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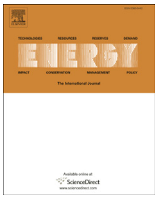

Comparison and verification of the deviation between guaranteed and measured wind turbine power performance in complex terrain

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A B S T R A C T

After a wind farm construction is completed, the power performance guaranteed by the wind turbine manufacturer is usually verified based on the international standard IEC61400-12-1. Because of an insufficient project budget and the constraint on the minimum separation distance of the meteorological mast from the installed wind turbines, it is a common practice to verify the power performance of one representative wind turbine and apply the result as the reference power performance guarantee for all the wind turbines. In this study, the power performances of five wind turbines operating at a commercial wind farm located on complex terrain were measured and analyzed. The results showed large power performance differences between the turbines. Because the power performance of one representative wind turbine cannot guarantee the power performances of all the wind turbines in a wind farm located on complex terrain, we submit that it is necessary to carry out power performance verifications on many or all of the wind turbines.

1. Introduction

Generally, a fully developed wind turbine receives a type certification by going through design evaluation, manufacturing evaluation, and type test processes in accordance with the international standard. In the type test, the power performance of the turbine is measured at an accredited testing laboratory, and most manufacturers present the power performance curve measured in this test as the guaranteed power performance curve when entering into a supply contract. A wind turbine manufacturer sets up a meteorological mast for wind measurement to verify the power performance of a wind turbine supplied to a specific wind farm and measures its performance for about a year. If the measured power performance does not meet the guaranteed power performance, they investigate the cause of the performance degradation and compensate the financial losses incurred from the reduction in the AEP (annual energy production) in accordance with the conditions of the contract. Usually, the wind turbine manufacturer guarantees that the AEP calculated from the measured power performance curve of a wind turbine at the site will be greater than or equal to 95% of the AEP calculated from the guaranteed power performance curve.

In addition to the wind energy resource, the power performance of the wind turbine is an important factor that determines the AEP of the wind farm. Thus, an accurate verification is required for it. The variation of the power performance of a wind turbine can be influenced by mechanical defects, aged deterioration, terrain characteristics, and the climate environment of the area.

A study by Clifton et al. confirmed that the characteristics of the wind conditions of the applicable area, such as the turbulence intensity and wind shear, can affect the performance of a wind turbine [1]. Monnich et al. provided study results on the effects on the power performance of a variation in the design load of a wind turbine due to air density variation and blade leading edge contamination and icing [2]. Hughes reported the power performance degradation of a wind turbine from aged deterioration at a wind farm in Europe with an operation record of more than 10 years [3]. Although the results of the above studies showed the effects of the wind characteristics, air density variations, icing, and aged deterioration on the power performance of a wind turbine, they did not confirm the difference between the measured power performance curve and guaranteed power performance curve for each wind turbine operating on complex terrain.

The wind characteristics, such as the turbulence intensity, wind shear, and flow inclination angle, which are generated as effects of the complex terrain, can vary even on the same wind farm depending on the surrounding terrain, resulting in different power

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performances for the wind turbines. This is the main cause of the difference between the results of a feasibility study and the AEP measured at an actual wind farm.

In this study, the relative error between the power performance of a wind turbine measured at a wind farm on complex terrain and the AEP calculated from the guaranteed power performance curve was calculated and analyzed, and the validity of the current verification method for the guaranteed power performance commonly applied in South Korea was investigated.

2. Wind farm terrain evaluation

The IEC61400-1 [4] defines a complexity index and provides guidelines on a terrain complexity evaluation to compensate the turbulence structural correction parameter (C_{CT}). IEC61400-12-1 [5] presents the terrain requirements for the test bed where the power performance test is to be carried out. Furthermore, the MEASNET [6] guideline defines a complex terrain to present the data processing requirements based on the terrain characteristics during met-mast operation. The commercial software WAsP, which is commonly used in wind farm design, applies a RIX (ruggedness index) and an experimental compensation method [7] to compensate the biased prediction of AEP in a linear analysis of a complex terrain. As mentioned above, there are criteria that can be used to define the terrain complexity for various objectives. However, even though IEC-61400-12-1 is a standard that deals with the site requirements and compensation method for a test bed, it is difficult to directly apply it to an evaluation of the terrain complexity of a commercial wind farm. The MEASNET guideline is also difficult to apply because it only provides a simple definition of complex terrain without offering any technical analysis method for identifying it. Therefore, this study applied the IEC61400-1 requirements and the ruggedness index used in WAsP for terrain evaluation. The wind farm targeted for evaluation is located in Gangwon Province, a mountainous inland region of South Korea. Its entire topographic map and the location information and altitudes above sea level of the wind turbines selected for the power performance test are shown in Fig. 1.

