.5%	2%	1%
09	1.5%	2%	1.25%
10	2%	1.5%	0.75%
11	2%	1.5%	1%
12	2%	1.5%	1.25%
13	2%	1.75%	0.75%
14	2%	1.75%	1%
15	2%	1.75%	1.25%
16	2%	2%	0.75%
17	2%	2%	1%
18	2%	2%	1.25%
19	2.5%	1.5%	0.75%
20	2.5%	1.5%	1%
21	2.5%	1.5%	1.25%
22	2.5%	1.75%	0.75%
23	2.5%	1.75%	1%
24	2.5%	1.75%	1.25%
25	2.5%	2%	0.75%
26	2.5%	2%	1%
27	2.5%	2%	1.25%

Table 7. Results of case studies to select the VG design variables.

Case	Cl	Cd	Maximum Vorticity at Position in the Direction of the Chord (1/s)			
			25%	50%	75%	100%
01	2.026	0.0285	10,363	3078	3033	1625
02	2.010	0.0302	10,289	3370	3054	1766
03	1.974	0.0627	13,641	3773	2535	1200
04	2.013	0.0293	13,554	3245	2472	1154
05	1.990	0.0327	16,308	3712	2374	975
06	1.978	0.0344	14,352	3912	2449	1128
07	2.014	0.0291	13,926	3205	2335	1128
08	1.996	0.0319	16,066	3698	2338	1101
09	1.978	0.0348	15,392	3675	2233	1112
10	2.113	0.0289	12,809	3092	2497	1205
11	2.001	0.0315	13,846	3471	2446	1061
12	1.991	0.0332	12,298	2876	1965	969
13	1.993	0.0306	13,626	2890	1859	830
14	2.004	0.0311	14,949	3463	2423	1141
15	1.854	0.0220	12,029	2490	1392	674
16	2.019	0.0287	14,391	3001	2391	1209
17	2.004	0.0314	16,751	3452	2255	1117
18	2.000	0.0309	16,487	3616	2237	1071
19	2.019	0.0285	13,107	2865	2409	1147
20	2.008	0.0309	14,943	3211	2177	1111
21	2.002	0.0322	12,821	2622	1704	955
22	2.021	0.0283	13,380	3134	2404	1235
23	2.010	0.0307	15,369	3498	2174	1196
24	1.996	0.0331	16,024	3433	2104	1097
25	2.020	0.0282	13,507	3228	2336	1266
26	2.009	0.0308	16,087	3596	2106	1195
27	2.002	0.0325	15,635	2373	1614	966

Figure 12. Cont.

Figure 12. Vorticity contours at the midpoint of the chord: (a) Case 1; (b) Case 2; (c) Case 3; (d) Case 5; (e) Case 8; (f) Case 11; (g) Case 20.

Figure 13. Cont.

Figure 13. Vorticity contours at the trailing edge: (a) Case 1; (b) Case 2; (c) Case 3; (d) Case 5; (e) Case 8; (f) Case 11; (g) Case 20.

Figure 14. Cont.

Figure 14. Surface plots of C_L showing the effect of three parameters on the lift coefficient: (a) $l = 1.5$; (b) $l = 2.0$; (c) $l = 2.5$; (d) $L = 1.5$; (e) $L = 1.75$; (f) $L = 2.0$; (g) $h = 0.75$; (h) $h = 1.0$; (i) $h = 1.25$.

Figure 15. Cont.

Figure 15. Surface plots showing the effect of three parameters on the maximum vorticity at the trailing edge: (a) $l = 1.5$; (b) $l = 2.0$; (c) $l = 2.5$; (d) $L = 1.5$; (e) $L = 1.75$; (f) $L = 2.0$; (g) $h = 0.75$; (h) $h = 1.0$; (i) $h = 1.25$.

3.5. Aerodynamic Characteristics of Wind Turbine Blade with VG

The CFD analysis of the viscous sub-layer was precisely performed by composing the entire grid with a hexahedron. Figure 16 shows the surface grid of the VG-mounted blade used for the simulation, and the number of grids is provided in Table 8. A pair of VGs each generates a vortex in the opposite direction and a high-energy fluid flows into the boundary layer region of the low-energy flow field. Figure 17 shows the characteristics of the fluid flow and the CFD results of the structural analysis of the vortex created by the VG. The analysis confirmed that a tip vortex was generated at the tip of the VG and a horseshoe-shaped vortex formed at the lower front of the VG. Figure 18a,b shows that the flow separation is relatively reduced on the suction side compared to the baseline blade. Figure 19a,b shows that the VG forms a vortex and pushes the separation fluid to a distance of 8 m from the root, where flow separation is dominant. The shaft power

was calculated by multiplying the torque and angular velocity of the simulation results. The calculated shaft power without and with the VG-mounted blade was 2365 kW and 2433 kW, respectively, confirming a 2.80% increase in the shaft power compared with the result before installation.

Figure 16. Surface mesh of VG-mounted blade.

Table 8. Number of elements of VG-mounted blade for numerical analysis.

Simulation Region	Volume	No. of Elements
VG Blade	VG	4,397,440
	Rotatory	49,693,662
	Stationary	1,584,000
	Total	55,675,102

Figure 17. Flow characteristics near VG and vortex formed by VG.

Figure 18. Surface streamline of wind turbine blade (a) without and (b) with the VGs.

Figure 19. Separation line and surface streamline of blade (a) without VG and (b) with VGs.

4. Conclusions

In this study, a CFD-based in-depth investigation was conducted to determine the effects of the shape of the VG and the layout of VGs on the power performance of a wind turbine. The RSM was used to investigate the influence of VG design variables, and complex simulations using more than 55 million elements were carried out. Based on the in-depth investigation, the following conclusions were drawn.

1. A CFD analysis of multi-MW wind turbine blades was performed, and subsequently validated by comparing the results with those obtained with the GH Bladed design values.

2. The influence of the VG design parameters was investigated using CFD analysis, which confirmed that the VG reduced the occurrence of separation flow, increased the lift, and reduced the drag at high angles of attack.
3. Analysis of the flow characteristics of the blade with the mounted VGs confirmed that the tip vortex generated by the VG reduced the separation area by allowing the high-energy fluid to flow to the low-energy separation area.
4. The VGs were confirmed to play an important role by improving the aerodynamics of multi-MW wind turbines by 2.80% at the rated wind speed. This was confirmed by the simulation at the rated wind speed with more than 55 million elements.
5. The results of this study are expected to be useful for selecting the mounting position and shape of the VG by conducting a full-scale simulation by automating the construction of the simulation environment.

The selected VG discussed in this study is currently installed in a 2.3 MW wind turbine and is being monitored using SCADA systems. The VG could also be installed on other large wind turbines by using the proposed method for constructing a computational environment.

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