Renewable Energy 54 (2013) 124–130

Contents lists available at SciVerse ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Blade pitch angle control for aerodynamic performance optimization of a wind farm

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ARTICLE INFO

Article history:
Received 6 February 2012
Accepted 13 August 2012
Available online 10 September 2012

Keywords:
Wind farm optimization
Power loss
Wind turbine wake
Pitch control
Blade element momentum theory
Eddy viscosity model

ABSTRACT

The power loss of a wind turbine due to wakes from upstream turbines is significant for a wind farm. This power loss is usually about 20% of wind turbine power, and this can increase to 40% for an extreme case. Such effects decrease the annual energy production of a wind farm. Thus, it is important to predict the effect of these types of wakes so as to maximize the power output of a wind farm. In this study, we investigate a method to control the pitch angle of turbines to maximize the aerodynamic power of a wind farm. The pitch angle of each wind turbine is controlled by its own pitch schedule or feedback algorithm to optimize the power output. However, these control methods cannot consider the effects of wakes, such as velocity defects and an increase of the turbulent intensity. Thus, controlling the pitch angle of the turbine does not guarantee the maximum aerodynamic power of the wind farm, which is why a comprehensive control method considering all of the wind turbines of a wind farm is needed. The blade element momentum theory (BEM) is used for the aerodynamic analysis. In addition, in order to evaluate the wind turbine wake, the eddy viscosity model (EVM) is used. The wake is assumed to be a two-dimensional Gaussian profile determined by the thrust coefficients of the fore-located turbines and the atmospheric conditions. A genetic algorithm (GA) was applied to calculate the optimal power. The results show that control of the pitch angle can maximize the power output of the wind farm.
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1. Introduction

A wind farm can utilize the wind resources of a certain area efficiently. Most large onshore wind farms over 500 MW in size are located in the United States or China. An offshore wind farm is a new trend in the wind energy industry. Sites located offshore are free from many environmental issues, such as noise and an adverse visual impact. Moreover, the energy of the wind is much more abundant offshore than it is in inland areas. Denmark and the United Kingdom have the most large offshore wind farms, each about 200–300 MW in size. Wind farms are under construction at present in many areas around the world. The total wind power capacity worldwide is rising rapidly, as well. It is expected to reach 1500 GW in 2020s [1].

On a wind farm, the outputs of the generators are reduced owing to wakes from upstream turbines. The power loss of a wind turbine due to wakes is an important issue in the design of a wind farm. It is essential to understand the wake phenomena and predict its effect on the downstream generators. After wind passes a generator, its speed decreases while the turbulence intensity increases. The wake velocity is recovered as the wind moves downstream, and its rate becomes higher as the turbulence intensity increases. 2-D wake models, the Park model [2], and the eddy viscosity model (EVM) [4] have been introduced to describe the wake velocity profile. Crespo suggested a 3-D wake model that was in better agreement with field data [5,9]. An empirical model was also developed to describe the added turbulence intensity of the wake [10]. Recently, models based on computational fluid dynamics (CFD) have also been used for the design of a wind park. As the part of the EU's Upwind Project, validation assessments of these models were conducted. The results of the models were also compared with data measured on an actual wind farm [6–8,11,12].

It is usually known that about 20% of the wind turbine power is lost, and this can increase to 40% when the wakes are ingested directly into a downstream turbine [6]. To improve the total power output of a wind farm, several studies on the optimized layout of

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http://dx.doi.org/10.1016/j.renene.2012.08.048

a wind farm have been conducted [13,14]. One of the goals of previous research was to position the turbines such that the wake effect is avoided as much as possible. However, for wind farms that are already operating, it is impossible to change the layout of the turbines. Layout optimization should be considered in the design stage, before installation. In the present work, the pitch angle of turbines is controlled to optimize the aerodynamic power output of a wind farm.

2. Numerical methods

2.1. Blade element momentum theory (BEM)

BEM is used to obtain the aerodynamic properties of a wind turbine. This model is commonly employed in the industry. It calculates the sectional aerodynamic performance of the rotor with a low computational cost compared to the vortex lattice method (VLM) or a CFD analysis. BEM is apt for this study, as repeated calculations are necessary in the design procedure.

