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A Simulation Study on the Annual Power Increase with Active Induction Wind Farm Control including Wind Direction Change

H Kim¹, K Kim¹, Y Song¹, I Paek¹

¹Department of Advanced Mechanical Engineering, Kangwon Nat'l Univ.
paek@kangwon.ac.kr

Abstract. Dynamic wind farm simulation tool developed from the previous study is used to study the annual power increase of the active induction wind farm control at an offshore site in Korea. The turbulent wind is generated from the veers model and the measured averaged wind data for 16 wind directions and used to estimate the power output of a virtual wind farm with 3 rows and 3 columns. A simple open loop wind farm control method was applied to find out the annual power increase considering the farm layout change according to the wind direction change. The power gains were found to be changed with different scale and shape parameters but the power increase was found to be very small.

1. Introduction

Wind farms, which consist of multiple wind turbines, are generally developed around commercial power generation systems such as WindPRO or WindSim, where the annual output is expected to be the highest[1, 2]. In recent years, many studies have been conducted in the wind farm such as improvement of output efficiency and load reduction in order to increase the economical efficiency of the wind farm constructed through the conventional method [3-9].

Wind farm wake control methods such as induction control is a technique to reduce the effect of the wake generated in the wind farm by appropriately controlling the operation of the upstream wind turbine. This technique is a familiar concept in which the power increase (or decrease) is confirmed through a lot of studies using simulations, wind tunnel tests, and full size model tests [3, 4]. However, most studies have been conducted on fixed wind farm layout in single row, but only very limited analysis has been conducted considering the layout change with respect to the wind direction change [3-9].

One of the oldest methods to reduce the overall wake effect in the wind farm is to control the pitch angle and the tip speed ratio of the upstream wind turbine [3, 9]. It is a method to slightly increase (or slightly decrease) the capacity factor and the maximum load of a wind farm. However, since the wake control strategy based on the induction control is based on the operating state of the wind turbine that changes according to the surrounding wind conditions, the loss is also caused by the wind turbine operating state [10]. Since such power losses act as a risk of generating economic losses in terms of the operator of the wind farm, it is a necessary task to determine whether or not to apply the wind turbine wake control method through analysis of the wind condition of the wind farm.

Therefore, this study presents the dynamic simulation of a virtual wind farm located offshore in Korea with an open loop active induction wind farm control by considering the wind farm layout change according to the wind direction change. Wind farm layout change mentioned in this study refers to wind turbine coordinate rotation considering wind direction change. For this, the turbulent wind generated for various wind speed bins based on the partly measured data was used with the
dynamic wind farm simulation tool developed previously to calculate the annual power with and without wind farm control for various Weibull parameters.

2. Wind farm construction

2.1. Meteorological analysis

In this study, the Weibull distribution function was used to calculate annual power production. The Shape and scale parameters of the Weibull distribution are derived from the wind data measured for one year. The met-mast for wind data measurement is located in the west sea of Korea and measures wind data at a height of 96 m from the sea surface. Wind data were stored as ten-minute averaged values. Figure 1 shows the location of the met mast, the wind rose, the Weibull distribution, and the turbulence intensity distribution. As can be seen from the figure, the wind at the measurement point occupies a high proportion of the relatively low wind speed, and the shape parameter and the scale parameter are 1.75 and 7.98, respectively. Also, as shown in Fig. 1(d), the annual average turbulence intensity at the measuring point is about 0.08 and like expected, the turbulence intensity tends to decrease as the wind speed increases.

Figure 1 Analysis of Wind Characteristics in Southwest Korea, (a) Meteorological mast installation point, (b) Wind rose with 16 direction (prevailing wind direction: Northern Northwest), (c) Weibull distribution \(k=1.75, c=7.98\), (d) Turbulence intensity distribution by wind speed

2.2. Wind Farm Layout

In this study, WindPRO, a commercial software widely used in wind turbine micrositing, was used to derive a reference wind farm arrangement. The reference wind farm is set to 3 by 3 of the parallel row method with the turbine spacing of 7 RD where RD represents the rotor diameter of the wind turbine. In the simulation, the layout changes for sixteen wind direction with an interval of 22.5°
3. Simulation Model

3.1. Wind Farm Modeling

Simulation of the wind farm was performed through an in-house simulation code based on the dynamics of the wind turbine to simulate the control effect of the wind farm. The in-house simulation code basically consists of C language and simulates the superposition of turbulent wind movements and wakes at the height of the wind turbine hub. The turbulent wind movement is based on Taylor's frozen turbulence theory and is constructed to propagate from the upstream to the downstream with the turbulent components retained. Also, the wake generated by the wind turbine is configured to simulate the wake change according to the operating state of the wind turbine using the Ainslie’s Eddy Viscosity Wake Model, which is one of the parabolic RANS models. Finally, the NREL 5 MW wind turbine was numerically modelled with the wind turbine controller for dynamic simulations and applied to the simulation code [11, 12].

The in-house simulation code of the wind farm simulation used in this study has a limitation that it is impossible to simulate the wind direction change in the time domain even though the wind turbine numerical model is applied. For the same reason, the wind direction change is implemented by rotating the wind farm layout instead. The wind farm layout was divided into 16 parts, such as the resolution of the wind rose. Annual energy production is calculated by dividing wind farm output for each wind direction by wind speed and summing them together.

