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Wind Turbine Power Performance Testing using Nacelle Transfer Function

나셀 변환 함수를 이용한 풍력터빈 출력성능평가

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Abstract : A study on power performance testing of a wind turbine which has no met-mast at a distance of 2~4 rotor diameter was carried out using the Nacelle Transfer Function, NTF, according to IEC 61400-12-2. The wind data for this study was measured at HanKyoung wind farm of Jeju Island. The NTF was modeled using the correlation between wind speeds from the met-mast and from the wind turbine nacelle within 2~4 rotor diameter from the met-mast. The NTF was verified by the comparison of estimated Annual Energy Productions, AEPs, and binned power curves. The Nacelle Power Curve, NPC, was derived from the nacelle wind speed data corrected by NTF. The NPC of wind turbine under test and the power curve offered by the turbine manufacturer were compared to check whether the wind turbine is properly generating electricity. Overall the NPC was in good agreement with the manufacturer's power curve. The result showed power performance testing for a wind turbine which has no met-mast at a distance of 2~4 rotor diameter was successfully carried out in compliance with IEC 61400-12-2.

Key Words : Wind energy(풍력에너지), Power performance testing(출력성능평가), Nacelle transfer function(나셀 변환함수), Nacelle power curve(나셀 출력곡선)

Nomenclature

AEP : Annual energy production
NTF : Nacelle transfer function
NPC : Nacelle power curve
WTG : Wind turbine generator
WS : Wind speed (m/s)
WD : Wind direction (°)

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AGL : Above ground level (m)
RIX : Ruggedness index
PC : Power curve
L : Distance from wind turbine to met-mast (m)
C_p : Power coefficient
$V_{nacelle,i}$: Average of the nacelle wind speed in bin i (m/s)
$V_{free,i}$: Average of the met-mast wind speed in bin i (m/s)
V_{free} : Free wind speed estimated using measured nacelle and met-mast wind speed data (m/s)
V_n : Normalized wind speed (m/s)
ρ_{10min} : Measured air density(kg/㎥)
ρ_0 : The reference air density of 1.225kg/㎥

1. Introduction

The existing method of power performance testing according to IEC 61400-12-1[1] is costly and time consuming because met-mast should be located at a distance of between 2~4 rotor diameter from a wind turbine under test. It is not possible to obtain a reliable power curve of a wind turbine located at a distance of more than 4 rotor diameter from met-mast since the correlation between wind speed and electric power output will be low. For that reason, many studies on power performance verification by nacelle wind speed have been carried out.

Albers et al.[2] reported that wind power performance verification using nacelle wind speed will reduce the cost to a third of that using met-mast wind speed. The study on relationship between wind speed derived from the measured electric power and wind speed measured from nacelle anemometer to verify wind direction under wake was conducted by Albers et al.[3] Smith et al.[4] found that there was specific correlation between nacelle and met-mast wind speed through various experiments.

IEC 61400-12-2[5] was published recently to provide a methodology to obtain power curves of wind turbines without met-mast based on nacelle wind speed. The purpose of this study is to carry out power performance testing of a wind turbine which is more than 4 rotor diameter away from a met-mast in accordance with the procedure regulated by IEC 61400-12-2. The uncertainty was not evaluated in this study, and that is our next research subject.

2. Test setup

The test site, test conditions, specification of wind turbine generator, WTG, and measurement equipment are shown in Fig. 1, Table 1, Table 2, and Table 3. The studies by Kim et al.[6] and Her et al.[7] on power performance testing in compliance with IEC 61400-12-1 were conducted in this test site.

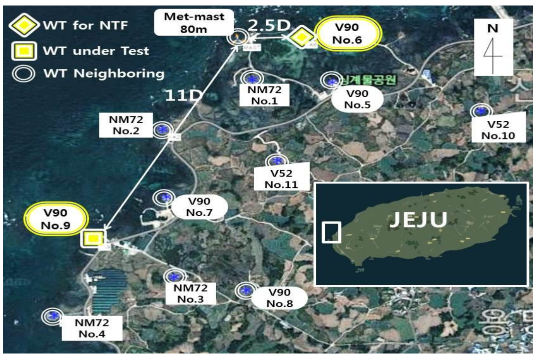

Fig. 1 Test site

Table 1 Test conditions

Item	Description
Measurement period	2009.09.17. ~ 2010.02.17.
Measurement location	HanKyung Wind Farm, Jeju city, Rep. of Korea
WTG for NTF	V90 No.6, 2.5D from met-mast
WTG under test	V90 No.9, 11D from met-mast

Table 2 Specification of WTG under test

Item	Description
WTG model	Vestas 90 3MW
Diameter / Hub height	90m / 80m
Cut-in / Rated /Cut-out Wind speed [m/s]	3.5 / 15 / 25
Control / RPM(rated)	Active pitch / 16.1rpm

