CONTROL OF PITCH ANGLES TO OPTIMIZE THE AERODYNAMIC PERFORMANCE IN THE WIND FARM

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ABSTRACT

The power loss of a wind turbine due to wakes from upstream turbines is significant in a wind farm. It is usually about 20% of wind turbine power, and it can increase up to 40% for a extreme case. Such effects decrease the annual energy production of the wind farm. Therefore, it is important to predict the effect of the wakes to maximize the power output of the wind farm. In this study, we investigate the pitch angle control of turbines to maximize the aerodynamic power in 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 increase of turbulent intensity. This means that controlling the pitch angle of the turbine does not guarantee the maximum aerodynamic power of the wind farm. Thus, the comprehensive control method considering whole wind turbines in 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 the two dimensional Gaussian profile determined by the thrust coefficients of the fore located turbines and the atmospheric conditions. Genetic Algorithm (GA) is used to calculate the optimal power. The results show that the pitch angle control can maximize the power output in the wind farm.

KEYWORDS

Wind farm optimization, Power loss, Wind turbine wake, pitch control, Blade element momentum theory, Eddy viscosity model

1. INTRODUCTION

A wind farm can utilize the wind resources of a certain area efficiently. Most of the large onshore wind farms are located in the United States and China over 500MW in size. An offshore wind farm is the new trend of wind energy industry. Sites located offshore are free from many environmental issues such as noise and visual impact. Moreover, the wind energy is much more abundant in the offshore than in inland areas. Denmark and United Kingdom are the leading country of the large offshore wind farm, which has about 200~300MW in size. Wind farms are under construction these days in the world. The total wind power capacities in the worldwide is rising rapidly, expecting to reach 1,500GW in 2020s. [1]

In the wind farm, the outputs of the generators are reduced because of wake from the upstream turbines. The power loss of a wind turbine due to wakes is an issue of the wind farm design. It is usually about 20% of the wind turbine power, and it can increase up to 40% when the wakes are ingested directly into the downstream turbine. [6] To improve the total power output of the wind farm, the studies on the optimized layout of the wind farm were conducted. [13,14] The goals of the researches are the placement of turbines which can avoid the wake effect as much as possible. For the wind farms already constructed is impossible to change the layout of turbines, the research cannot be applied to it. The layout optimization should be considered in the design step, before the installation. In the present work, the pitch angle of turbines is controlled to optimize the wind farm aerodynamic power output.

It is essential to understand the wake phenomena and predict its effect on the downstream generators. After the wind passes a generator, its speed decreases and, the turbulence intensity increase. The wake velocity is recovered as the wind moves downstream, and its rate becomes higher as turbulence intensity increases. 2-D wake models, Park model, [2] and eddy viscosity model (EVM) [3], are introduced to describe the wake velocity profile. Crespo suggested the 3-D wake model in better agreement with the field data. [5,9] Empirical model is also developed to describe the added turbulence intensity of the wake. [4,10] Recently, the models based on computational fluid dynamics (CFD) are also used for a wind park design. As the part of the EU's Upwind project, the validation of the presented models are conducted. The results of the models are compared with data measured in the wind farm. [6,7,8,11,12]

2. NUMERICAL METHODS

2.1 Blade Element Momentum Theory (BEM)

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

The BEM code can consider the non-uniform inflow circumstance such as the wind shear, 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 leads to predict the aerodynamic performance of the rotor. Thrust coefficient, one of the properties from the BEM result, is a main factor determining the wake velocity characteristics. The induction factor of the rotor segment is defined as the ratio between the induced velocity in normal direction of the airfoil $v_{i,n}$ and the wind inflow velocity to the rotor plane V_0.

$$a = \frac{v_{i,n}}{V_0} \tag{1}$$

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.

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

Tip loss factor and Glauert’s correction model are also applied to the code to improve the accuracy.

