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A Study on Method for Identifying Capacity Factor Declination of Wind Turbines

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***Abstract*—**The investigation on wind turbine degradation was carried out using the nacelle wind data. The three Vestas V80-2MW wind turbines of Sungsan wind farm in Jeju Island, South Korea were selected for this work. The SCADA data of the wind farm for five years were analyzed to draw power curve of the turbines. It is assumed that the wind distribution is the Rayleigh distribution to calculate the normalized capacity factor based on the drawn power curve of the three wind turbines for each year. The result showed that the reduction of power output from the three wind turbines occurred every year and the normalized capacity factor decreased to 0.12%/year on average.

***Keywords*—**Wind energy, Power curve, Capacity factor, Annual energy production.

I. Introduction

A wind turbine becomes less efficient with ages due to mechanical wear and tear and erosion. It was recently reported that the reduction ratio of power performance of wind turbines was 0.4-0.9%/year on average in the UK and Denmark [1]. It was also found that the capacity factor (CF) decreased annually up to 1% in Canada [2].

G. Hughes [1] reported that the power performance of wind farms in Europe was decreasing after analyzing the operational records over ten years. The life time of a wind turbine is required to be at least 20 years according to IEC 61400-1 [3] which proposes design requirements of wind turbine. Thus, the decreasing ratio of the capacity factor described above cannot be negligible for analyzing economic feasibility for a potential wind farm.

Albers et al. [4] reported that wind power performance verification using the nacelle wind speed would reduce by 1/3 of the cost for the verification using met mast wind speed. Smith et al. [5] found that there was the specific correlation between the nacelle and the met mast wind speed through a variety of experiments.

IEC 61400-12-2 [6] was published to provide a method to obtain the power curve of a wind turbine using the Nacelle Transfer Function (NTF) which is the correlation between the nacelle and the met mast wind speed data. In the previous study, wind turbine degradation in on-shore wind farm situated near the coast was clarified using the NTF obtained in accordance with IEC 61400-12-2 [7]. A met mast was needed to derive NTF in the previous study. However, it is costly and time consuming to install a met mast and to collect wind data from it.

Meanwhile, it is not easy to eliminate the inter-annual wind variation for analyzing wind turbine degradation fairly. Bach [8] studied on declining of wind turbine performance with the wind energy index.

The purpose of this study is to suggest the method for identifying wind turbine degradation regardless of inter-annual wind variation using nacelle wind data only. In addition, we clarified the degradation of wind turbines in Sungsan wind farm using the method proposed in this paper.

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II. Test Setup

Fig. 1 shows Jeju Island and Sungsan wind farm including the layout of wind turbines. The Sungsan wind farm is located on the eastern part of Jeju Island, South Korea. Jeju Island is surrounded by the sea. There are ten wind turbines in the wind farm. Number 1, 2, and 3 wind turbines were tested using the nacelle wind speed for five years for analyzing the wind turbine degradation.

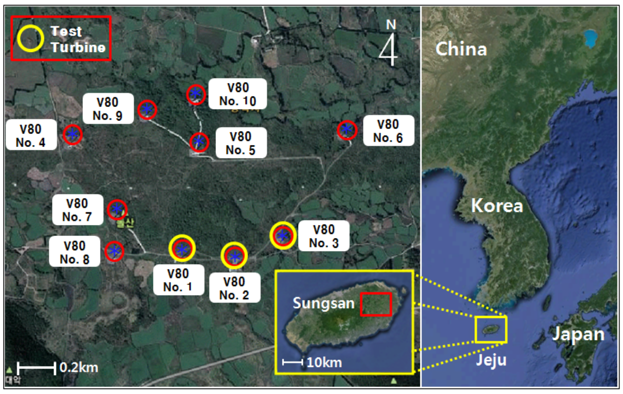

Fig. 1 Jeju Island and Sungsan wind farm including the layout of wind turbines

The prevailing wind direction of South Korea is from the northwest. As a result of analyzing ASOS (Automated Surface Observing System) data of a nearby observatory which is positioned at 7km away from the wind farm, the prevailing wind direction of Sungsan wind farm was similar to that of South Korea as shown in Fig. 2. The ASOS data were analyzed for the same measurement period for this work.

