DEVELOPMENT AND VERIFICATION OF OFFSHORE WIND FARM LAYOUT OPTIMIZATION NUMERICAL MODEL WITH WAKE LOSSES

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ABSTRACT

This research proposes a reliable numerical wind farm layout optimization model with wake losses aimed to maximize the Annual Energy Production (AEP) and a verification against industry standard CFD software. An example study of a 10 km offshore wind farm off the Songkhla coast in the South of Thailand, where wind speed data at 100m altitude is available, is performed with Vestas V126-3.3MW, IEC IIIA class wind turbines. Ten units of wind turbine are arranged in a 7Dx8D pattern within a 3km diameter circular area. AEPs of the example wind farm is calculated using measured wind speed data from a nearby onshore location with several wake losses models [1-3]. Calculations are performed with the example wind farm rotated 360º at each degree of rotation to determine the direction which produces the maximum AEP. The optimum rotation angle is found to be 124º, which has been verified with WindSim simulations. The capacity factor errors between 119º-129º are below 5%, hence the proposed wind farm layout optimization model and the AEP computation mathematical models with wake losses may be used with confidence.

1. INTRODUCTION

Harvesting wind energy is not as easy as a common power plant, since a dozen of factors must be considered. In this research, we will only focus on the impact of wake losses on the AEP of wind farms. Wake losses are reduction of the downwind wind speed resulting in performance drop of the downwind units within the wind farm. Thus wind farm layout optimization aims to achieve a wind farm layout with minimum effects of wake loss, in order to achieve a maximum Annual Energy Production.

This research proposes a reliable numerical wind farm capacity factor calculation model based on previous research [4] with an additional verification using industry standard CFD software (WindSim) which attempts to perform a simple optimization process with only one parameter.

2. METHODOLOGY

This study will perform a calculation of offshore wind farm located 10 km off the Songkhla coast in the South of Thailand. A 16-directions Weibull distribution of wind speed data [5] measured at 100m altitude shall be used. Since Thailand is in the low wind speed region, the selected wind turbine model is "Vestas V126-3.3MW" with IEC IIIA class which meet the requirements for IEC 61400-1 wind turbine standard [6] and suitable for the average wind speed 6.4m/s over the site area.

The calculation of wake losses is based on the assumption of no elevation of terrain since most of offshore wind farms are usually located sufficiently far from the shoreline. The numerical model of wake losses performed in this study are proposed by Jensen [1], Husien [2] and Muhammad [3]. The single-wake and multi-wake models are combined as 4 models as shown on Table 1.

Table 1. Combined wake losses models.

Model No.	Single-wake model	Multi-wake model	Combined model
1	Husien	Muhammad	H-M
2	Jensen	Muhammad	J-M
3	Husien	Husien	H-H
4	Jensen	Husien	J-H

2.1 Wake loss models

Wake loss models are mathematical models which predict the wind speeds downwind of a wind turbine rotor. In actual application, a downwind wind turbine may experience wake loss effects from one or more upwind turbines, therefore two categories of wake loss models, namely single-wake and multi-wake models, are required.

2.1.1 Single-wake models

Single-wake models predict the reduction downstream wind speed caused by flow energy dissipation at a single upstream wind turbine rotor. Two well established single-wake models are considered in this study. Firstly, Jensen [1] model is based on the assumption of steady and one dimensional incompressible flow with linear expansion of wake cone. The downwind wind speed within the wake v_1 is given by

$$v_1 = v_0 + v_0\left(\sqrt{1 - C_T} - 1\right)(r_0/r)^2 \qquad (1)$$

where v_0 denotes the free stream wind speed, C_T is the thrust coefficient of wind turbine, r_0 is the radius of the rotor blade and r is the radius of wake cone.