2.2 Eddy Viscosity Model (EVM)

EVM is an empirical model to determine the wind turbine wake velocity profile. The region in the range of 2~4 rotor diameters downstream is the near wake region where just after the wind passes through the rotor. In this near wake region, rapid pressure drop and velocity decrease is found due to the energy extraction by the rotor. The velocity is recovered beyond 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. 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,

$$\mathrm{U}\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial r} = -\frac{1}{r}\frac{\partial (r\overline{uv})}{\partial r} \tag{3}$$

$$-\overline{uv} = -\varepsilon \frac{\partial U}{\partial r} \tag{4}$$

The ε is the eddy viscosity, used to model the Reynolds stress $\overline{uv}$. The turbulence intensity of the wake added after the turbine is,

$$TI_{add} = 5.7{C_T}^{0.7}{TI_{amb}}^{0.68}(x/x_n)^{-0.96} \quad (5)$$

x_n, the near wake length, is usually about two diameters length. TI_{amb} is turbulence intensity of the atmosphere.

2.3 Genetic Algorithm (GA)

The optimization procedure is described in the Figure 1. The objective function is total aerodynamic power output of the wind farm. The atmospheric conditions, the operational conditions (pitch angle, rotational speed of the rotor, etc.) of each turbine, wake characteristics are variables of the objective function. It is difficult to find the analytical solution for the problem, because the parameters interact with each other complicatedly. In this case, a stochastic method should be utilized such as a genetic algorithm, 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 turbines enabling the maximum aerodynamic power output of the wind farm. The GA is generally employed to optimize the complex objective functions in engineering fields with many applications.

3. RESULTS

The validation of the BEM and EVM code which predict the wind farm power output is conducted for the first step. Data used for the validation is measured in the Horns Rev and Nysted offshore wind farms located in the Denmark. The data of power loss of the generators in the wind farms is measured and analyzed as a part of EU's Upwind Project. [6,7,8,11,12]

3.1 Horns Rev

The array of the Horns Rev is comprised of eighty wind generators, ten turbines in each row and eight turbines in each column. The turbine spacing is seven diameters distance in both row and column directions. Figure 2 shows the layout of the 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 of GH WindFarmer, which is widely used to design a wind farm. The data are measured at an inflow velocity of 8m/s. 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.

Figure 3 presents the numerical result of ER(top) and ER+5° (bottom) case. In the ER case, most turbines are affected on the wake directly from their upstream turbines. The power loss of the turbines on the second column is significant up to 40%. The rate of power loss maintains to the downstream turbines. The power loss pattern of ER+5° case is similar to the ER case. The wind turbines behind the first turbine on the row are affected on the wake inflowing almost directly, lost 30% of the power output which is also significant. For these cases the BEM/EVM code shows a good agreement with the measurement data for the cases. Figure 4 shows the numerical result of ER+10° (top) and ER+15° (bottom) case. In both case, the power loss due to the wake from the front generator is less than 10%. The wakes from the wind turbine on the neighboring row have a big effect on the power reduction of the generator; decrease in power is 30%. The BEM/EVM code could not catch the power loss pattern reducing linearly in the middle region. The results of GH wind farmer describe the region well and show better agreement than the results of BEM/EVM code.

3.2 Nysted

Nysted is the Danish offshore wind farm located in the southeastern sea. The 72 turbines comprise the farm array, eight turbines in each row and nine turbines in each column.

The turbine spacing is seven diameters length in the column direction and 10.4 diameters length in the row direction, 3.4 diameters length longer than that of the Horns Rev. Figure 5 is the layout of the Nysted in the rotor diameter length scale. The atmospheric conditions are the same as the Horns Rev. Numerical calculation is conducted for the four wind direction cases, ER, ER-5°, ER-10°, and ER-15°.

In each case, the amounts and the patterns of power losses are quite similar to those of the Horns Rev although the distance between turbines is longer, as shown in Fig. 6 and 7. The numerical results also could not match the power reducing linearly in the middle region in the Fig. 7, Despite the disagreement in the region, the numerical results of the BEM/EVM code show better agreement compared to the result of GH WindFarmer for the Nysted.