3.2. Wind Farm Control

Wind farm control basically consists of a wind speed estimator, a wind farm model and an power output calculator. The wind speed estimator estimates the wind speed of the current wind turbine by measuring the current operation status of the wind turbine such as the blade pitch angle of the wind turbine, the rotor rotation speed, the output amount, and the generator rotation speed. The wind speed estimator basically estimates the rotor average wind speed using the following equation (1).

\[
T_a = \frac{1}{2} \rho \pi R^3 \left( \frac{C_p(\lambda, \beta)}{\lambda} \right) V^2
\]

Where T is torque, \( \rho \) is air density, R is rotor radius, \( C_p \) is output coefficient, \( \lambda \) is tip speed ratio, and V is rotor mean wind speed. The wind speed estimated from the state of the wind turbines is used to predict the output capability of the wind turbines constituting the wind farm. One of the features of the wind farm controller is that the controller itself has a separate wind farm model. However, since the wind farm controller basically uses the optimization algorithm to find the optimal power command that can increase the overall power of the wind farm, it only collects the steady state values according to the wind turbine power command and wind speed command. It consists of relatively simple forms of wind turbines. A virtual wind farm consisting of relatively simple wind turbines is configured to have the same layout as the wind farm to be controlled. In order to predict the wake effect between wind turbines, the same wake model as the in-house simulation code was applied [13].

Finally, the power output calculator aims to find the optimal power command that can increase the total output of the wind farm to be controlled. The power output calculator basically uses Nelder Mead Simplex, one of the function minimization algorithms, and finds the optimal power command that minimizes the following cost function.

\[
J = \left| TSO_{CMD} - \sum WFC_{gen,i} \right|
\]

TSO_CMD in Equation (2) uses the rated power of the wind turbine multiplied by the number of wind turbines constituting the wind farm to find the power command for increasing the total output of the wind farm. \( WFC_{gen,i} \) means the generated power of the i^th turbine of the virtual wind farm built internally by the wind farm controller to derive the optimal power command.
4. Simulation Result

4.1. Electrical Power

As the result of the simulation using the shape and scale parameters calculated from the measured wind, the annual power generation gain was 0.045%, which is lower than the previous results available in the literature considering only the ideal situation. This result can be regarded as an integrated result considering wind direction speed changes. Table 1 below shows the changes in annual power generation with changes with shape and scale parameters. As can be seen from the table, the annual power increase varied with the Weibull parameters but the variation was not much.

| k  | 1.22 (-30%) | 1.4 (-20%) | 1.58 (-10%) | 1.75 (Ref) | 1.93 (+10%) | 2.10 (+20%) | 2.27 (+30%) |
|----|-------------|-------------|-------------|------------|------------|------------|------------|
| c  | 7.98        | 7.98        | 7.98        | 7.98       | 7.98       | 7.98       | 7.98       |
| Pwr, Increase [%] | 0.037       | 0.039       | 0.042       | 0.045      | 0.047      | 0.048      | 0.049      |

Table 2. Variation of annual power production gain with change of scale parameter

| k  | 1.75  | 1.75  | 1.75  | 1.75  | 1.75  | 1.75  | 1.75  |
|----|-------|-------|-------|-------|-------|-------|-------|
| c  | 5.59  | 6.38  | 7.18  | 7.98  | 8.78  | 9.98  | 10.37 |
| Pwr, Increase [%] | 0.049  | 0.048  | 0.047  | 0.045  | 0.043  | 0.040  | 0.038  |

4.2. Tower Load

In order to check the effect of the wake control of the wind farm on the load variation of the tower, the load in the time domain was converted into DEL (damage equivalent load). The effect of the wake control was confirmed by comparing the load of the wind turbine located at the most upstream position in the wind farm, and DEL was calculated by the following equation (3).

\[ D_{eq} = \left( \frac{\sum n_k S_k^{m_k}}{N_{eq}} \right)^{\frac{1}{m}} \]  

In equation (3), \( S_k \) is the stress of tower load having \( k \)th magnitude out of the total tower load during simulation time, \( n_k \) is the number of cycle of \( S_k \) and \( N_{eq} \) is the equivalent of cycle of \( D_{eq} \).
Figure 2 below shows the tower load variation with wake control application. As can be seen from the figure, it can be seen that the wake control through power command control can obtain a considerable gain in terms of tower load. In particular, the load gain in the previous section of the rated wind speed is about 18%, which is much higher than the power output gain.

5. Conclusion
This study compares the changes in annual power production with a simple open-loop wind farm control for changes in shape and scale parameters using in-house simulation code. The virtual wind farm consists of nine NREL 5 MW wind turbines. Each wind turbine is equipped with the power demand tracking control algorithm in addition to basic torque and pitch control algorithms, so that it operates according to the output command from the wind farm controller. The distance between wind turbines is 7RD in lateral and the longitudinal directions, and the farm layout was rotated to simulate the change in the power generation due to the wind direction change. As the result of simulations, the output gain of 0.045% was found in terms of annual power generation when wind turbine wake control was applied, and it was confirmed that the value varied according to shape parameter and scale parameter. On the other hand, the wind farm wake control shows a much higher gain than the power output in terms of wind turbine tower load. In particular, the power command of the most upstream wind turbine was controlled to reduce the load by up to 20%.

This study is a basic study to establish an indicator to determine the feasibility of the wind farm control method by changing the shape parameter and the scale parameter. Therefore additional research is needed in the future.

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