The second single-wake model in this study is proposed by Husien [2]. This wake model is based on the basis of mass conservation and linear expansion of wake cone similar to the Jensen model. The downwind wind speed within the wake v_{w0} can be calculated by

$$v_w(x) = v_0 + (v_{w0} - v_0)(r_{rot}/r(x))^2 \qquad (2)$$

where the wind speed immediately downwind of the rotor v_{w0} is a function of axial induction factor a and free stream wind speed v_0. The wind speed v_{w0} is given by

$$v_{w0} = (1 - a)v_0 \qquad (3)$$

2.1.2 Multi-wake models

When multiple wakes are cast on a single wind turbine rotor, a multi-wake model must be used to combine the effects of all wakes in the flow field. Two multi-wake models are considered in this study. Both are based on the root-sum-square method. The first model is proposed by Husien [2] and the combined wake wind speed v is given by

$$v = v_0 - \sqrt{\sum_{for\ all\ wakes}^{n} (v_0 - v_w)^2} \qquad (4)$$

The second multi-wake model proposed by Muhammad [3] includes a weighting factor $\beta_{Tj,Th}$ (ratio between rotor area affected by the wake and the total rotor swept area) to correct the effect of each single-wake on the focused wind turbine. The expression for combined wake wind speed v_{tj} is given by

$$v_{tj} = u\left(1 - \sqrt{\sum_h \beta_{Tj,Th}\left(1 - \frac{v_{ps,Th}}{u}\right)^2}\right) \qquad (5)$$

Where u is the free stream wind speed and $v_{ps,Th}$ is the single-wake wind speed.

2.2 Verification of wake loss models

Chosen wake loss models are verified against actual collected data from an offshore wind farm in Denmark [7]. The wind farm consists of 80 units of wind turbine arranged in a grid pattern as shown in Figure 1.

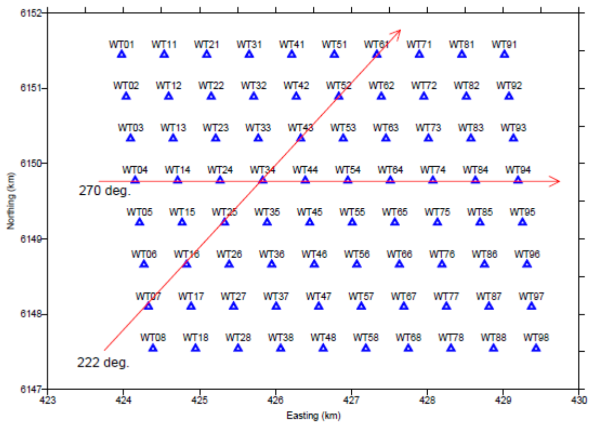

Fig.1. Layout of Horns Rev offshore wind farm with illustrations of 222° and 270° wind directions [7]

The effects of wake losses are represented by the local wind speeds at the wind turbine rotors. Figure 2 shows a comparison of wind speeds that wind turbines along row 4 of the wind farm experience during a constant 12m/s free stream wind speed from 270° direction. The results suggest that all four wake loss model combinations produce compatible trends and accurate magnitudes within 10% of the recorded data. Therefore, the wake loss mathematical models may be confidently used.

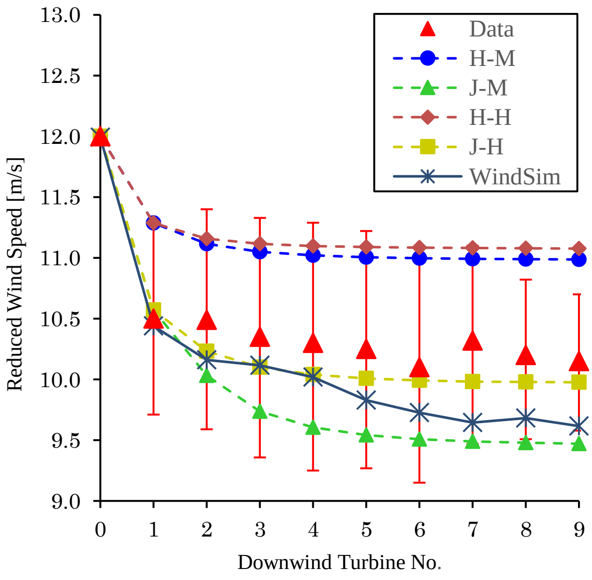

Fig.2. Comparison of wind speeds at wind turbines on row 4 of Horns Rev offshore wind farm with 12m/s free stream wind speed and 270° incoming direction

2.2 Optimization method

A simple wind farm layout optimization procedure is attempted. A 10-unit stack wind farm layout of Vestas V126-3.3MW are arranged in a 7Dx8D pattern (7 and 8 times the rotor diameter, respectively) within a 3km diameter circular area as shown in Figure 3.

