Effects of lateral turbine spacing and inflow turbulence on the power generation of large wind farms: An LES study

Yu-Ting Wu*, Chang-Yu Lin

[1]Department of Engineering Science, National Cheng Kung University, Tainan, Taiwan
* Correspondence: bulawu@gmail.com

SUMMARY:
In this study, we use large eddy simulation (LES) technique to examine the effects of lateral turbine spacing and inflow turbulence on the power generation of large wind farms operating in a neutrally-stratified atmospheric boundary layer flow. An in-house LES code is used to simulate a wind farm 24,000 meters long (the streamwise direction) and 1,272 meters high (the vertical direction). The spanwise spacing between turbines varies and are 320 meters, 480 meters, and 640 meters, which corresponding to 4, 6, and 8 rotor diameters. Later, it results in the width of the simulation domain of 1,280 meters, 1,920 meters, and 2,560 meters, respectively. The entire simulation domain of the wind farms are all evenly divided into 1,200×160×160 vertically-staggered grid points with uniform spacing in the streamwise, spanwise, and vertical direction. Three wind farm layouts, three lateral turbine spacings, and four inflow turbulence levels are considered. Overall, the power generation of a large wind farm is dominated by inflow turbulence more than the wind farm layout and the lateral turbine spacing.

Keywords: large eddy simulation, lateral turbine spacing, wind farm

1. INTRODUCTION

This study focuses on the effects of lateral turbine spacing and inflow turbulence on the power generation of large wind farms operating in a neutrally-stratified atmospheric boundary layer flow. A large-eddy simulation (LES) framework is used to solve the filtered conservation of mass and the filtered incompressible Navier-Stokes equation. This LES framework uses a Lagrangian scale-dependent dynamic model for the subgrid-scale (SGS) (Stoll and Porte-Agel, 2006) stress, with an actuator-disk model with rotation (ADM-R) to explore the power output and wake characteristics in different cases.

This study considers to simulate a wind farm 24,000 meters long (the streamwise direction) and 1,272 meters high (the vertical direction). The spanwise spacing between turbines varies and are 320 meters, 480 meters, and 640 meters, which corresponding to 4, 6, and 8 rotor diameters. Later, it results in the width of the simulation domain of 1,280 meters, 1,920 meters, and 2,560 meters, respectively. The entire simulation domain of the wind farms are all evenly divided into 1,200×160×160 vertically-staggered grid points with uniform spacing in the streamwise, spanwise, and vertical direction. Regardless of the layouts of turbines, the simulated wind farm has 4 rows and 30 columns for a total of 120 turbines, and the streamwise spacing between turbines is 560 meters. The Vestas V80-2MW is chosen as a modelled wind turbine, which has a hub height of 100 meters and a rotor diameter of d=80 meters.

To investigate the power performance of wind turbines under different conditions, this study changes the three parameter values to perform the cross simulations. In addition to the spanwise spacing between turbines mentioned above, the other two parameters are the siting configurations of turbines and the turbulence intensity of the incoming flow. Simulating the different turbine layouts in a wind farm, such as the aligned, laterally-staggered, and vertically-staggered configurations, can reveal how much a turbine affects the power output of adjacent fans. Schematics of the wind farms with three different types of turbine configuration, as shown in Figure 1. Figure 1a and Figure 1c show a top view and a side view of the aligned configuration, Figure 1b and Figure 1c are two views of the laterally-staggered configuration, and Figure 1a and Figure 1d are two views of the vertically-staggered configuration. It can be seen in figures that the laterally-staggered configuration means the arrangement of turbines is staggered in the horizontally plane, and the vertically-staggered configuration is in the vertical plane.