3.2 Optimization

The aerodynamic power of the ER case in the Horns Rev is optimized. This case can clearly show the effects of the optimization compared to the other cases. The control variables for the optimization are the pitch angles of the wind turbines. It is general that the maximum power coefficient increases as the pitch angle rises, for the given rotor rotational speed. Significant pitch angle should be avoided because of the load on the 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 is determined that the power of each turbine should be lower than the rated power. The optimization direction is to maximize the objective function. The calculation repeated 27000 times. The aerodynamic power rises about 4.5% compared to that of the ER case. Figure 8 is the normalized power output of each turbine after the optimization. The averaged inflow velocity to each rotor plane increased for all cases, as shown in Fig. 9. Figure 10 shows the pitch angle variations relative to the normal operating condition.

4. CONCLUSION

When the momentum of the wind is extracted by the wind turbine rotor, the wake velocity is decreased, but the turbulent intensity is increased adversary compensating the low wake velocity. Therefore, the aerodynamic powers of the downstream wind turbines can be controlled by that of upstream generators. However, it is difficult to understand the effect of each parameter on the generators. In the Fig. 10, the optimized pitch angle of the first three turbines on the row is bigger than the pitch angles on the normal operating conditions. The power outputs of the turbines are decreased or maintained compared to those of the not 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 on the fourth column to the last column, more kinetic energy can be extracted from the wind. Excessively high pitch angle provide low power output for the generator. Adversary, the wake from the turbine in the 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 high velocity recovery rate of the wake. The optimization is to fine the balance point where the total aerodynamic power of the wind farm is maximized.

This study is inspired by an idea of controlling the pitch angles of the turbines to increase the wind farm output. It is found that the optimized pitch variation of the turbines can lead to the 4.5% increase of the power in the Horns Rev for the ER inflow direction case. This optimization method can be applied to the wind farm already constructed, which is impossible to change the layout to improve the power output. This study gives an intuition to control the wake actively to optimize the wind farm efficiency.