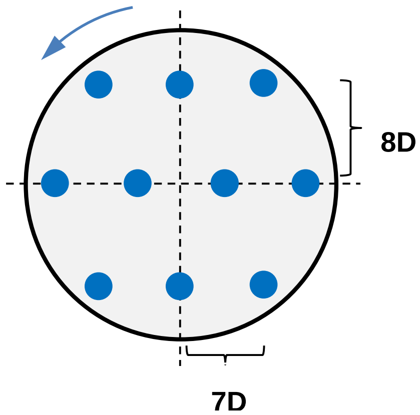

Fig. 3. Top view of initial wind farm layout with 7Dx8D spacing and rotation direction

The wind farm layout in Figure 3 is rotated about the center for one complete revolution in a CCW direction with 1 degree increment. Recorded wind speed and direction data from Songkhla, Thailand will be used in this study, as shown in Figure 4. Capacity factors are computed at each rotation increment to determine the angle which yields the maximum value of capacity factor. Finally, a verification with WindSim simulation will be performed.

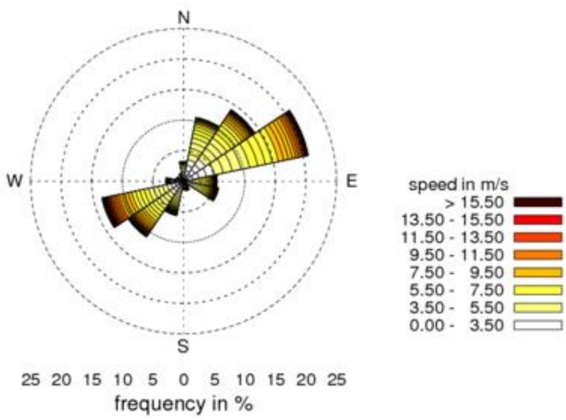

Fig.4. Wind rose representing wind speed and direction data at 137m height at 10km from Songkhla shoreline

3. RESULTS AND DISCUSSIONS

Four combinations of single-wake and multi-wake models, as described in Table 1, are used to determine the capacity factor of a 10-turbine wind farm arranged in a pattern illustrated in Figure 3. The variation of capacity factors as the wind farm undergoes a 360° rotation about its centre is shown in Figure 5. It shows 16 peak values which correspond to the 16 wind directions of the wind rose. The variation shows a periodic pattern at 180° rotation angle because of the symmetry of the wind farm layout.

Given that the capacity factor for this wind farm without wake losses is 26.47%, the results in Figure 5 show a range of capacity factor between 23%-26%, a drop up to 3.5% from the ideal case, suggesting that wake losses can have a significant impact on the wind farm power output. It is found that the maximum capacity factor is achieved at rotation angles of 124° and 304°, where only 0.5% drop from the ideal case is experienced. The wind farm optimal design is said to be achieved at these two angles.