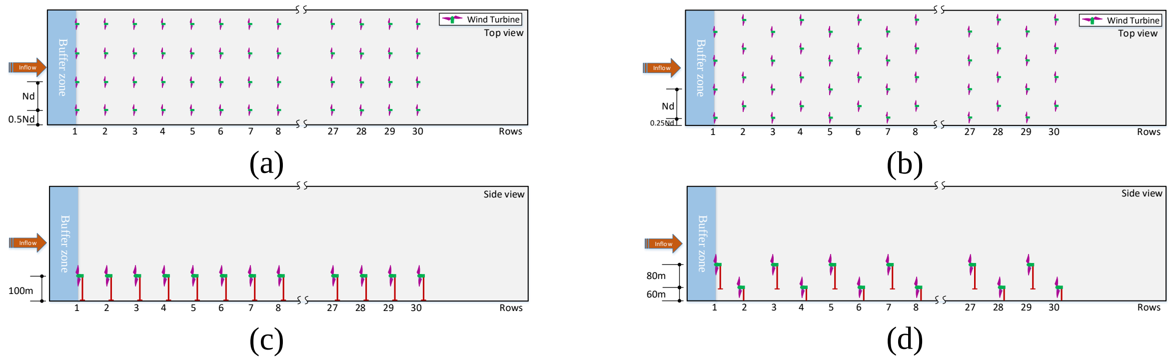

Figure 1 Schematics of the wind farms with three different types of turbine-array configurations: (a) aligned and vertically-staggered configuration (top view), (b) laterally-staggered configuration (top view), (c) aligned and laterally-staggered configuration (side view), (d) vertically-staggered configuration (side view).

The turbines are placed on horizontally flat surfaces with different aerodynamic roughness lengths z_0=0.5,0.1,0.01,0.001m, and according to the V80-2MW operation report (Hansen et al.), the incoming flow at the hub height is set 9m s^{-1}. Using precursor simulations of the turbulent boundary layer flows without wind turbines, turbulence intensities of incoming flows can be obtained as 11% (ABL11), 9% (ABL09), 7% (ABL07), and 5% (ABL05) relative to roughness length from large to small.

In this study, the pseudo-spectral numerical scheme of the spatial derivatives has been used in the horizontal directions and finite differences in the vertical direction. Time advancement is done using a second order accurate Adams-Bashforth scheme. The top boundary condition is a flux-free condition, and the bottom boundary condition consists of the similarity theory (Monin-Obukhov similarity) to calculate the filtered surface shear stress as a function of the velocity at the lowest vertical grid point. The lateral boundary conditions are set as periodicity, but this setting may reverse the wake of the last few columns of turbines to the first few columns of turbines, which affect the correctness of the simulation results. To avoid it, a buffer zone upstream of the wind turbine is employed to adjust the flow from the very-far-wake downwind condition to that of an undisturbed boundary-layer inflow condition, as shown in Figure 1. In this study, all numerical simulations were run for a period of time sufficient to ensure quasi-steady flow conditions and statistical convergence of the results shown in the next section.

2. PRELIMINARY RESULTS

To symmetric describe the simulated turbine power production results, a normalized power is defined as the power output of each turbine divided by the average of the first turbine row in the aligned wind farm with the ABL11 incoming flow condition. This mean power output of the first turbine row coincides with the manufacturer-provided power output data at the wind speed of 9 m s^{-1} (Wu and Porte-Agel, 2015).

Figure 2 shows the mean normalized power output distributions of the thirty-six wind farm scenarios. This power is the average of normalized values calculated from the turbines of 1-10, 11-20, 21-30, and 1-30 rows to find out the performance of power production in the upstream, midstream, and downstream farm areas.

The results show that for the same turbine siting density (i.e., the equal spanwise turbine spacing), an increase in the turbulence intensity of the incoming flow, representing more energy in the flow, increasing the amount of power production in all of the arrangements. Under the same inflow conditions, increasing the spanwise turbine spacing also increases power because the incoming flows are less affected by the turbines of each other. If the spanwise turbine spacing is not large enough, such as 4d, the power output along the turbine row continues to decrease. In contrast, if the spacing is large enough, the power increase becomes smaller and smaller as the spacing increases. This phenomenon can be seen from this figure that when the turbulence intensity of the incoming stream is ABL11, and in the aligned and vertically interleaved turbine rows, the average normalized power output between 6d and 8d differs by less than 3%.

