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Behaviour of Wind Turbine Farms under Downbursts

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SUMMARY

Wind farms are commonly installed in rural locations to allow the serving of other civil usages in urban areas. Rural areas are vulnerable to thunderstorms and strong wind events, which are anticipated to become more frequent and severe due to climate change. Downbursts are High Intensity Wind (HIW) events linked with thunderstorms that occur frequently in a rapid and localized manner. In this study, a previously developed numerical model to investigate the behaviour of a single wind turbine under downbursts is extended such that a group of wind turbines can be studied under such events. The developed numerical model, HIW-FARM, incorporates the downburst wind field generated using previously conducted Computational Fluid Dynamics (CFD) simulations integrated with an array of wind turbine structural models. HIW-FARM takes into account downburst characteristics and considers different wind farm layouts and different pitch angles of the blades. A parametric study is carried out on different wind farm layouts to predict the peak moments at the tower base with various pitch angles. Downburst critical configurations which lead to the maximum straining actions on the towers are determined for each blade pitch angle. An optimum pitch angle for the blades is suggested in order minimize the downburst effect on a maximum number of wind turbine towers.

Keywords: Wind turbine farm, Downburst, Numerical model (HIW-FARM).

1. INTRODUCTION

Wind turbines are built at the same location in a group called a wind farm to take full advantage of local wind resources for producing clean and sustainable power (Hansen, 2015). Because land suitable for wind turbine installation competes with other uses for the land that may be more valuable than electricity generation, wind turbine farms are frequently located in rural areas far from cities to maximize land utilisation. Meanwhile, these areas may be vulnerable to thunderstorms and extreme wind events, which are expected to become more frequent and severe as a result of climate change (GFDL, 2021). Downbursts are one of these extreme events associated with thunderstorms that occur frequently in a sudden and localised manner. During a thunderstorm, a downburst is defined as a jet of fast-moving air that descends suddenly to the ground and spreads out in all directions, forming vortices (Fujita, 1985). Many wind turbine tower failures have recently been reported during thunderstorms and extreme wind events (Ma et al., 2019). Meanwhile, wind loads incorporated in codes of practice, standards, and design recommendations for wind turbines (GL, 2010; GL Wind, 2005; IEC 61400-1, 2005) are based on large-scale wind events such as hurricanes and typhoons without taking into account high-intensity winds such as downbursts. Only a few studies have been undertaken to investigate the downburst wind effect on a number of wind turbines in a wind farm. Nguyen and Manuel (2013) and Lu et al. (2021) assessed downburst loads on a group of wind turbines. A deterministic-stochastic hybrid model was used to investigate only one wind farm layout of 5-MW wind turbine models using the open-source code, FAST (2016). They concluded that downbursts have critical impacts on multiple wind turbines simultaneously in a wind farm. As a result, the current research seeks to evaluate the behaviour of a group of wind turbines in a wind farm during simulated downburst wind events and aims to achieve the following: 1) obtain the critical downburst configurations that result in the maximum number of unsafe wind turbine towers in a wind farm in comparison to the loads calculated using the wind turbine design code (IEC 61400-1, 2005), and 2) suggest the optimum blade pitch angle (β) and the optimum wind farm layout that minimize the downburst effect on the tower for a maximum number of wind turbines in a wind farm.

2. METHODOLOGY

The numerical model, HIW-TUR, developed and validated by Ahmed et al. (2022), is expanded in the current study to create the numerical model, HIW-FARM, in order to examine a group of wind turbines subjected to the downburst wind effect. HIW-FARM incorporates the same downburst wind field used in HIW-TUR integrated with an array of wind turbine structural models. The presence of a group of wind turbines can affect the generated downburst wind field. As such, CFD simulations based on the Reynolds Averaged Navier–Stokes (RANS) and Large Eddy Simulation (LES) methods are conducted in this study in order to investigate the effect of a group of wind turbines on the generated downburst wind field. The developed numerical model is capable of predicting the effect of downbursts on a group of wind turbines in a wind farm taken into account the uncertainty of the downburst size and location, as well as the variability in the blade pitch angle and the wind farm layout.

2.1 Downburst Wind Field

The downburst wind field incorporated into HIW-FARM is based on the CFD simulations developed and validated by Kim and Hangan (2007). These CFD simulations were conducted on a small-scale impinging jet model based on the RANS method. These CFD simulations led to the development of space and time variations for both the radial component (V_{RD}) and vertical component (V_{VL}) of the downburst wind field. Based on the downburst jet diameter (D_j) and jet velocity (V_j), the velocity fields of these two components fluctuate in time and space.

2.2 Wind Farm Model

The arrangement of wind turbines in a wind farm can have a total number, N_T, that is divided into an array of N_X x N_Y, where N_X and N_Y are the numbers of wind turbines in one row in the X and Y directions, respectively. The X-axis and Y-axis represent the dominant wind direction and the crosswind direction, respectively. In a wind farm, depending on a variety of factors, wind turbines may be arranged in a regular or irregular (staggered) array. Figure 1 depicts a schematic design of a wind farm layout together with a generic downburst configuration. The wind turbine units are identified by index numbers and separated by distances denoted as S_X, S_Y, and S, where S_X and S_Y are the distances measured along and across the ambient wind direction, respectively, between the wind turbine units, and S is the distance measured along the wind direction between the wind turbine units positioned in two successive rows.