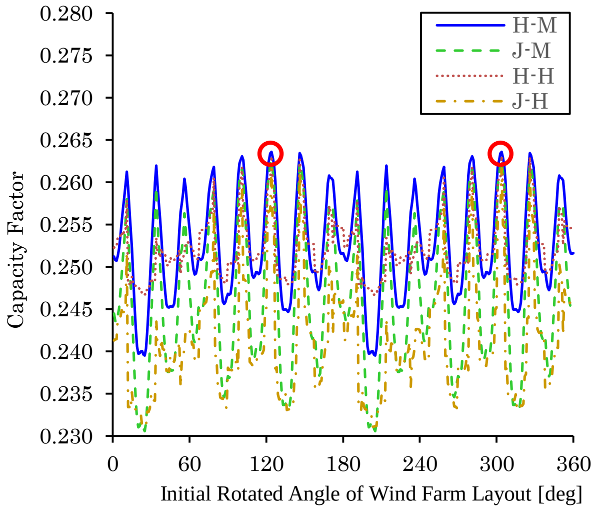

Fig. 5 Variation of Capacity Factor for each rotated angle

The capacity factor calculations using wake loss models are further verified with WindSim over a small range of wind farm rotation angles. The verification shown in Figure 6 suggests that all 4 wake loss model combinations agree well with the results obtained using WindSim with errors under 5% at ±5° from the optimum angle. Jensen-Muhammad (J-M) models appear to produce results closest to that of WindSim.

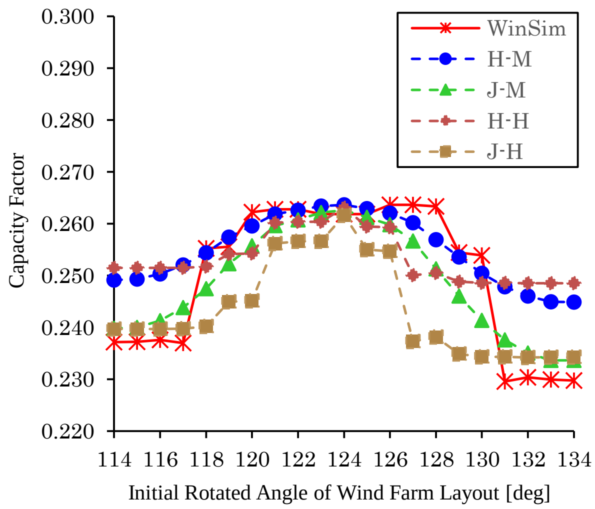

Fig. 6 Variation of Capacity Factor for each rotated angle

The wind farm optimal layout is achieved at 124° and 304°, which corresponds to the wind direction data from Songkhla, Thailand. There are two dominant wind directions at 67.5° and 247.5° as shown in Figure 4. It is, therefore, understandable that the optimal layout is achieved when the turbines are arranged such that the wind farm lateral axis is perpendicular to the dominant wind directions.

CONCLUSION

Results presented in this study show that the wake loss mathematical models are able to predict wind speeds within wind farms substantially accurately, when verified against measured data and CFD (WindSim). The mathematical models also offer a much computationally cheaper calculation procedure than CFD. However, the optimization method presented in this study is still limited to one parameter which is still not practical in real application. Future work will involve optimization of where each wind turbine position in the wind farm.

REFERENCES

[1] F. González-Longatt, P. Wall, V. Terzija, "Wake effect in wind farm performance: Steady-state and dynamic behavior", *Renewable Energy*, p. 329-338, 2012

[2] Walid Husien, Wedad El-Osta, Elhadi Dekam, "Effect of the wake behind wind rotor on optimum energy output of wind farms", *Renewable Energy*, p. 128-132, 2013

[3] Muhammad Ali, Julija Matevosyan, J.V. Milanovic, "Probabilistic assessment of wind farm annual energy production", *Electric Power Systems Research*, p. 70-79, 2012

[4] Chawin Chantharasenawong, Danai Kollasuta, Dusadee Sukawat, "Development of offshore wind farm layout optimization numerical model with wake losses", *2015 AEDCEE*, p. 183-184, 2015

[5] King Mongkut's University of Technology Thonburi, "Micro-Siting Wind Resource Assessment of Thailand", *Thailand: Ministry of Energy*, 2008

[6] IEC, "IEC 61400-1: Design requirements", 3rd ed., *IEC*; 2005

[7] Sten Frandsen, Rebecca Barthelmie, Ole Rathmann, "Summary report: The shadow effect of large wind farms: measurements, data analysis and modelling", *Riso National Laboratory*, p. 21-22, 2007

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