In Figure 2b, at the incoming flow ABL11 with the laterally-staggered configuration, the mean normalized powers of the even-row turbines are higher than the adjacent odd-row turbines, and as the spanwise turbine spacing increases, the differences are more pronounced, especially in 8d. In all cases of laterally-staggered configuration, powers gradually approach a constant value along the turbine row.

Powers have an ups-and-downs distribution of vertically-staggered configuration at the height of the turbine hub, as shown in Figure 2c. Since the logarithmic incoming velocity profile of the kinetic energy increases with height, the turbines with higher hub heights are more susceptible to significant inflow wind speeds and increase power productions. It is noted that in ABL07, ABL09, and ABL11 of this configuration, the mean normalized powers of the spanwise turbine spacing 6d and 8d are almost equal.

In all cases, the mean normalized power of the first ten-row $\bar{p}_{1-10}$ is higher than $\bar{p}_{11-20}$ or $\bar{p}_{21-30}$. The maximum difference is about 24.8% of the laterally-staggered configuration, and the minimum difference is about 4.3% of the aligned configuration. The $\bar{p}_{11-20}$ is not necessarily higher than $\bar{p}_{21-30}$, but the difference between the two is tiny, and the maximum difference does not exceed 4%. Therefore, the parameters such as the turbulence intensities of the incoming flow, the spanwise turbine spacings, and the turbine arrangements, have no significant effect on $\bar{p}_{11-20}$ and $\bar{p}_{21-30}$.

In each turbulence intensity of incoming flow with different turbine configuration, the maximum mean normalized power of $\bar{p}_{1-30}$ is 53.2% to 77.5% of the laterally-staggered configuration, and the minimum one is 51.8% to 64.2% of the vertically-staggered configuration. The value 77.5% is in the incoming flow of the laterally-staggered configuration ABL11, and the spanwise turbine spacing is 8d.

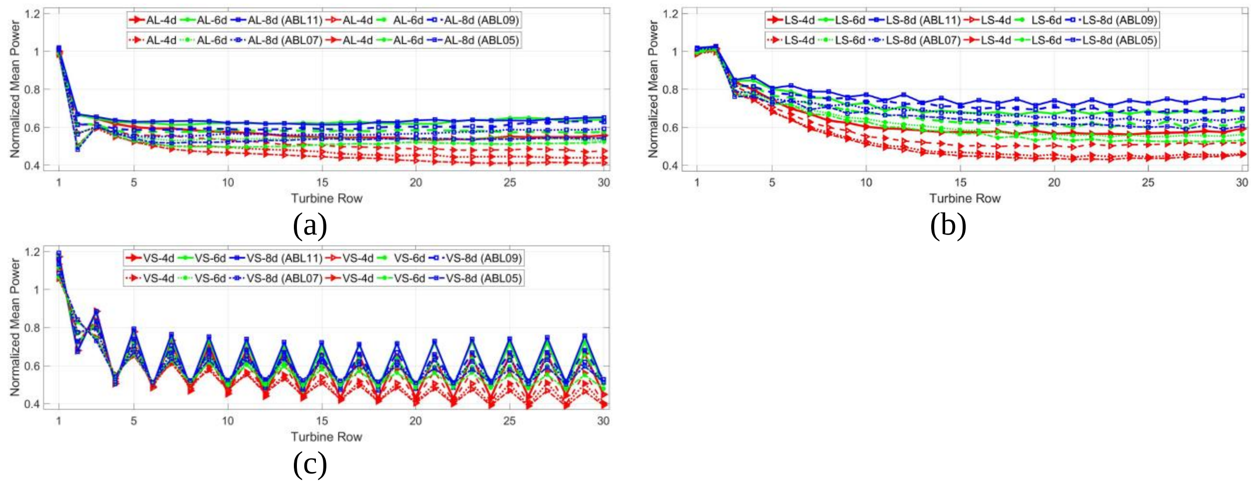

Figure 2 Distribution of the mean normalized power outputs in the wind farms. (a) aligned turbine rows, (b) laterally-staggered turbine rows, (c) vertically-staggered turbine rows