The wind turbines tested are Vestas V80-2MW wind turbines. The FT ultrasonic anemometer is mounted on the nacelle of each wind turbine. The nacelle wind data were collected from the Vestas SCADA system. The measurement period is for five years from April, 2009 to March, 2014. The test conditions, measurement equipment and specification of wind turbine are shown in Tables I and II.

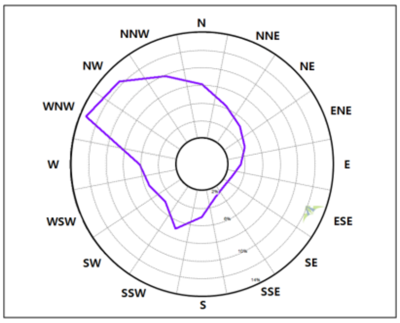

Fig. 2 Wind rose for five years at a nearby observatory

TABLE I
TEST CONDITION AND MEASUREMENT EQUIPMENT

Item	Description
Measurement period	April, 1. 2009 - March, 31. 2014
WTG under test	No.1, 2 and 3 Vestas V80
Nacelle wind speed & direction	FT ultrasonic (78m)
Electric power / Temperature	Vestas SCADA system
Pressure	ASOS data in Sungsan observatory

TABLE II
SPECIFICATION OF WIND TURBINE

Item	Description
WTG model	Vestas V80-2MW
Rotor diameter / Hub height	80m / 78m
Cut-in / Rated / Cut-out wind speed [m/s]	3.5 / 15 / 25
IEC class	IA
Control / RPM(rated)	Active pitch / 16.1rpm

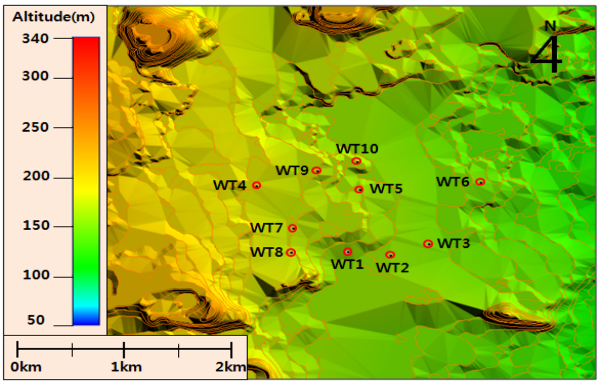

Fig. 3 Three-dimensional map of Sungsan wind farm

The Sungsan wind farm is located at mountainous areas where there are some obstacles affecting on wind flow. Fig. 3 shows the three-dimensional map of Sungsan wind farm. In this work, the wind data affected by the obstacles within 20 times the rotor diameter from the test turbines were removed for obtaining the more accurate power curve of the wind turbines tested according to IEC 61400-12-1 [9].

III. Analysis of Wind Turbine Degradation

Fig. 4 shows the capacity factor of the three turbines including annual average wind speed at 10m above ground level at a nearby observatory for five years. Inter-annual capacity factors followed the trend of inter-annual wind variation. To identifying wind turbine degradation, the wind variation should be eliminated and normalized. In other words, the analysis of wind turbine degradation cannot be fairly evaluated by the conventional CF. In this work, the analysis of wind turbine degradation was fairly done based on power curves for each year derived from the nacelle wind speed and the Rayleigh wind speed distribution.

