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Maximum wind loads on a wind turbine under operating conditions

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Introduction

With the rapid increase of wind energy in Japan, troubles of the wind turbines have been reported. The prime cause of such troubles was that the wind conditions at site didn't satisfy those used in the design of wind turbines. In IEC61400-1 (International Electrotechnical Commission), the design of wind turbines is based on the standardized class, which specified the 50 years return period wind speed, annual mean wind speed and turbulence intensity. Often in Japan, site specific conditions are different from those specified in IEC class. For example, the annual mean wind speed is low and the turbulence intensity is high. For this reason, the assessment of structural integrity by load calculations with reference to site specific conditions is required in IEC. However, the formula to calculate the wind load is not proposed because the wind loads are affected by the pitch control under operating condition.

In this study, the mechanism of wind load characteristics under operating conditions are investigated using the time history analysis of 2 MW wind turbine model based on the finite element method. Then, simplified formulas for the estimation of the expected maximum base moment are proposed and verified by the field test of the commercial 1.5 MW wind turbine. Finally, extrapolation coefficients are proposed to estimate the extreme wind load with 50 years return period for different annual mean wind speeds and turbulence intensities.

1. Wind turbine model

In this study, a typical onshore wind turbine with the rated power of 2MW is considered and the characteristics of this wind turbine are shown in the below table. The wind model and the turbulence model in IEC are used. The wind load on the wind turbine depends on the pitch and torque control shown in the following equations. The time series of wind loads under operating conditions are simulated by the software GH Bladed.

Wind model

- IEC normal wind profile model
- IEC normal turbulence model

$$I_1 = I_{ref}\left(0.75 + 5.6/V_h\right)$$

I_1 : turbulence intensity
V_h : mean wind speed at hub height
I_{ref} : expected value of the turbulence intensity when V_h is 15m/s

Characteristics of wind turbine

Rated power	2 (MW)
Hub height	76.5 (m)
Type	Upwind
Rotor diameter	80 (m)
Control	Variable speed Variable pitch angle
Rotating speed	10~18 (rpm)
Range of operation	4~25 (m/s)
Rated wind speed	12 (m/s)
Gross Weight	249.4 (ton)

Turbulence model

- IEC Kaimal spectrum model
- IEC exponential coherence model

Aerodynamics model

- Blade element momentum theory

Control model

- PI control

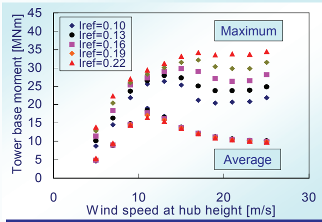
$$\Delta Q_{Dem} = 380y + 80.85y_I$$

$$\Delta\theta_{Dem} = \kappa\left(0.1152y + 0.05486y_I\right)$$

y : deviation of generator speed
y_I : residual of generator speed
ΔQ_{Dem} : demand of torque
$\Delta\theta_{Dem}$: demand of pitch angle

2. Characteristics of wind load under operating conditions

To examine the wind load characteristics, the wind loads are calculated for 11 different mean wind speeds, from 5 m/s to 25 m/s with 2 m/s interval, and 3 different turbulence intensities.

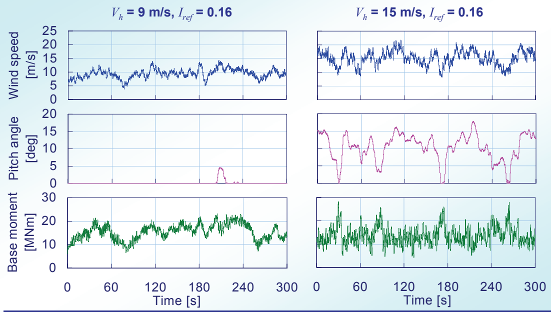


Tower base moment

- Below the rated wind speed (<12m/s), the maximum base moment increases as the average base moment increases.
- Above the rated wind speed, the average base moment decreases. The maximum base moment decreases at low turbulence intensity, but it increases at high turbulence intensity.

Characteristics of wind load

- When the mean wind speed is 9 m/s, i.e., below the rated wind speed, the change of base moment follows the change of wind speed as shown in the left figure.
- When the mean wind speed is 15 m/s, the maximum base moment increases as the wind speed decreases as shown in the right figure. This increase of the maximum base moment is excited by the pitch control.



3. Wind load evaluation

To evaluate the wind load on turbines installed in the complex terrain, the simplified formula is required. In this study, the formulas for estimating the maximum wind load are proposed.

The maximum tower base moment (M_{Dmax}) under operating conditions is expressed by assuming the equivalent static method.

$$M_{D\max} = M_D \times G_D$$

Average base moment (M_D) can be calculated by the thrust coefficient, and Gust factor (G_D) is expressed as follows,

$$G_D = \frac{M_{D\max}}{M_D} = \frac{M_D + g_D\sigma_{MD}}{M_D} \approx 1 + 2I_1 g_D\sqrt{K}\sqrt{1+R_D}$$

where K is size reduction factor and g_D is peak factor. R_D is ratio represented by

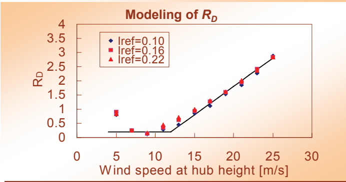
$$R_D = \sigma_{MDR}^2/\sigma_{MDQ}^2$$

where σ_{MDR}^2 is resonance response variance and σ_{MDQ}^2 is back ground response variance.