The BEM code can consider a non-uniform inflow circumstance such as the wind shear, and tilt/yaw error conditions. The inflow to the rotor area, partly influenced by the wake from the upstream turbine, is commonly non-uniform. The main objective of the model is to find the axial induction factors of the blade segments accurately, which then allows a prediction of the aerodynamic performance of the rotor. The thrust coefficient, one of the properties from the BEM result, is the main factor determining the wake velocity characteristics. The induction factor of the rotor segment is defined as the ratio between the induced velocity in the normal direction of the airfoil, $v_{i,n}$ and the wind inflow velocity to the rotor plane, v_0 [3].

$$a = v_{i,n}/v_0 \tag{1}$$

The thrust coefficient is defined as the ratio of the thrust force on the rotor blade and the aerodynamic force of the free stream on the rotor area. It can be also described as a function of the axial induction factor, a. Tip loss factor, F, and Glauert's correction model, f_g, are also applied to improve the accuracy. The thrust coefficient is described as,

$$C_T = 4aF\left(1 - f_g a\right) \tag{2}$$

where the tip loss factor is,

$$F = 2/\pi \cos^{-1}\left(e^{-f}\right) \tag{3}$$

$$F = (B/2)((R - r)/(r \sin \varphi)) \tag{4}$$

The B is number of the blades and the R is the rotor blade length. The Glauert's correction factor is,

$$\begin{aligned} F_g &= 1 \quad (a \le a_c) \\ &= (a_c/a)(2 - (a_c/a)) \quad (a \ge a_c) \end{aligned} \tag{5}$$

a_c, the critical axial induction factor, is around 0.2 [3].

2.2. Eddy viscosity model (EVM)

EVM is an empirical model that can be used to determine the wind turbine wake velocity profile. The region in the range of 2–4 rotor diameters downstream is known as the near-wake region. This is the region just after the wind passes through the rotor. In the near-wake region, a rapid drop in the pressure and decrease in the velocity occur due to the energy extraction by the rotor. The velocity is recovered beyond this region due to the mixing process in the wake shear layer. The width of the shear layer increases as the wake moves downstream and reaches to the center of the annular layer section. Beyond this point, the far-wake region begins and the wake velocity profile can be modeled as a Gaussian function [4]. The velocity recovery rate mainly depends on the turbulence intensity of the wake; it increases as the turbulence intensity increases. It is assumed that the wake is fully turbulent and 2-D axisymmetric. The momentum deficit of the wind is determined by the thrust coefficient of the turbine. The govern equation describing the wake is as follows [8]:

$$U(\partial U/\partial x) + V(\partial U/\partial r) = -1/r(\partial(ru'v')/\partial x) \tag{6}$$

$$u'v' = \varepsilon(x)(\partial U/\partial r) \tag{7}$$

The $u'v'$ is the Reynolds stress and the ε is the eddy viscosity of the wake.

The initial condition of the wake velocity can be denoted as the Gaussian profile,

$$1 - U(r)/U_0 = D_M \exp\left(-3.56(r/b)^2\right) \tag{8}$$

The b is the wake width described as,

$$b = (3.56C_T/(8D_M(1 - 0.5D_M)))^{0.5} \tag{9}$$

The D_M is the deficit rate of the wake velocity, which is derived from the function of the wake turbulence intensity and the C_T of the rotor calculated by the BEM.

$$D_M = C_T - 0.05 - (16C_T - 0.5)\mathrm{TI}/1000 \tag{10}$$

The turbulence intensity of the wake added after the turbine is expressed as follows:

$$\mathrm{TI}_{add} = 5.7C_T^{0.7}\mathrm{TI}_{amb}^{0.68}(x/x_n)^{-0.96} \tag{11}$$

In this equation, x_n, the near-wake length, is usually about the length of two diameters. TI_{amb} denotes the turbulence intensity of the atmosphere. The wind velocity profile at the downstream distance can be calculated using equations (6) and (7) numerically with the parameters.

