Wind Load Evaluation of Wind Turbine Tower Design

Enjun Wu¹, Hongjun Chen¹, Wenfeng Qu¹, Chong Huo¹, Zhengzhao Liang¹, Xiangzhao Huang², Zhenrong Li¹, Hang Li¹, Bin He¹, Tao Yang² and Zhongming Shen²

1. State Power Investment Group Xuwen Wind Power Co., Ltd., Zhanjiang 524000, Guangdong Province, China; 2. School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, Hubei Province
Email: iccareshen@163.com

Abstract. According to the current main wind turbine design specifications, the necessary parameters for wind load assessment of wind turbine tower are discussed. According to IEC61400-1 (IEC2019) and Japan's Guidelines for Design of Wind Turbine Support Structures and Foundations (JG2010), the wind load assessment of the tower structure of a 2MW horizontal axis generator is carried out, and the calculation results are compared. It can be seen from the comparison that the design value from the evaluation formula of JG2010 and the design value from the load condition of IEC2019 by using GH bladed simulation matches well. The main reason is that the evaluation formula of JG2010 itself is derived according to the response spectrum method. So, JG2010 is a good reference for the design of domestic wind turbines and the formulation of relevant specifications.

1. Introduction
As of the end of 2018, China's installed wind power capacity has accounted for 35.4% of the world's total capacity [1]. With the large-scale development of wind power, its reliability has gradually been paid attention by experts and scholars at home and abroad [2-3]. Due to the severe impact of the typhoon, there have been several accidents in recent years that caused the destruction of wind power towers by strong winds [4-12]. Onshore wind power towers are generally less redundant and may collapse once local buckling occurs [13-15], and wind power towers in the same wind field are generally similar in design. Once the response exceeds its damage threshold under extreme action, all wind power towers are Face the risk of destruction. Therefore, a comparative study on the wind load assessment specifications of wind power towers has certain guiding significance for the design.

At present, the domestic wind load assessment of wind turbines is mainly based on the following specifications and guidelines:

1) For the representative international standard IEC61400-1 [16] related to the strength design of wind power generation equipment, the fourth edition was released in 2019, referred to as IEC2019.

2) GL Wind Power Guide (2010) [17], widely used in design points of wind power generation equipment. GL Wind was originally developed by the German civil society German Classification Society (Germanischer Lloyd) in 1993. At present, in addition to the compilation and publication of the guidelines, it has become the most authoritative organization in the world for conducting experiments and certification of various wind power generation equipment. This article is abbreviated as GL2010.

3) "Guide and Explanation of Wind Turbine Equipment Tower Structure Design" (2010 edition) [18] compiled by JAPAN SOCIETY OF CIVIL ENGINEERS, referred to as JG2010.
4) Some domestic basic building design codes, such as "Building Structure Load Code", "High-rise Structure Design Code", etc.

This article will discuss some basic parameters of wind load evaluation, and use the above criteria to calculate and evaluate the wind load of the horizontal axis wind turbine tower, and discuss the differences in the calculation results of different methods and the reasons.

2. Basic Parameters

In order to obtain the maximum wind load for the ultimate wind speed (storm) required by the wind turbine tower structure design and the wind load and fatigue load during power generation, it is necessary to determine the design wind speed, wind speed distribution, turbulence intensity and statistical data.

2.1. Design Wind Speed

The design wind speed of a wind turbine refers to a 10-minute average wind speed with a 50-year recurrence period at the hub height.

IEC2019 and GL2010 adopt the method of defining the wind turbine grade. The wind turbine grade is defined according to the wind speed and turbulence parameters. It does not provide any accurate representation of any specific site. It is the general reproduction of wind speed and turbulence parameters at different sites. It aims to cover most applications and achieve the goal of full utilization. The basic parameter table of its wind turbine class is shown in Table 1 and Table 2.

Table 1. Basic parameters of IEC2019 fan grade

| fan grade | I  | II  | III | S  |
|-----------|----|-----|-----|----|
| $V_{e50}$ (m/s) | 70 | 59.5| 52.5|    |
| $V_{e50,T}$ (m/s) |    | 79.8|     |    |
| $V_{ref}$ (m/s) | 50 | 42.5| 37.5|    |
| $V_{ref,T}$ (m/s) |    | 57  |     |    |
| $V_{ave}$ (m/s) | 10 | 8.5 | 7.5 |    |
| A+ | $l_{ref}$ | 0.18 |
| A | $l_{ref}$ | 0.16 |
| B | $l_{ref}$ | 0.14 |
| C | $l_{ref}$ | 0.12 |

Table 2. Basic parameters of GL2010 fan grade

| fan grade | I  | II  | III | S  |
|-----------|----|-----|-----|----|
| $V_{e50}$ (m/s) | 70 | 59.5| 52.5|    |
| $V_{ref}$ (m/s) | 50 | 42.5| 37.5|    |
| $V_{ave}$ (m/s) | 10 | 8.5 | 7.5 |    |
| A | $l_{15}$ | 0.18 |
| a |       | 2   |
| B | $l_{15}$ | 0.16 |
| a |       | 3   |

The parameter values in the table apply to the hub height.