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FIGURES

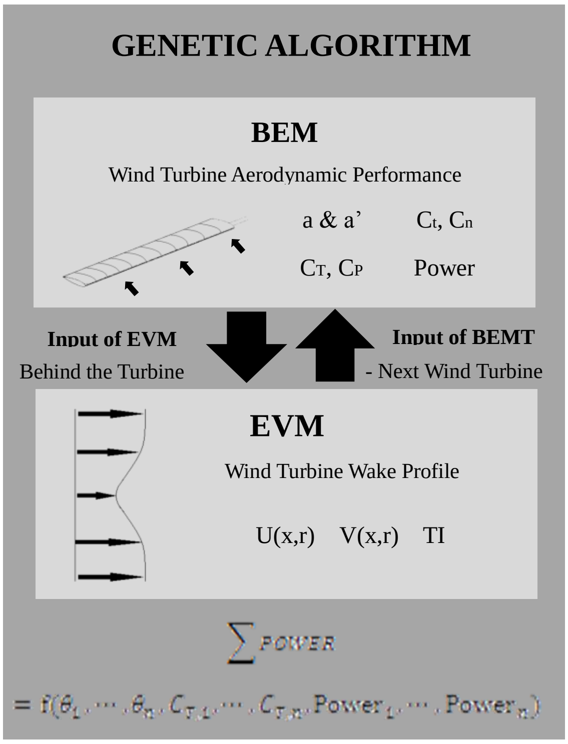

Fig. 1. Optimization procedure

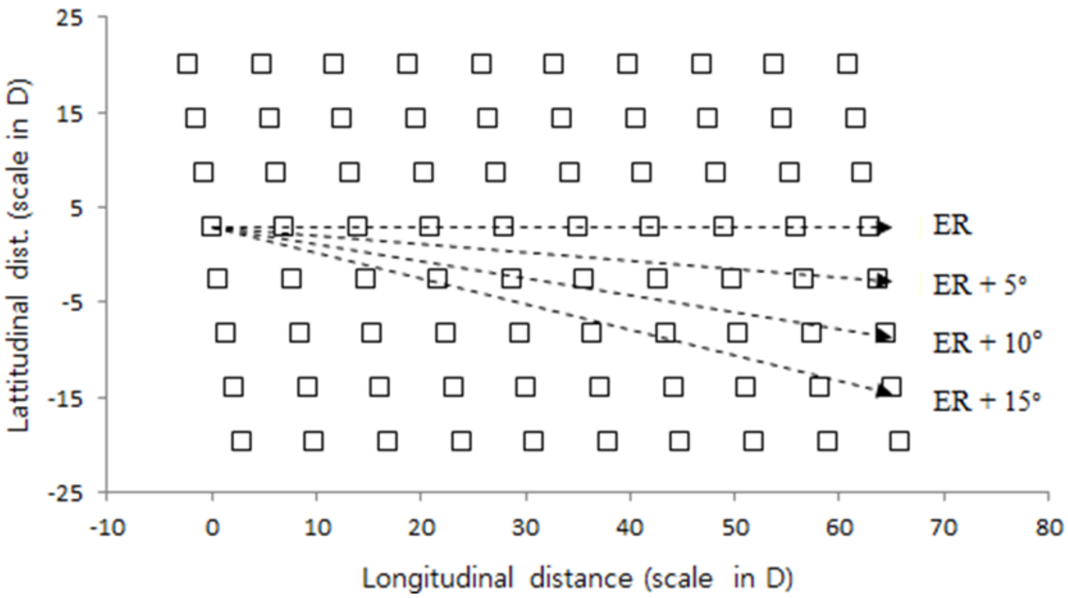

Fig. 2. Layout of the Horns Rev offshore wind farm

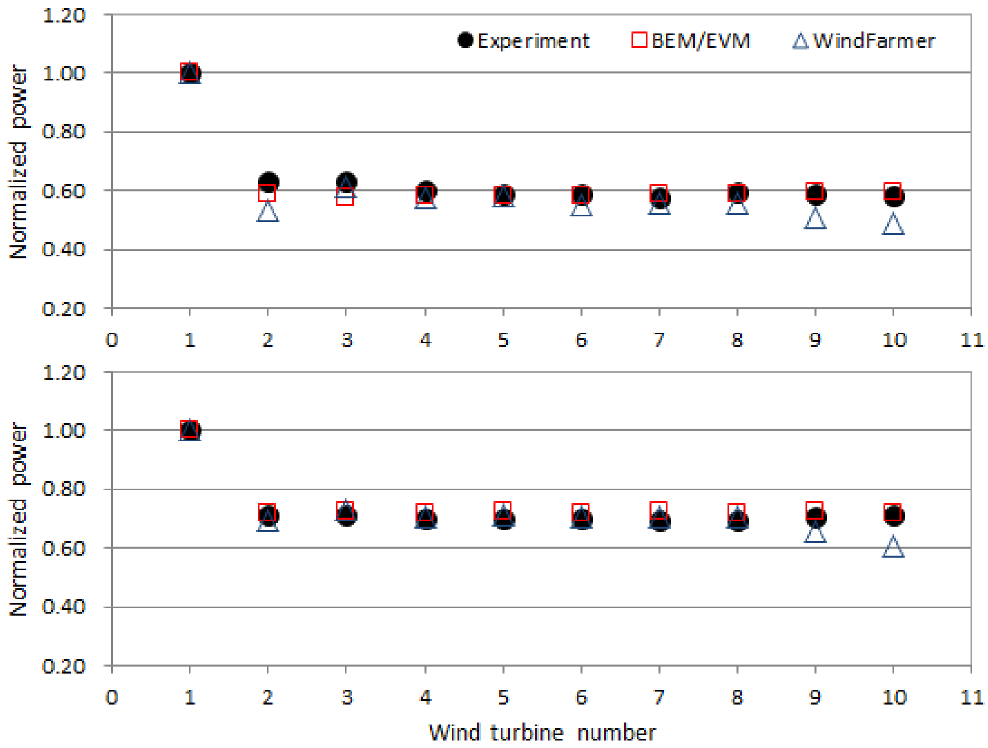

Fig. 3. Normalized power at Horns Rev offshore wind farm of the ER case(top) and ER+5° case(bottom).

