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Study on methods to determine rotor equivalent wind speed to increase prediction accuracy of wind turbine performance under wake condition

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ABSTRACT

A downstream wind turbine located within the reach of the wake region of an upstream wind turbine experiences a decrease in power output due to wake effects. For this reason, when designing a wind farm, various engineering wake models are used to predict the power deficit and wind farm layout is designed in the optimal way to minimize the wake losses. Generally, in the process of calculating the loss of wind farm AEP, in most cases the single point-measured wind speed is used. However, this results in an error when predicting the loss of AEP under wake conditions. When predicting the AEP of a wind turbines affected by wakes, the rotor equivalent wind speed (REWS), which considers the effect of wake wind shear, should be applied. This research examined $REWS_{power}$ converted from the power output of a wind turbine to demonstrate the need of rotor equivalent wind speed under upstream turbine's wake condition and furthermore suggested a method to calculate $REWS_{spws}$ using the nacelle-measured wind speed. By analyzing 48 months collected data of Supervisory Control and Data Acquisition (SCADA) system from a wind farm, error percentages among $REWS_{power}$, $REWS_{spws}$, and the nacelle-measured wind speed were compared.

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Introduction

As the capacity of wind turbines and the scale of wind farms grow, wake effects caused by neighboring turbines are becoming increasingly important. While the power deficit arising from these wake effects varies depending on the surrounding geographic environment and the wind farm layout, it is reported to be between 5 and 15% (Schepers et al., 2012). On an offshore wind farm in particular, the wind speed, which drops in the wind turbine behind, does not recover as fast as on an onshore wind farm, resulting in a higher loss in power output. When designing an offshore wind farm, it is therefore important to predict the loss of power output caused by wake effects and to optimize the layout design in order to minimize the loss. To determine wind turbine wake effects, a large number of engineering wake models have been developed, and many empirical studies have been conducted to increase and verify the prediction accuracy of such models.

David Ryan Van Luvanee and Thomas Sørensen et al. examined the Horns Rev. wind farm in Demark and conducted verification (VanLuvanee, 2006; Sørensen et al., 2008) of the prediction accuracy of engineering wake models, such as Jensen (1983), Katic et al. (1986), Ainslie Eddy Viscosity (1988), and Larsen (1988), which were implemented in the wind farm design software WindPRO (EMD International A/S). The results showed that the prediction accuracy of these wake models differed depending on changes in atmospheric stability and surface roughness. The simple N.O. Jensen wake model, which expresses wake changes in the form of a uniform velocity profile, was found to be most precise in its prediction results on sector averaged power.

R. J. Barthelmie et al. analyzed Supervisory Control and Data Acquisition (SCADA) data measured on the Danish offshore wind farms Nysted and Horns Rev. and compared (Barthelmie et al., 2010) the acquired wake loss values with values simulated by using engineering and research wake models developed by DTU-Riso, Garrad Hassan, ECN, and NTUA. The results showed that all of the wake models had a higher prediction accuracy of wake loss under high wind speed and full wake conditions than under low wind speed and partial wake conditions.

The EERA-DTOC Project (Gaumond et al., 2012) compared wake loss values measured from Horns Rev. and Lillgrund with those predicted by the N.O. Jensen, G. C. Larsen, and Fuga wake models, and found that the wake models overestimated wake loss. This may be because the wind speed decrease in the wake center is underestimated due to the high uncertainty of wind direction data. A study on how this uncertainty of

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measured wind direction data affects wake loss estimation is now being conducted by the IEA-Task 31: WakeBench Project (Moriarty et al., 2014).

Within the wake region of a wind turbine, a velocity deficit always occurs. The wind speed decreases most in the wake center region, and as the distance from the wake center increases, the speed gradually recovers until it reaches the ambient wind speed (Mckay et al., 2012). If the wake flow developed in the rear of an upstream wind turbine behind moves into a downstream wind turbine, the rotor disk of the downstream turbine is influenced by wake wind shear in the radial direction (horizontal and vertical direction). If only the single point wind speed measured at the height of a hub is applied when conducting power performance assessment on a downstream wind turbine influenced by wakes, it is highly likely that erroneous results will be obtained. For this reason, the representative wind speed, which incorporates wake wind shear, should be applied. As mentioned above, however, many previous studies have until now used the single point wind speed value to predict the power performance of a wind turbine located in the wake condition, so that the wake wind shear effect is not fully taken into account.

In this regard, many similar studies are being conducted on the application of the rotor equivalent wind speed (REWS) to increase measurement precision of the power performance of a wind turbine not influenced by wakes in which vertical wind shear only is being considered.

Rozenn Wagner and Clifton A. et al. measured the wind speed at five different heights in front of the rotor disk and presented a REWS calculation method (Wagner et al., 2009; Wagner et al., 2011; Clifton et al., 2013) using the average value calculated after segment weighting was applied to each height measured wind speed. The results of a comparison between the power curve where the REWS was applied and the actual power curve was far more accurate than using the point-measured wind speed. It was further verified by experimental method that the percentage error of prediction of the Annual Energy Production (AEP) could be reduced from −2.3% to −0.5%.