2.3. Genetic algorithm (GA)

The objective function of the optimization is the total aerodynamic power output of the wind farm. The atmospheric conditions, the operational conditions (e.g., the pitch angle and rotational speed of the rotor) of each turbine, and the wake characteristics are the variables of the objective function. It is difficult to find an analytical solution to this problem, as the parameters interact with each other in a complicated manner. In this case, a stochastic method should be utilized, such as a genetic algorithm, an evolutive strategy, or simulated annealing. These methods can lead to the realistic optimal points of the function. In this study, a genetic algorithm (GA) is used to find the optimal pitch angle of the turbines to enable the maximum aerodynamic power output of the wind farm. The GA is commonly employed to optimize complex objective functions in engineering fields in many applications [15]

3. Results

The validation of the BEM and EVM codes to predict the wind farm power output was conducted as the first step. Data used for

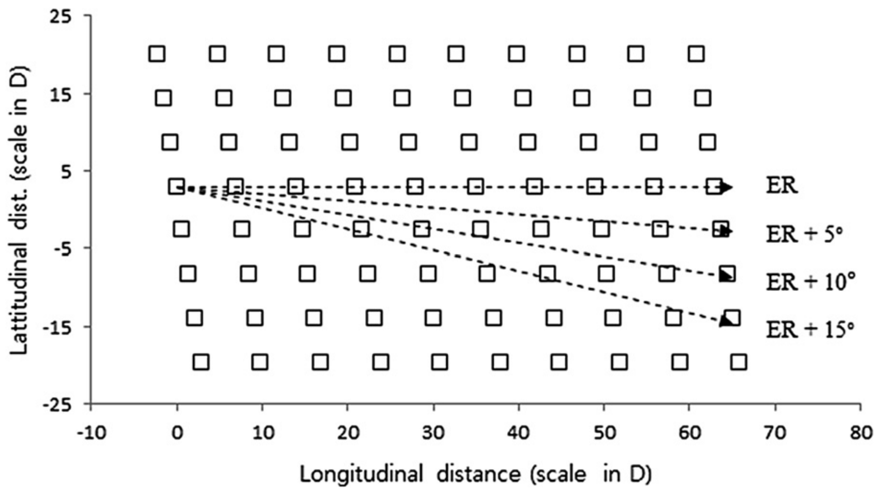

Fig. 1. Layout of the Horns Rev offshore wind farm.

the validation was measured at the Horns Rev and Nysted offshore wind farms located in Denmark. The power loss data of the generators at these wind farms was measured and analyzed as a part of EU's Upwind Project [6–8,11,12].

3.1. Horns Rev

The array of Horns Rev is comprised of eighty wind generators, ten turbines in each row and eight turbines in each column. The turbine spacing is a distance of seven diameters in both the row and column directions. Fig. 1 shows the layout of Horns Rev in the rotor diameter length scale. The calculation is conducted for four wind directions: ER, ER + 5°, ER + 10°, and ER + 15°. The result of the BEM/EVM code is compared with the measured data and result by GH WindFarmer, which is widely used to design wind farms [7]. The data are measured at an inflow velocity of 8 m/s. The turbulence intensity at the location is about 8% at the wind speed. The power of each turbine is normalized to that of the turbine facing the free stream.

Fig. 2 presents the numerical result of ER (top) and ER + 5° (bottom) case. In the ER case, most of the turbines are directly affected by the wake from their upstream turbines. The power loss of the turbines on the second column is significant up to 40%. The rate of power loss is maintained to the downstream turbines. The power loss pattern of the ER + 5° case is similar to that of the ER case. The wind turbines behind the first turbine in the row are affected by the wake inflowing almost directly, losing 30% of their power output, which is also significant. For these cases, the BEM/EVM code shows good agreement with the measurement data. Fig. 3 shows the numerical result of the ER + 10°(top) and the ER + 15°(bottom) cases. In both cases, the power loss due to the wake from the front generator is less than 10%. The wakes from the wind turbines on neighboring row have a considerable effect on the power reduction of the generator, with a power loss of 30%. The