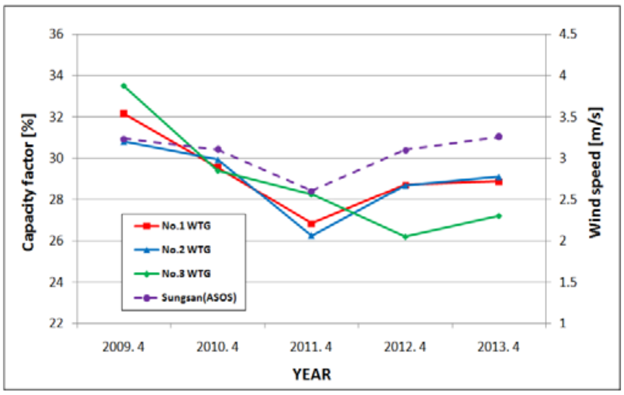

Fig. 4 The CFs of the three wind turbines in Sungsan wind farm and wind speed at a nearby observatory

A. Measurement Sector

The disturbed wind caused by nearby wind turbines was excluded in accordance with the IEC 61400-12-1. The measurement sector is derived from (1):

$$\alpha = 1.3\tan^{-1}(2.5D_n / L_n + 0.15) + 10 \tag{1}$$

where D_n is the rotor diameter of the neighboring wind turbine and L_n is the distance from the test turbine to the neighboring wind turbine.

The obstacles within 20D from test turbines were also calculated as the rotor diameter and excluded from (2):

$$D_e = \frac{2\,l_h\,l_w}{l_h + l_w} \tag{2}$$

where, D_e is the equivalent rotor diameter. l_h and l_w are height and width of the obstacle, respectively.

The measurement sectors of each turbine are shown in Fig. 5. The SCADA data within the measurement sector of the wind turbines were analyzed for obtaining the corresponding power curves.

B. Wind Speed Normalization

Because the air density varies with the location, the wind speed data were normalized to reference air density at sea level according to (3).

$$V_n = V_{10\min}\left(\frac{\rho_{10\min}}{\rho_0}\right)^{\frac{1}{3}} \quad (3)$$

where V_n is the normalized wind speed and V_{10min} is the measured wind speed averaged over 10-minute. ρ_{10min} is the air density averaged over 10-minute. ρ_0 is the reference air density of 1.225 km/m^3. In this work, the air density was derived from temperature measured at Sungsan wind farm and pressure at a nearby observatory.