Table 3 Measurement equipment

Parameter	Sensor type	Height AGL
Mast WS	Cup anemometer	80m
Mast WD	Potentiometer	80m
Pressure	Vaisala PTB100A	1m
Temperature	Thies 2.1280.00.141	77m
Nacelle WS	FT ultrasonic	80m
Nacelle WD	FT ultrasonic, Revised by the specific offset	80m
Electric power	Vestas SCADA, Verified by comparing transducer end signals	

* Data acquisition sampling rate : 1Hz
Data set store period : 10 minute

3. Nacelle transfer function

The nacelle wind speed data is not suitable for power performance testing because nacelle wind flow is disturbed due to rotation of the wind turbine rotor. For that reason a NTF assesses the effect of the wind turbine rotor on nacelle wind speed and predicts what free wind speed would be at the upwind.

For NTF derivation, the hub-height free wind speed measured by anemometer on the met-mast and the nacelle wind speed of No.6 WTG that is located at 2.5 rotor diameter from met-mast were used in this investigation.

3.1 Measurement sector for NTF

From both of the met-mast and the No.6 WTG, the directions having significant obstacles and neighboring WTGs were excluded from NTF measurement sector according to IEC 61400-12-1. As a result, for No.6 WTG the wind speed data coming from directions from 252° to 46° were available for NTF establishment.

3.2 Terrain evaluation

The test site should be assessed to check the effect of wind flow distortion due to topographical variation. One should identify whether the site is complex and power output of WTG is available without a site calibration for accurate power performance testing.

Fig. 2 shows circular area for terrain evaluation, where L is a distance from WTG to met-mast. The circle was divided into the measurement sector and the excluded sector for measurement.

The terrain evaluation was carried out in compliance with the regulations of IEC 61400-12-1. The result is shown in Table 4. Evaluated maximum slopes and maximum terrain variations were lower than the criteria. Accordingly, no site calibration was needed.

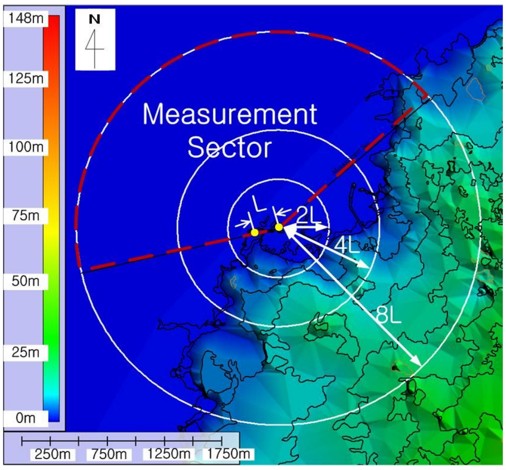

Fig. 2 Area for terrain evaluation

Table 4 Terrain evaluation

Distance	Sector	Maximum slope[%]	Max. terrain variation[m]
<2L	360°	0.63<3 *	4.40 <0.04(H+D) *
≥2L&<4L	Measurement sector	0.00<5 *	0 <0.08(H+D) *
≥2L&<4L	Outside Measurement sector	1.74<10 *	Not application
≥4L&<8L	Measurement sector	0.46<10 *	7.39 <0.13(H+D) *

* Criteria in accordance with IEC 61400-12-1
H : Hub height=80m, D : Rotor diameter=90m

3.3 Correlation of nacelle and met-mast wind speed

Simultaneously measured wind speed data from the met-mast and the nacelle of No.6 WTG were plotted in Fig. 3. The met-mast wind speed data were binned against the nacelle wind speed data according to the method of bins with 0.5 m/s interval. Then each linear interpolation between bins was made using the following formula :

$$V_{free} = (V_{free,i+1} - V_{free,i})/(V_{nacelle,i+1} - V_{nacelle,i}) \times (V_{nacelle} - V_{nacelle,i}) + V_{free,i}$$

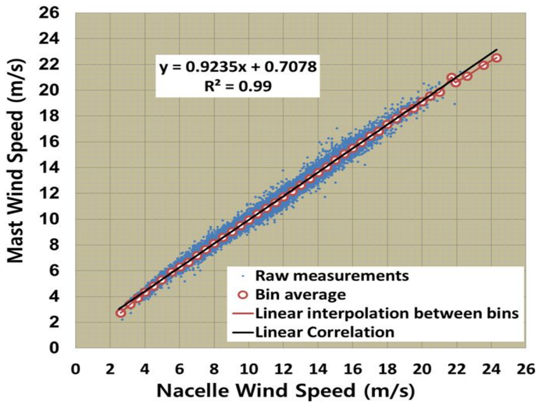

Fig. 3 Correlation of met-mast and nacelle wind speed

The fitted linear correlation, as shown in Fig. 3, can be used for free wind speed estimation. Energy research Center of the Netherlands, ECN, conducted the study on wind farm efficiency using the method of fitted linear correlation.[8] In this study, to obtain a more accurate result, all of nacelle wind speed data were corrected by each linear equation between neighboring bins derived by NTF for obtaining free wind speed.