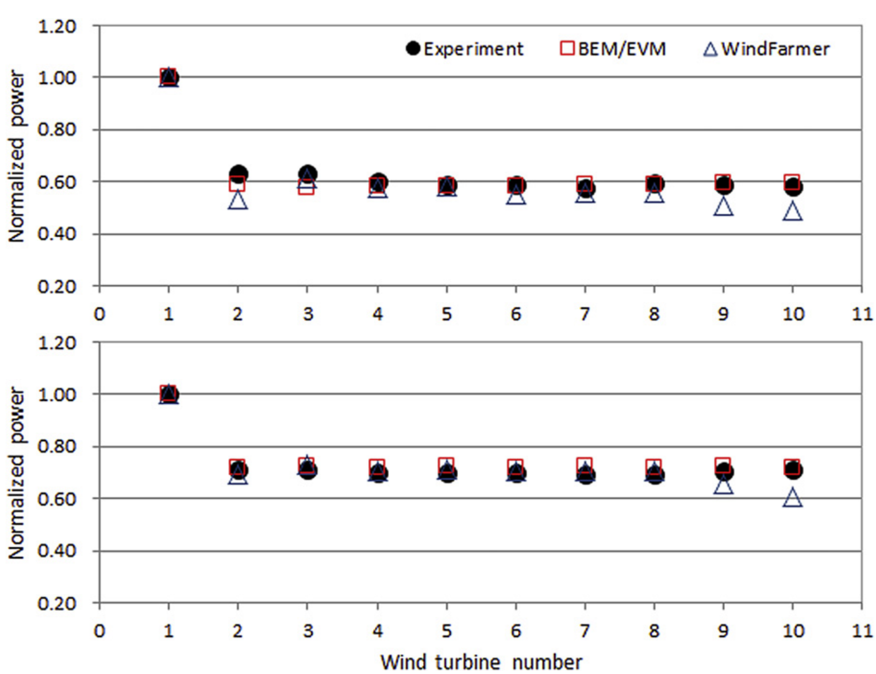

Fig. 2. Normalized power at Horns Rev offshore wind farm of the ER case (top) and ER + 5° case (bottom).

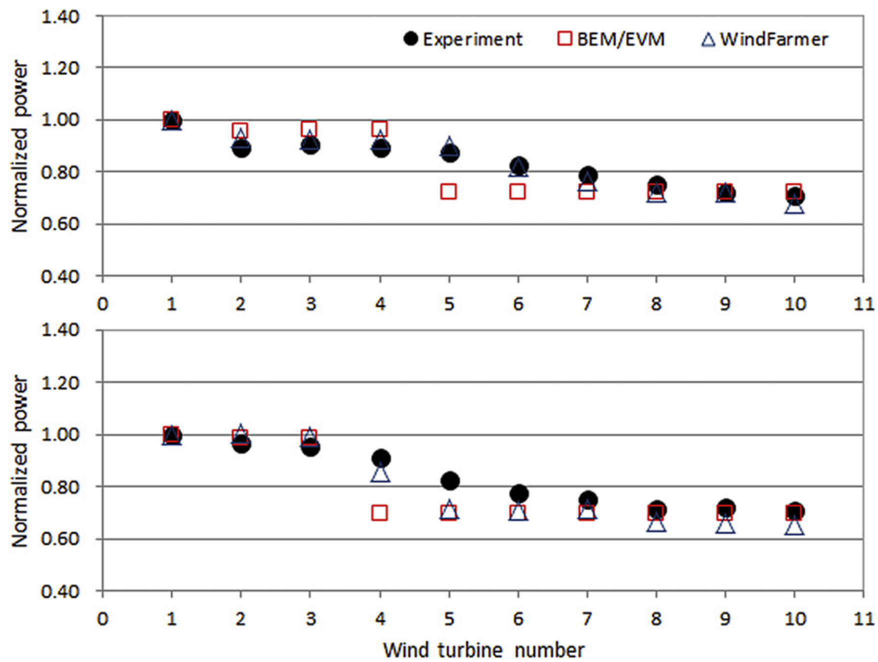

Fig. 3. Normalized power at Horns Rev offshore wind farm of the ER + 10° case (top) and ER + 15° case (bottom).

BEM/EVM code could not show the power loss pattern reducing linearly in the middle region. The results of GH WindFarmer describe the region well. These results are in better agreement compared to the results of BEM/EVM code.

3.2. Nysted

Nysted is a Danish offshore wind farm located at the south of Lolland. 72 turbines comprise the farm array, eight turbines in each row and nine turbines in each column. The turbine spacing is a length of seven diameters in the column direction and 10.4 diameters in the row direction. This is 3.4 diameters in length longer than that of Horns Rev [7]. Fig. 4 shows the layout of Nysted in the rotor diameter length scale. The atmospheric conditions are identical to those of Horns Rev. A numerical calculation was used for the four wind direction cases of ER, ER − 5°, ER − 10°, and ER − 15°.