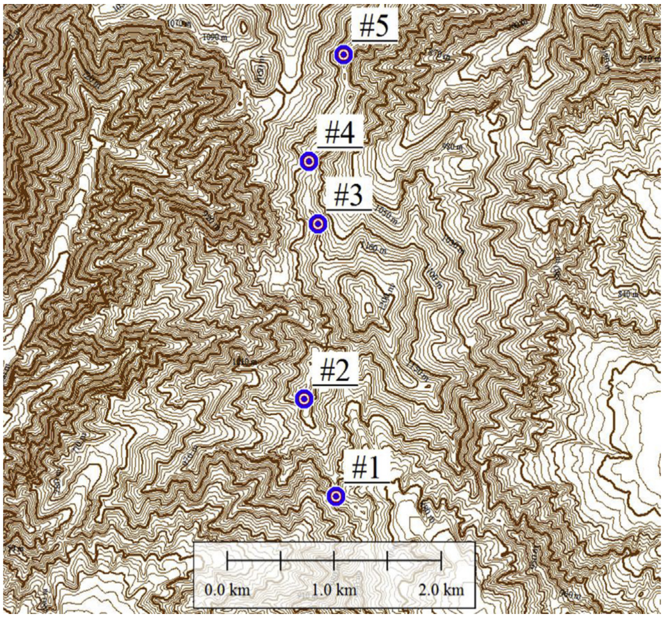

Fig. 1. The wind farm topographic map indicating the selected wind turbine locations.

Table 1
Terrain complexity indicators in accordance with IEC61400-1.

Distance range from wind turbine	Sector amplitude	Max slope of fitted plane	Maximum terrain variation
$<5\ Z_{hub}$	360°	<10°	$<0.3\ Z_{hub}$
$<10\ Z_{hub}$	30°		$<0.6\ Z_{hub}$
$<20\ Z_{hub}$	30°		$<1.2\ Z_{hub}$

2.1. Terrain evaluation according to IEC61400-1

Table 1 lists the terrain complexity evaluation criteria for a wind farm based on IEC61400-1. If the maximum slope of the terrain with respect to the wind turbine exceeds 10° in the specified analysis range, or the maximum terrain variation exceeds the criteria, the terrain is judged to not satisfy the requirements. The spacing of the contour lines on the digital map used in the terrain complexity evaluation cannot exceed 1.5 Z_{hub} or 100 m. For wind containing ≥15% of its wind energy in the prevailing wind direction, if the terrain in the same direction as the prevailing wind direction exceeds all the constraints, the corresponding region is classified as a fully complex terrain. With wind that has 5%–15% of its wind energy in the prevailing wind direction, the region is classified as a partially complex terrain, whereas when less than 5% of its wind energy is in the prevailing wind direction, the region is classified as a non-complex terrain.

In this study, to confirm the distributions of the prevailing wind direction and wind energy of the wind farm that was the target of the power performance verification, the AWS (Automatic Weather System) data for the corresponding area from KMA (Korea Meteorological Administration) were analyzed, and the long-term wind frequency and wind energy roses were obtained. The AWS data were measured at a location about 7 km in the SE direction from the evaluated wind farm for about 10 years from January 1, 2004, to March 21, 2014. The wind frequency and wind energy roses are shown in Fig. 2.

The prevailing wind direction was widely distributed from the W to the NW direction, with a wind distribution concentration of about 35%, and the wind energy distribution was concentrated in the W and SWW directions, each with a ≥25% wind energy distribution. Therefore, both the W and SWW directions were designated as prevailing wind directions. The topographic variation was assessed in the west direction (W, 270°) in the terrain complexity evaluation.

The digital maps (Korea TM, GRS80) [8] from the NGII (National Geographic Information Institute) use a 1:25,000 scale and show contour lines spaced at 10-m intervals, satisfying the minimum topographic resolution required by international standards.

The terrain variation results are shown in Fig. 3, and the terrain complexity results are provided in Table 2. The maximum slope at the locations of wind turbines #1 and #5 were less than the reference value, but the maximum terrain variation conditions at these locations all exceeded the reference value. At the locations of wind turbines #2, #3, and #4, the maximum terrain variations were less than the reference value, but the maximum slope all exceeded the reference value. Therefore, the values of maximum slope or variation at 5 Z_{hub}, 10 Z_{hub}, and 20 Z_{hub} of the selected wind turbines exceeded all the reference values, and the wind energy distribution in the prevailing wind direction was ≥25%, indicating that the region has a fully complex terrain.

2.2. Terrain evaluation based on RIX

The predicted AEP results for the wind farm on the complex terrain obtained from WAsP showed relatively large differences