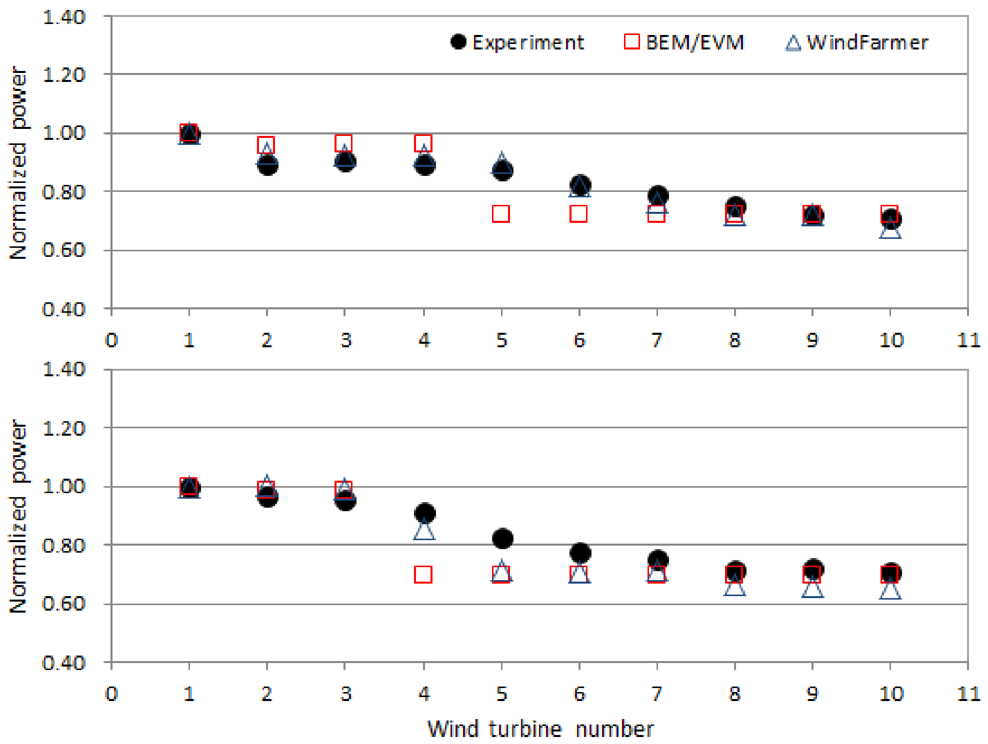

Fig. 4. Normalized power at Horns Rev offshore wind farm of the ER+10° case(top) and ER+15° case(bottom).