In addition, V. Barth et al. predicted the total AEP of a wind farm by using the REWS suggested by Rozenn Wagner and confirmed (Barth and Wassie Tsegai, 2014) that it provided results that were more accurate than those predicted by the point-measured wind speed. A method to measure the power performance using the REWS will be incorporated in a revision to IEC 61400–12-1 (2013).

As mentioned above, a working group is revising the international standard (IEC61400-12-1) with regard to the power performance test of a wind turbine. Therefore the standard only concerns wind turbines that are not influenced by wakes so that it only takes vertical wind shear into consideration.

However, when predicting the power performance of a wind turbine in the wind farm affected by wakes, the impact of wake wind shear, which is defined as the velocity gap between the wake center and wake flow edge, needs to be considered. In particular, to calculate wind farm power performance when verifying the prediction accuracy of various wake models, REWS that takes into account the effect of wake wind shear, rather than the single point decision wind speed calculated from wake models, needs to be introduced. As mentioned above, however, most previous studies have predicted the power performance of a wind turbine influenced by wakes by means of a wind speed acquired at a certain point from wake analysis results, and have verified wake models through comparison with measured data.

The results of verification of wake models could result in an error due to gaps in applied wind speed, so a thorough review is required on the differences in the single point wind speed and the REWS in the wake region of a wind turbine. Therefore, this study presents experimental results on gaps between $\text{REWS}_{\text{power}}$, calculated using the power curve measured from wind turbines in operation on a wind farm, and the point wind speed measured from the nacelle anemometer. Considering the REWS calculation method suggested by Rozenn Wagner, the study also provides a method to calculate $\text{REWS}_{\text{spws}}$, which uses the wind speed measured from the nacelle anemometer, and verifies its applicability through comparison with $\text{REWS}_{\text{power}}$.

Wind farm layout information and SCADA data classification

Wind farm measured for the study

The nacelle wind speed and power curve used in this study were acquired through analysis of SCADA data measured from operational wind turbines on the Sungsan wind farm. The Sungsan wind farm, operated by Korea Southern Power Co., Ltd. (KOSPO), is a 20 MW onshore wind farm located on Jeju Island and has 10 VESTAS V80–2 MW turbines with a hub height and rotor diameter of 80 m. Unlike most wind farms designed on a rectangular layout, this site has wind turbines installed at irregular intervals, so the layout is favorable for wake impact assessment according to changes in separation distance.

S.H. Jeon et al. (2015) used SCADA data obtained from the Sungsan wind farm (over 38 months) and conducted research (Jeon et al., 2015) on the verification of prediction accuracy of engineering wake models under single wake conditions. They showed that differences in the prediction accuracy of the models depended on the speed of the wind blowing into upstream wind turbines as well as changes in downstream distance. This study categorized SCADA data with a method identical to that of previous studies and utilized data gathered over 48 months in order to reduce uncertainty in the measured data.

Fig. 1 illustrates the wind turbine layout of the Sungsan wind farm. Seven wind turbines (WT03–WT09) are paired in four separation distances, and these distances were defined as the downstream distances (x). As shown by the dotted lines in the figure, the straight line connecting the hub center points of two wind turbines, when upstream and downstream turbines are located on a straight line with wind direction, is defined as the wake center line (x_{wcl}).

Table 1 shows separation distances of paired wind turbines. The wind turbines located upstream of the wake center line (WT04, WT06, WT07, WT09) were operated without being influenced by wakes while the wind turbines located downstream (WT03, WT05, WT07, WT08) were operated under the influence of wakes. Exceptionally, WT07 is defined as a wind turbine located upstream of WT08 under the condition of $x = 2.55D$ (rotor diameter), and located downstream of WT04 under the condition $x = 5.1D$.

SCADA data categorization depending on changes in relative offset angle

The SCADA data acquired on the Sungsan wind farm was analyzed in order to examine gaps in $\text{REWS}_{\text{power}}$ converted from power output, and the single point wind speed measured from the nacelle anemometer. The results of comparison depending on the distance between upstream and downstream wind turbines and changes in free stream wind speed are then presented.

The SCADA data was categorized into three key wind speed ranges measured from the nacelle anemometer at upstream wind turbines: 7 m/s (6.5 m/s–7.5 m/s), 9 m/s (8.5 m/s–9.5 m/s), and 11 m/s (10.5 m/s–11.5 m/s). Because power output of wind turbine corresponds to the kinetic energy flux through the swept rotor area, power output data from downstream wind turbines collected in the same time converted into $\text{REWS}_{\text{power}}$. For conversion of $\text{REWS}_{\text{power}}$ in downstream wind turbines, the individual power curves measured for 48 months excluding affected time of wake from neighboring wind turbine were used. The wind speed range under 7 m/s and above 11 m/s were excluded from data analysis as they were affected by blade pitch control needed for cut-in operation and power regulation, which made it incomparable in comparison between the nacelle wind speed and $\text{REWS}_{\text{power}}$.

The nacelle wind speed and $\text{REWS}_{\text{power}}$ of downstream wind turbines being affected by wakes were compared and examined for four

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