In each case, the amounts and the patterns of the power losses are quite similar to those of Horns Rev, although the distance between turbines is longer, as shown in Figs. 5 and 6. The numerical results also could not show the power reducing linearly in the middle region in Fig. 6. Despite the disagreement in this region, the numerical results of the BEM/EVM code show better agreement compared to the result of GH WindFarmer for Nysted.

3.3. Optimization

The aerodynamic power of the ER case at Horns Rev is optimized. This case was selected because it can clearly show the effects of the optimization process compared to the other cases. The control variables for the optimization are the pitch angles of the wind turbines. It is common for the maximum power coefficient to increase as the pitch angle rises for the given rotor rotational speed. A large pitch angle should be avoided due to the load on the

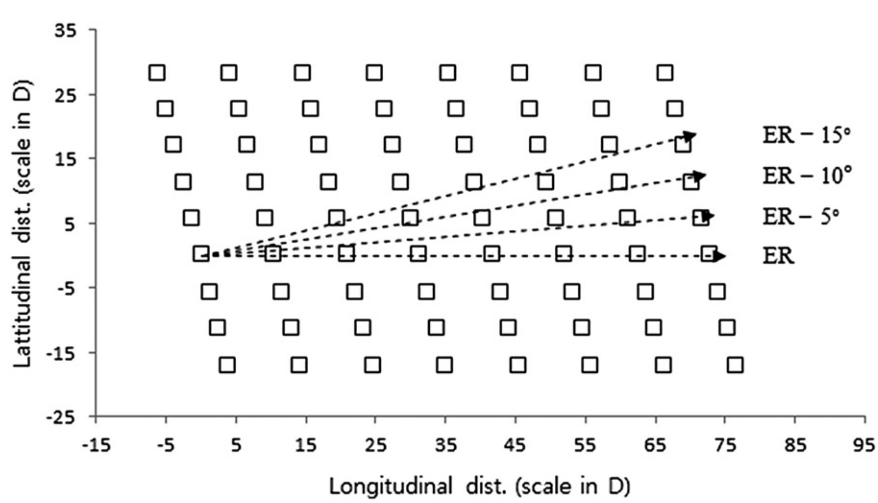

Fig. 4. Layout of the Nysted offshore wind farm.

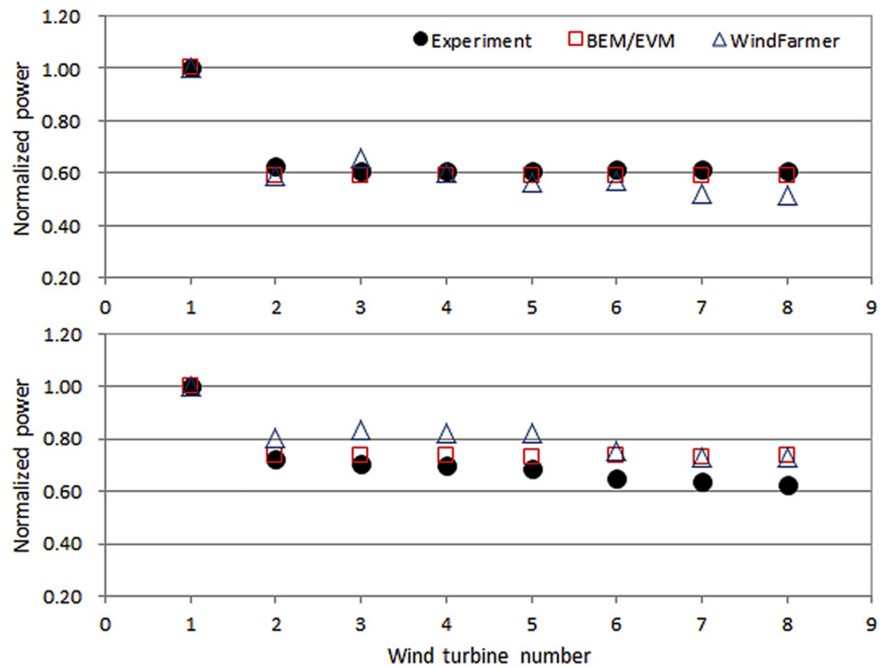

Fig. 5. Normalized power at Nysted offshore wind farm of the ER case (top) and ER − 5° case (bottom).