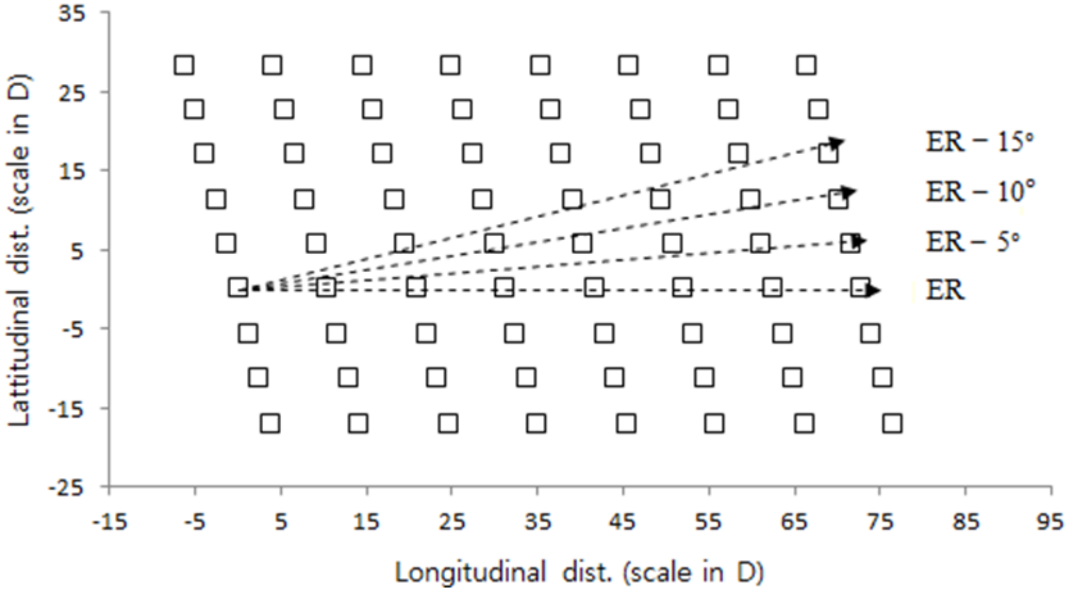

Fig. 5. Layout of the Nysted offshore wind farm

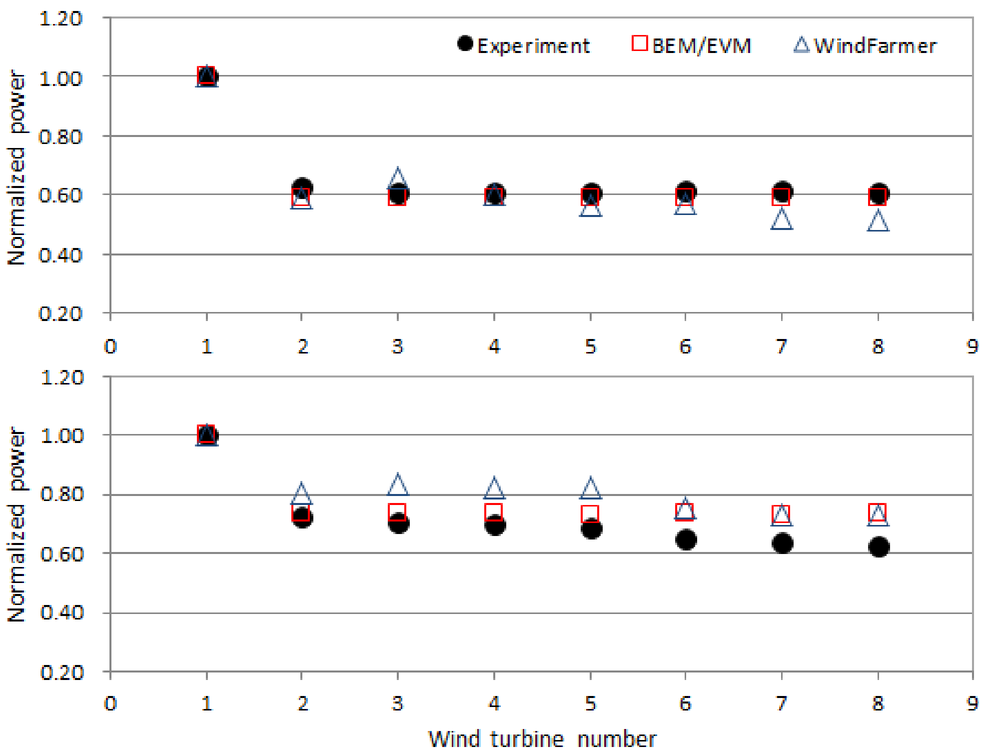

Fig. 6. Normalized power at Nysted offshore wind farm of the ER case(top) and ER-5° case(bottom).