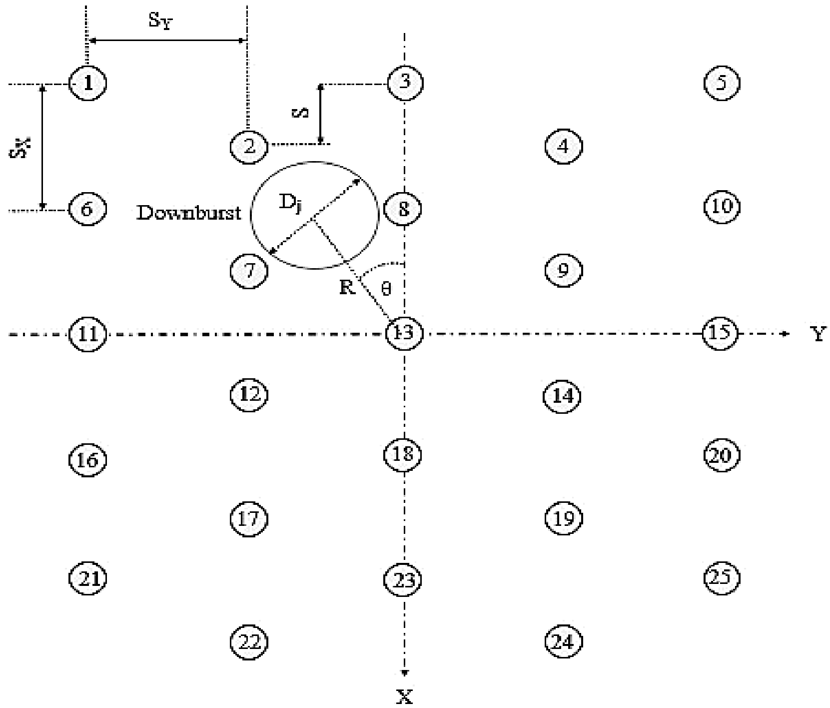

Figure 1. A schematic diagram for turbine units in a wind farm with a downburst configuration

3. STUDIED CASES AND RESULTS

S70/1500 HAWT including a tower and three blades, which was studied by Ahmed et al. (2022), is under consideration in this study. This study investigates a wind farm with a maximum area of 2 km x 2 km containing 25 wind turbines in a 5 × 5 array. As illustrated in Figure 1, the wind turbines are symmetrically positioned in reference to the X-axis. To evaluate the downburst effect on various wind turbine sites in a wind farm, four combinations of S_X, S_Y, and S values are investigated, resulting in four wind farm layouts represented by Layouts 1, 2, 3, and 4. The wind turbines are installed in a regular array in Layouts 1 and 2, and in a staggard array in Layouts 3 and 4. Layouts 1 and 3 have more space between the wind turbine units than Layouts 2 and 4. A parametric study is performed for each wind farm layout by varying the downburst parameters to cover all conceivable downburst occurrences that might impact the farm. The downburst jet diameter (D_j) is chosen to range from 500 m to 2000 m with a 500 m increment in order to cover the entire wind farm area. Also, the ratio R/D_j is assumed to vary from 0 to 2 with an increment of 0.1. The angle (θ) varies between 0° and 360° with an increment of 15°. The parametric study is carried out assuming a fixed value of a peak radial velocity, V_{RDmax}, of 70 m/s, which matches the maximum gust wind speed for synoptic wind at the hub height for Class I turbines according to the IEC 61400-1 (2005).

Figure 2 shows the variation of number of unsafe towers in different wind farm layouts with the change of blade pitch angle (β). The number of unsafe towers is minimized when setting the pitch angle (β) = 90° for all wind farm layouts. Layouts 1 and 3 result in fewer unsafe towers than layouts 2 and 4.

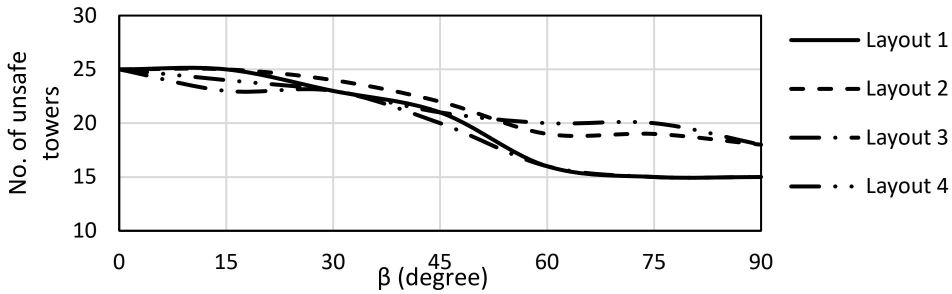

Figure 2. Variation of number of unsafe towers in different wind farm layouts with the blade pitch angle (β)

4. CONCLUSIONS

It is concluded that adjusting the blade pitch angle (β) = 90º reduces the number of unsafe wind towers in a wind farm if subjected to downburst wind events. It is also found that the number of unsafe wind towers decreases when the distance between wind turbines increases, regardless of how the blade pitch angle and wind turbine pattern in the wind farm are adjusted. As such, it is recommended that the wind farm can be planned with the maximum practicable spacing between the wind turbines, which is approximately 10 times the wind turbine rotor diameter, in a staggered manner to optimize land utilization and reduce the probability of wind turbine tower failures during downburst wind events.

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