Empirical formulas of K, g_D, and R_D were proposed by using simulation data for each of below and above the rated wind speed.

The maximum base moment derived by using the proposed formulas showed good agreement with the measured data acquired from 1.5 MW GE wind turbine at Suzu wind farm in Japan.

Modeling of R_D

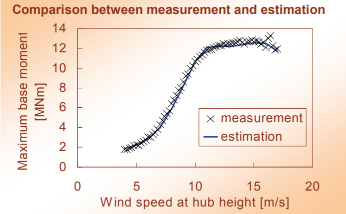


Simplified formulas under operating conditions

	Below rated wind speed	Above rated wind speed
K	$0.15\sin\left(\pi\frac{V_h - V_r}{V_{in} - V_r}\right) + 0.15$	$0.45\frac{V_h - V_r}{V_{out} - V_r} + 0.15$
g_D	$-0.3\sin\left(\pi\frac{V_h - V_r}{V_{out} - V_r}\right) + 3.0$	$\sin\left(\frac{7\pi}{8}\left(\frac{V_h - V_r}{V_{out} - V_r}\right)\right) + 3.0$
R_D	0.2	$2.6\frac{V_h - V_r}{V_{out} - V_r} + 0.2$

V_r : the rated wind speed
V_{in} : the cut-in wind speed V_{out} : the cut-out wind speed

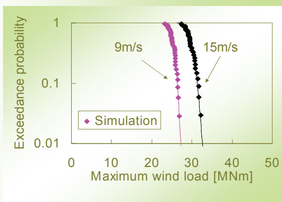
Comparison between measurement and estimation



4. Extrapolation coefficient

In IEC, the evaluation of extreme wind load is required by calculating wind load with a 50 years return period (M_{D50}) based on expected maximum wind load (M_{Dmax}) and extrapolation coefficient (r_e).

$$M_{D50} = M_{D\max} \times r_e$$



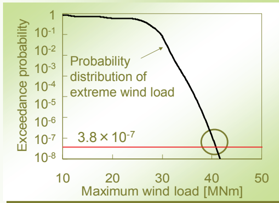
The probability distribution of extreme value s for each bin wind speed is assumed to follow the three parameter Weibull distribution.

$$F_{ext}\left(s\middle|V;T\right) = \exp\left\{-\left(\frac{s-u}{a}\right)^k\right\}$$

When the observation period is T, the probability of exceeding s on extreme value is described by

$$F_{ext}\left(s;T\right) = \int_{V_{in}}^{V_{out}} F_{ext}\left(s\middle|V;T\right)f\left(V\right)dV$$

V_a : 10m/s
I_{ref} : 0.16



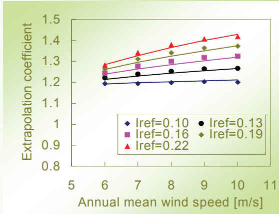
where $f(V)$ is assumed to follow Weibull distribution. Extreme wind load with a 50 years return period (M_{D50}) is the intersection of the probability distribution of extreme wind load (black line) and the exceedance probability with a 50 years return period (red line).

A formula of extrapolation coefficient (r_e) was proposed by simulation data. It can be described only by environmental parameters; annual mean wind speed (V_a), expected value of turbulence intensity (I_{ref}), and shape parameter of Weibull distribution (k).

$$r_e = A\ln\left(V_a\right) + K_e$$

$$A = \left(0.25k - 2.9\right)I_{ref} - 0.2k + 0.24$$

$$K_e = \left(-5.85k + 8.9\right)I_{ref} + 0.5k + 0.4$$



Conclusions

In this study, it was realized to estimate maximum wind loads on wind turbines under operating conditions.

(1) It was clarified that the maximum base moment is excited by the fluctuation of the wind speed below the rated wind speed and by the pitch control of the wind turbine blade above the rated wind speed.

(2) Simplified formulas for the maximum base moment under operating conditions were proposed, which cover different wind speeds and turbulence intensities.

(3) A formula to derive the extrapolation coefficient to estimate the extreme wind load with a 50 years return period was proposed. It was described only by wind environmental parameters; therefore, this formula can be applied to wind turbines in any places under any environmental conditions.

References

1) New Energy and Industrial Technology Development Organization, 2005. The wind turbine availability improvement committee and accident investigation committee in 2005.

2) International Electrotechnical Commission, 2005. IEC 61400-1 Wind turbines – Part 1: Design requirements Ed. 3, 55-60.

3) L.V.Binh. et al, 2008. A Peal Factor for non-Gaussian Response Analysis of Wind Turbine Tower, Journal of Wind Engineering and Industrial Aerodynamics Vol. 96, 2217-2227.

4) Maruyama, Y. et al, 2009. Field Measurement for Wind Resistant Design of Wind Turbine Located in Mountainous Area, Wind Engineers Vol.34 No.2, 255-258.

5) P.J.Moriarty. et al, 2004. Extrapolation of Extreme and Fatigue Loads Using Probabilistic Methods, NREL-NWTC, Golden, CO.