structures. The pitch angles are randomly chosen in the range from −5° to 5° considering the operating conditions above. The objective function is the total power output of the wind farm. The constraint condition was determined such that the power of each turbine should be lower than the rated power. The optimization direction is to maximize the objective function. The calculation was repeated 27,000 times. The aerodynamic power rises by about 4.5% compared to that of the ER case. Fig. 7 shows the normalized power output of each turbine after optimization. The average inflow velocity to each rotor plane increased in all cases, as shown in Fig. 8. Fig. 9 shows the pitch angle variations relative to the normal operating condition.

4. Discussion

When the momentum of the wind is extracted by the wind turbine rotor, the wake velocity is decreased while the turbulent intensity is increased, however, offsetting the low wake velocity. Thus, the aerodynamic power of downstream wind turbines can be controlled by adjusting the power of the upstream generators.

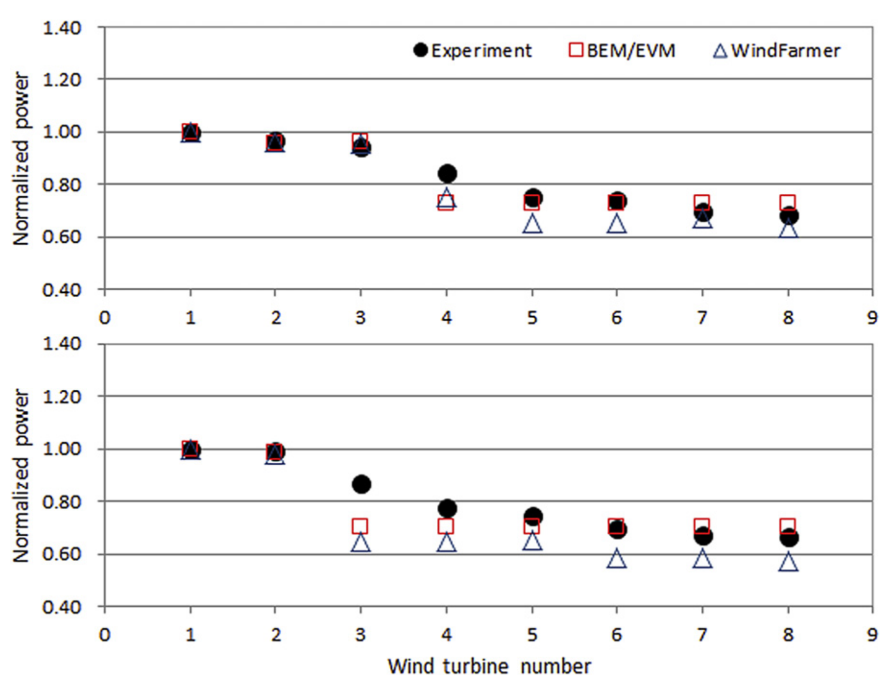

Fig. 6. Normalized power at Nysted offshore wind farm of the ER − 10° case (top) and ER − 15° case (bottom).

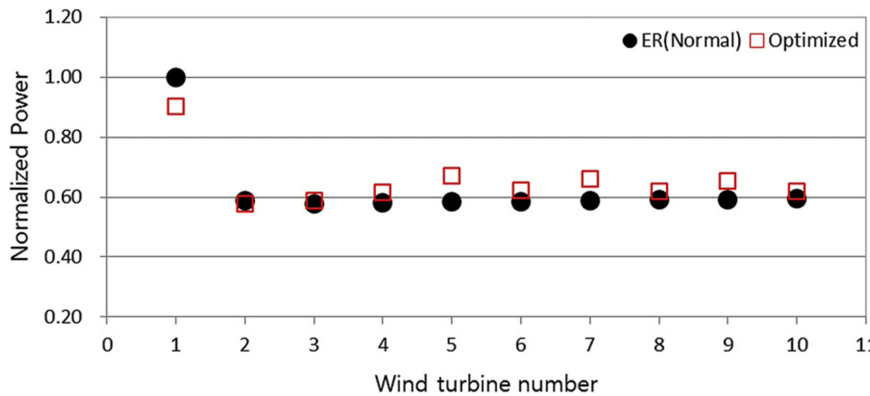

Fig. 7. Optimized result of the normalized power of each wind turbine compared to the normal condition.