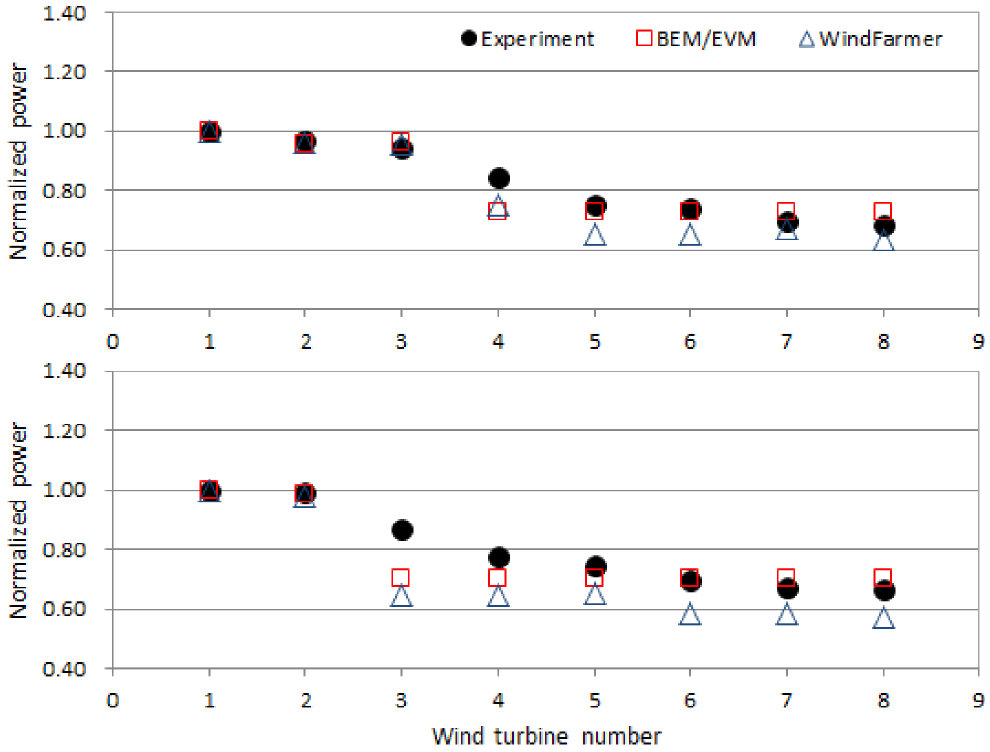

Fig. 7. Normalized power at Nysted offshore wind farm of the ER-10° case(top) and ER-15° case(bottom).

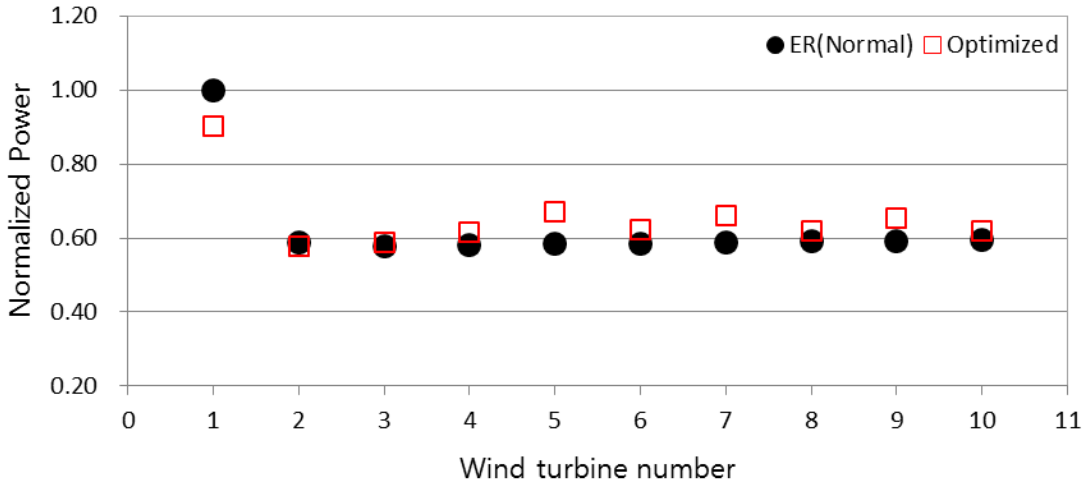

Fig. 8. Optimized result of the normalized power of each wind turbine compared to the normal condition.