3.4 Verification of NTF

The met-mast wind speed and nacelle wind speed corrected by NTF should be compared as form of binned power curve as well as AEP to verify NTF. The power curve derived from nacelle wind speed corrected by NTF is named as Nacelle Power Curve, NPC.

According to IEC 61400-12-2, the maximum difference in power per bin should be less than 1% of bin's power or 0.5% of rated power. Table 5 shows the power differences of bins. All the differences were less than the criterion of 15kW, which is 0.5% of the rated power.

The AEPs were calculated using power curves with Rayleigh distribution supposing availability of 100%. The maximum difference in AEP should be less than 1% for annual average wind speed 4 m/s to 11 m/s at hub height. Table 6 shows the AEP differences. The differences in AEPs were less than the criteria.

Accordingly, the NTF was verified by Tables 5 and 6. Thus the NTF is applicable to other nacelle wind data to estimate free wind speed.

Table 5 Power differences of bins

Bin no.	No.6 WTG + mast WS [kW]	No.6 WTG + nacelle WS [kW]	Difference [kW]	Criterion [kW]
8	58	58	0	15
9	108	112	4	15
10	171	175	4	15
11	251	254	4	15
12	363	359	4	15
13	454	452	2	15
14	566	560	4	15
15	692	688	4	15
16	821	814	7	15
17	1011	996	15	15
18	1235	1225	10	15
19	1465	1459	6	15
20	1697	1701	4	15
21	1922	1929	8	15
22	2141	2148	7	15
23	2356	2362	6	15
24	2551	2551	0	15
25	2704	2713	9	15
26	2819	2826	7	15
27	2903	2905	2	15
28	2944	2950	6	15
29	2972	2977	5	15
30	2986	2988	2	15

Table 6 AEP differences

Annual avg. WS [m/s]	AEP_ Mast PC [MWh]	AEP_ NTF PC [MWh]	Difference [MWh]	Criteria [MWh]
4	1572	1567	5	16
5	3187	3179	8	32
6	5225	5215	10	52
7	7402	7394	8	74
8	9440	9435	5	94
9	11130	11127	3	111
10	12371	12370	1	124
11	13156	13158	2	132

4. Nacelle power curve

The NTF was applied to the nacelle wind data of No.9 WTG under test. It is located at 11 times the rotor diameter from the met-mast.

4.1 Measurement sector for NPC

The disturbed wind direction sector from No.9 WTG was excluded according to the IEC 61400-12-1. Fig. 4 shows the measurement sector and excluded sector for power performance testing of No.9 WTG.

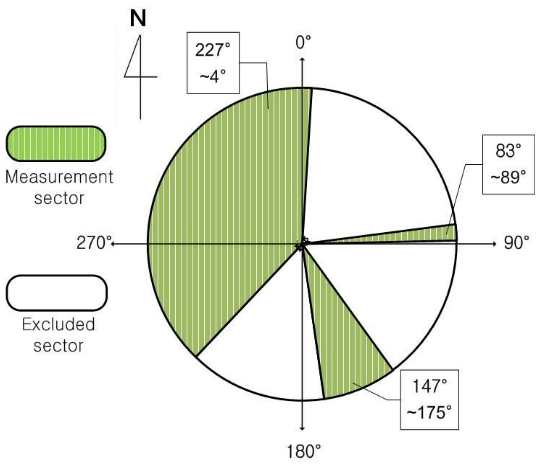

Fig. 4 Measurement sector for No.9 WTG

There should be no wind distortion in the measurement sector. Even in the excluded sector, a NTF can be valid, or in measurement sector, a NTF cannot be valid. Thus, it is necessary to check if there is wind distortion in the measurement sector through self-consistency check.

Fig. 5 shows self-consistency check of No.9 WTG. The rectangular parts are excluded sectors. V_p is wind speed derived from power output in combination with NPC. V_{free} is wind speed calculated by nacelle wind speed in combination with NTF. Ideally, V_p should be identical to V_{free}, if there is no wind distortion.

Within the excluded sector, there were high ratios of V_p to V_{free} at directions having the neighboring wind turbines. In the measurement sector, the ratios were within allowable limit, which is between 0.97 and 1.03. Accordingly, it was verified that the wind data in the measurement sector was available for NPC of No.9 WTG.