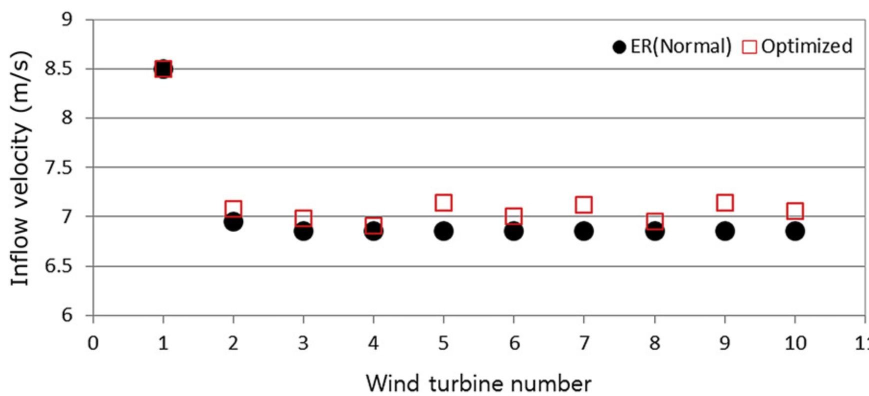

Fig. 8. Optimized result of averaged inflow velocity on the rotor plane.

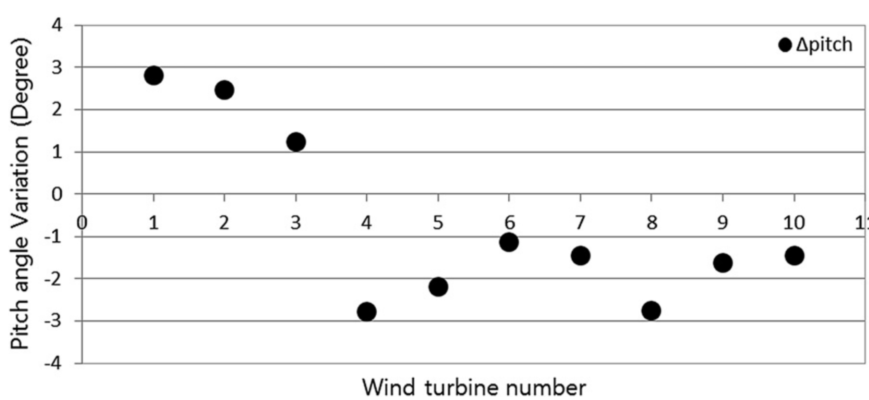

Fig. 9. Pitch variation of each turbine optimizing the wind farm power output.

However, it is difficult to determine the effect of each parameter on the generators. In Fig. 9, the optimized pitch angle of the first three turbines in the row is higher than the pitch angles under normal operating conditions. The power outputs of the turbines are decreased or maintained compared to those of the non-optimized cases. The rise of the pitch angle decreases the rotor angle of attack, yielding the kinetic energy of the wind to the downstream turbines. By reducing the pitch angles of the turbines from the fourth column to the last column, more kinetic energy can be extracted from the wind. An excessively high pitch angle provides low power output for the generator. In contrast, the wake from the turbine at a low pitch angle reduces the power of the downstream turbines. The balance between the velocity and the turbulence intensity of the wake is important to maintain a high velocity recovery rate of the wake. The optimization process determines the balance point at which the total aerodynamic power of the wind farm is maximized.

5. Conclusion

This study was inspired by the idea of controlling the pitch angles of turbines to increase the output of a wind farm. It was found that optimizing the pitch variation of the turbines can lead to a 4.5% increase in the power generated by Horns Rev for the ER inflow direction case. This optimization method can be applied to an operating wind farm, for which it is impossible to change the layout to improve the power output. This study provides an intuitive method to control the wake actively and thus optimize the efficiency of a wind farm.

Acknowledgments

This work was supported by the Human Resources Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy (No. 20094020100060) and the New and Renewable Energy of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy (No. 20104010100490).

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