$V_{e50}$: Extreme wind speed with 50-year recurrence period
$V_{e50,T}$: Extreme wind speed with 50-year recurrence period in areas affected by tropical cyclones
$V_{ref}$: 10 minutes average standard wind speed
$V_{ref,T}$: 10-minute average standard wind speed in areas affected by tropical cyclones
$V_{ave}$: Annual average wind speed
$l_{ref}, l_{15}$: Expected value of turbulence intensity at wind speed of 15m / s
a: Slope parameter
For normal wind conditions, IEC2019 and GL2010 assume that the average wind speed at height $z$ is given by a power function:

\[ V(z) = V_{hub}(z/z_{hub})^\alpha \]  

(1)

Where $z_{hub}$ is the height of the hub [m], assuming that the power index $\alpha$ is equal to 0.2.

The design wind speed $V(z)$ at the hub height in JG2010 can be determined by multiplying the reference wind speed $V_0$ by the average wind speed increase and decrease coefficient $E_{tv}$ and height correction coefficient $E_{pv}$ considering the influence of terrain, as shown in equation (2).

\[ v(z) = E_{tv}E_{pv}V_0 \]  

(2)

The reference wind speed $V0$ is a 10-minute average wind speed with a recurrence period of 50 years at a height of 10 m from the roughness class II ground.

For units designed in accordance with IEC2019 and GL2010 standard fan ratings, the design should ensure that they can resist the environmental conditions at the hub height and the 10-minute average wind speed with a recurrence period of 50 years equal to or less than $V_{ref}$. JG2010 is related to the terrain of the site and the specific roughness category of the terrain. At the same time, GL2010 stipulates that the complexity of the terrain can be determined by the deviation from the terrain. When the terrain is determined to be a complex terrain, the influence of the terrain must be considered. You can refer to formula (2) to evaluate the design wind speed of the domestic wind turbine construction site.

![Figure 1. Comparison of height correction coefficients](image)

Figure 1 is a comparison chart of the height correction coefficients of JG2010 and GB50009 in Class A and Class B ground roughness. The height correction coefficients of Class B ground roughness are basically the same. The calculated value of Class A JG2010 is larger, mainly because the meteorological conditions and terrain conditions in Japan are more special. Due to typhoons and complex terrain, the design wind speed is often greater than other standards.

The average wind speed correction factor is preferentially determined by a similar method of JG2010 through actual measurement and numerical analysis results, or according to the relevant provisions of Section 8.2.2 of GB50009.

2.2. Wind Speed Distribution

For the design of standard-grade wind turbines, IEC2019 and GL2010 adopt the Rayleigh distribution shown in equation (3) for the distribution of wind speed.

\[ P_R(V_{hub}) = 1 - \exp[-\pi(V_{hub}/2V_{ave})^2] \]  

(3)

Here, $V_{hub}$ is the 10-minute average wind speed at the height of the hub, and $V_{ave}$ is the annual average wind speed at the height of the hub. As shown in table 1, the Weibull distribution is adopted for JG2010, while the Reilly distribution is a model with only the average wind speed as a parameter, which is often applied due to its simple use.
2.3. Turbulence Intensity

The content related to turbulence is mainly to determine the turbulence intensity of extreme wind speed and normal different wind speed, and the power spectral density of pulsating wind speed.

1) Turbulence intensity of extreme wind speed

Figure 2 is a comparison of the turbulence intensity of JG2010 and GB50009 in A and B ground roughness. From the figure, the turbulence intensity of IEC2019 and GL2010 for standard wind turbines at extreme wind speeds is closer to the value calculated in JG2010 roughness category A. In addition, in the extreme wind speed model, the index $\alpha$ representing the vertical distribution of the average wind speed is defined as 0.11, so the evaluation of the wind load of a standard wind turbine is close to the airflow of JG2010 using roughness category A.