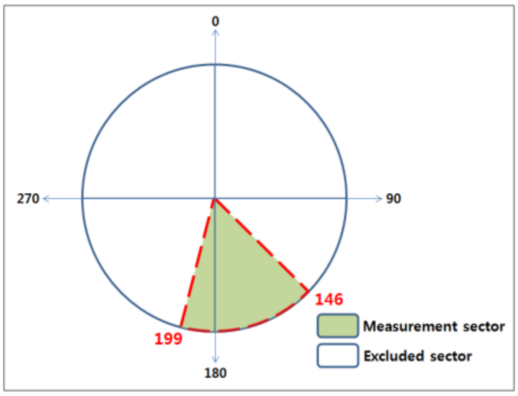

Fig. 5 (a) Measurement sector of No.1 WTG

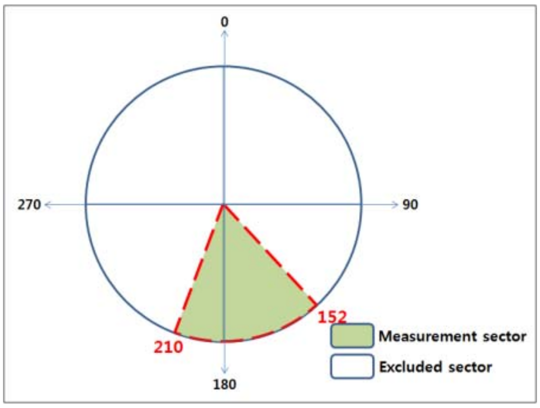

Fig. 5 (b) Measurement sector of No.2 WTG

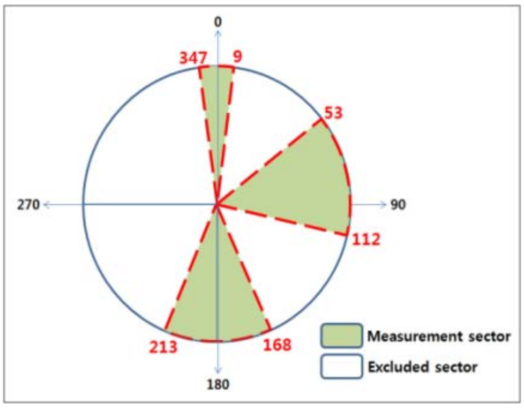

Fig. 5 (c) Measurement sector of No.3 WTG

C. Power Curve

The power curves of three turbines for each year are shown in Fig. 6. The range of power curves is from 3.5m/s to more than 16.5m/s. Each bin with 0.5m/s interval has more than three wind data (30-minute) which is required in IEC 61400-12-1.

The red-line is a power curve of a wind turbine provided by a turbine manufacturer. The derived power curves could not reach manufacturer's power curve because the nacelle anemometer measured the wind speed reduced by effects of blade rotation. The nacelle wind data should be corrected using the NTF to reduce the uncertainty.

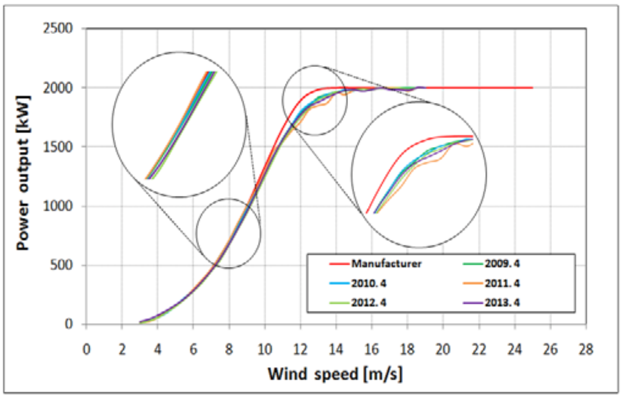

Fig. 6 (a) Power curve of No.1 WTG

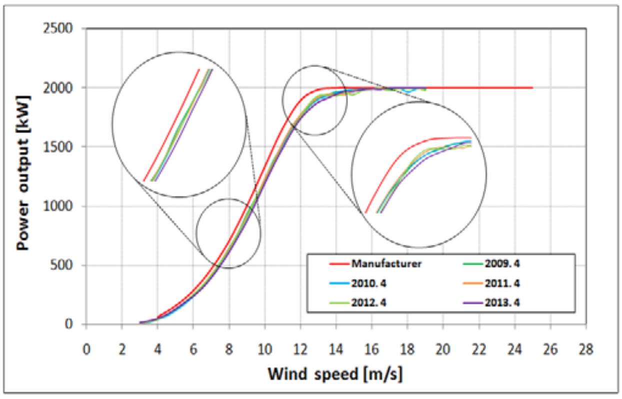

Fig. 6 (b) Power curve of No.2 WTG

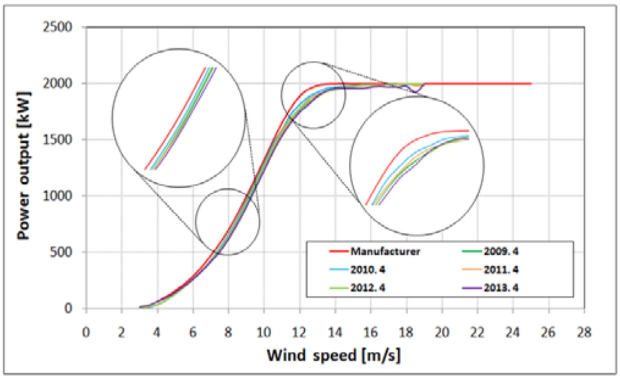

Fig. 6 (c) Power curve of No.3 WTG

However, a met mast should be installed for obtaining the NTF, which is costly and time consuming [10]. In this work, just the nacelle wind data were used for analyzing wind turbine degradation because the correlation between the nacelle and the met mast wind speed data was close to 1 [11]. As shown in Fig. 6, it is confirmed that the power curves were less and less as years went by.