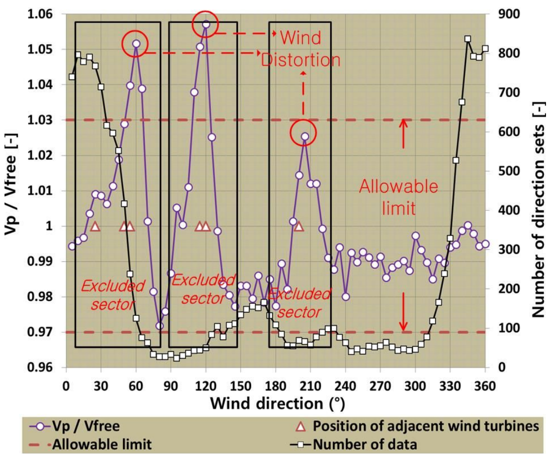

Fig. 5 Self-consistency check for No.9 WTG

4.2 Terrain classification for NTF

To apply the NTF, the terrain on which NTF was established should be similar to the terrain where the NTF would be applied. According to IEC 61400-12-2, assessment of ruggedness index, RIX, and terrain slope for the two local terrains should be made, and the difference between the two final terrain classes should be ± 1 for application of the NTF.

Since No.6 WTG and No.9 WTG are situated on the coast close to the sea, the two local terrains are very flat. The terrain classification led that the two local final terrain classes were 1. Thus, local terrains do not influence the NTF and the NPC so that the NTF can apply to the wind speed data from the nacelle of the No.9 WTG under test.

4.3 Power performance database

In order to represent the power curves more accurately, the wind speed data was normalized to reference air density at sea level according to the following formula :

$$V_n = V_{free} \times (\frac{\rho_{10\min}}{\rho_0})^{1/3}$$

Fig. 6 shows scatter plots of the average, the maximum, the minimum, and the standard deviation of measured power outputs of No.9 WTG. The wind speed ranges from 4 m/s to 21.5 m/s. Each bin with 0.5 m/s interval has more than three data, which is minimum requirements for reliable power curve according to IEC 61400-12-1. There are no significant signal noise or data influenced by mounting structure.

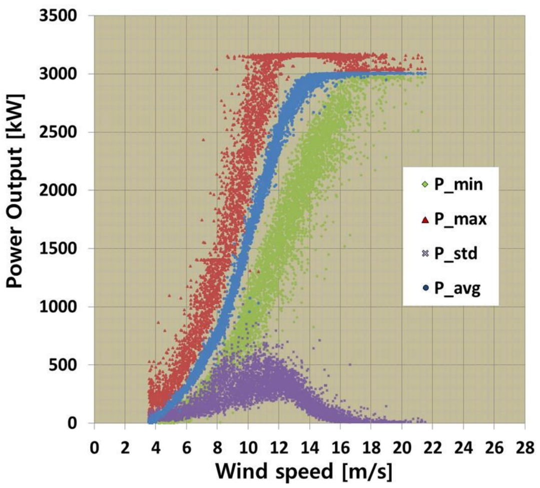

Fig. 6 Power performance scatter plots of No.9 WTG

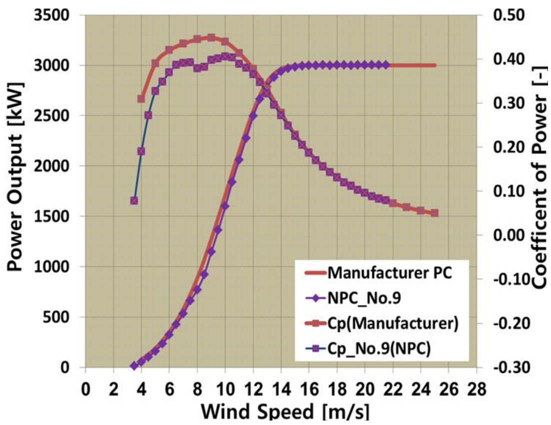

Fig. 7 NPC of No.9 WTG and power curve of the manufacturer

4.4 NPC of WTG under test

Fig. 7 shows the NPC and the power coefficient, C_p, of No.9 WTG, compared to the manufacturer's. Overall power outputs of bins were well matched with those offered by the manufacturer. The power outputs and C_p at wind speed lower than rated wind speed of 15m/s were slightly lower than those of the manufacturer's. At wind speed higher than the rated wind speed, the power output and C_p of both No.9 WTG and manufacturer's are almost the same.

5. Conclusions

(1) The power performance testing was successfully conducted using the NTF in compliance with the procedure provided by IEC 61400-12-2.

(2) The reasonable NTF was derived from the nacelle and the met-mast wind speed. It was verified by analysing the differences of the power of bins and the AEP.

(3) Overall the NPC of wind turbine under test was matched well with the power curve provided by the manufacturer.

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