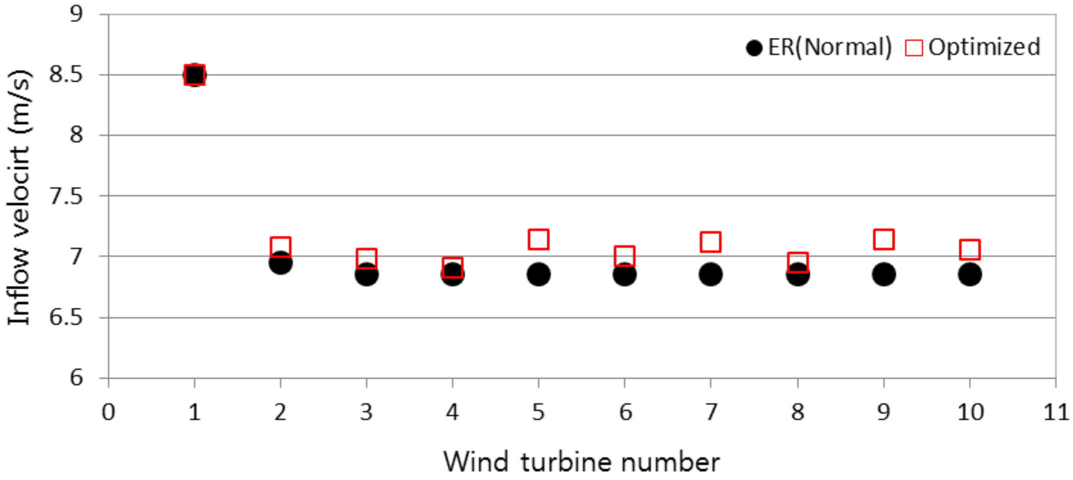

Fig. 9. Averaged inflow velocity on the rotor plane in optimized condition.

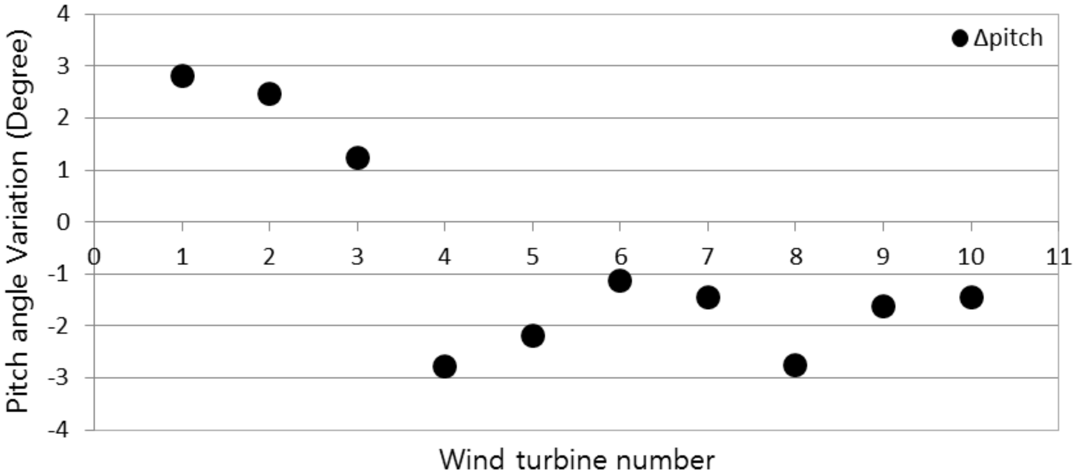

Fig. 10. Pitch variation of each turbine optimizing the wind farm power output.