D. Normalized Capacity Factor

To calculate the normalized CF based on the derived power curve of the three wind turbines for each year, it was assumed that wind speed distribution is the Rayleigh distribution with 7m/s of annual average wind speed at Sungsan wind farm. The cumulative probability distribution function of the Rayleigh distribution, F (V), is given as:

$$F(V) = 1 - \exp\left(-\frac{\pi}{4}\left(\frac{V_{10\min}}{V_{avg}}\right)\right)^2 \tag{4}$$

where V_{avg} is the annual average wind speed. Fig. 7 shows the Rayleigh distribution whose mean wind speed is 7m/s.

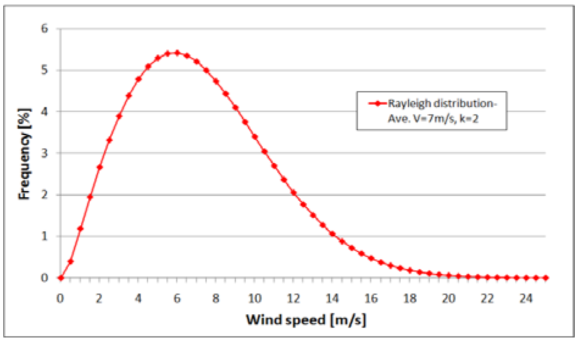

Fig. 7 Rayleigh distribution

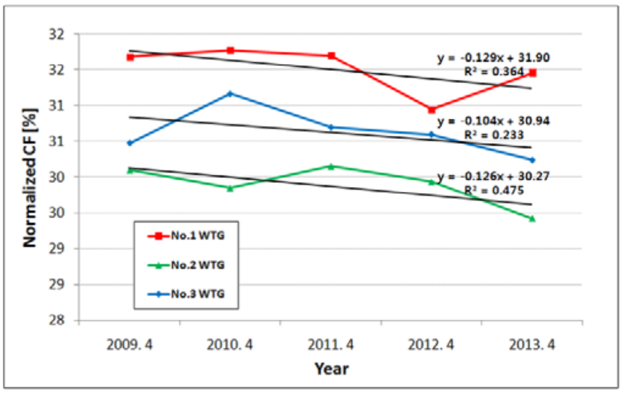

Fig. 8 Normalized CF of each wind turbine for five years

The annual energy production (AEP) and the CF are expressed as (5) and (6), respectively.

$$AEP = 8760\sum_{i=1}^{N}[F(V_i) - F(V_{i-1})]\left(\frac{P_{i-1} + P_i}{2}\right) \tag{5}$$

$$CF = \frac{AEP}{8760 \times Rated\ Power} \tag{6}$$

where N is the number of bins, and V_i and P_i are the averaged wind speed and power output in bin i, respectively. The wind data with the Rayleigh distribution in Fig. 7 were applied to (5) for obtaining the normalized CF.

Fig. 8 shows the normalized CFs of each wind turbine for five years. Linear regression method was applied to the CFs to estimate the average slope of each year's CF. The normalized CFs decreased with year and the reduction ratio of the three turbines was about 0.12%/year on average.

IV. Conclusions

An analysis of wind turbine degradation using the nacelle wind speed data was done on Jeju. The wind data except the disturbed wind was used to eliminate the wake effect behind obstacles and wind turbines. Also the power curves of three turbines for each year were drawn using only the nacelle wind data within measurement sector because the correlation between the nacelle and the met mast is normally close to 1. The AEP and the normalized CF were calculated under the assumption that the wind speed distribution at the site is Rayleigh distribution having wind speed of 7m/s.

It was confirmed that the power performance decreased with year and the reduction ratio of normalized CFs of the three wind turbines was 0.12%/year on average. The suggested method for identifying wind turbine degradation may be useful for wind farm operators and economic analysts because it is not necessary to install and monitor a met mast.

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