![Figure 2. Comparison of turbulence intensity (ground roughness category A)](image)

2) Normal turbulence intensity at different wind speeds

The turbulence intensity of IEC2019 and GL2010 for normal different wind speeds are given by equations (4) and (5) respectively.

$$I_{\text{IEC2019}} = \frac{I_{\text{ref}}(0.75V_{\text{hub}}+5.6)}{V_{\text{hub}}}$$  \hspace{1cm} (4)

$$I_{\text{GL2010}} = \frac{I_{\text{ref}}(3V_{\text{hub}}+15)}{(a+1)V_{\text{hub}}}$$  \hspace{1cm} (5)

In fact, the basic parameters of the A and B turbulence intensity of the second edition of IEC1999 are consistent with GL2010. From the third edition in 2005, the turbulence intensity classification was changed from A and B categories to A, B and C categories. In the fourth edition of 2019, A + category has been added to apply to tropical cyclone-affected areas. The turbulence intensity formula of JG2010 is consistent with formula (4), where $I_{\text{ref}}$ is directly obtained from the observation value or calculated by the following formula from the turbulence intensity $I_{\text{h}}$ corresponding to the design wind speed $V_{\text{hub}}$.

$$I_{\text{ref}} = I_{\text{h}} \frac{V_{\text{hub}}}{0.75V_{\text{hub}}+3.75}$$  \hspace{1cm} (6)

3) Power spectral density

The part of pulsating wind speed can be simulated by the Gaussian stationary random process with zero mean value. Its generation requires the use of theoretical or measured power spectral density function, and the Kaimal power spectral model can be uniformly adopted. The formula is as follows.

$$\frac{\sigma^2}{\sigma^2} = \frac{fI_{h}k_{h}V_{\text{hub}}}{(1+6fL_{k}V_{\text{hub}})^{3/2}}$$  \hspace{1cm} (7)

Where, $V_{\text{hub}}$ is the average wind speed at the height of the hub, $S(f)$ is the power spectral density of the pulsating wind speed, $f$ is the frequency, $L_{k}$ is the integral scale of each pulsating wind speed component, and $\sigma$ is the standard deviation of each pulsating wind speed component.

In addition to the Kaimal model as shown in equation (7), there is also a Mann power spectrum model in IEC2019, which can be either.
3. Wind Load Assessment

In this section, the above specifications and the parameters set are used to evaluate the design value of wind load for a type 2MW IA class standard fan and compare the difference of calculation results.

Since the design principles of IEC 6140-1 and GL Wind are similar [19], the calculation results are not much different. This paper will only refer to the design conditions of IEC2019, and use GH Bladed software [20] for simulation calculation. The design standard of GH Bladed itself [21] is derived from the IEC standard in Europe, and has obtained the authoritative certification of Germanischer Lloyd. At the same time, according to the relevant evaluation method in JG2010, the wind load at the time of power generation and the occurrence of storms is calculated and compared with the results of IEC2019.

3.1. Wind Turbine Parameters

The basic data parameters of the wind turbine generator set are shown in Table 3. The airfoil adopts LS1m21r2 in Bladed. The diameter and thickness of each section of the tower are shown in Figure 3.

### Table 3. Summary and design parameters of 2MW wind turbine units.

| Parameter                | Content / Value |
|--------------------------|-----------------|
| Design standard wind speed $V_{hub}$ | 50m/s |
| Average annual wind speed at hub height $V_{ave}$ | 10m/s |
| Turbulence intensity $I_{ref}$ | 0.16 |
| Ground roughness(JG2010) | 1 |
| Rated power              | 2000kW |
| Diameter of the rotor D  | 80m |
| Hub height $H_h$         | 78.761m |
| Generator                | Doubly-fed generator |
| Types of operation control | Variable pitch variable speed |
| Cut-in / rated / cut-out wind speed | 3/11/25 |

**Figure 3.** Parameters of each section of the fan tower.

3.2. Wind Load Design Value of JG2010

The expected value of peak shear force during power generation with a repetition period of 50 years $Q_{0.50}$ and the expected value of peak bending moment during power generation with a repetition
period of 50 years \( M_{D50} \) are respectively equal to the expected value of peak shear force during power generation and the expected value of peak bending moment multiplied by statistics Extrapolation coefficient \( \gamma_e \) and safety partial coefficient \( \gamma_f \). As shown in formulas (8) and (9).

\[
Q_{D50} = \text{max}(Q_{Di} \times G_{Di}) \times \gamma_e \times \gamma_f \tag{8}
\]

\[
M_{D50} = \text{max}(M_{Di} \times G_{Di}) \times \gamma_e \times \gamma_f \tag{9}
\]

The average shear force \( Q_{Di} \) and average bending moment \( M_{Di} \) of the wind turbine corresponding to each wind speed level \( V_{Hi} \) during power generation are calculated according to the following formulas (10) and (11), respectively.

\[
Q_{Di} = \frac{1}{2} \rho V_{Hi}^2 C_{Ti} \pi R^2 + \frac{1}{2} \rho V_{Hi}^2 C_{DN} A_N + \int_R^{H_t} \frac{1}{2} \rho V_i(z)^2 C_{DT} d(z) dz \tag{10}
\]

\[
M_{Di} = \left( \frac{1}{2} \rho V_{Hi}^2 C_{Ti} \pi R^2 + \frac{1}{2} \rho V_{Hi}^2 C_{DN} A_N \right) \times (H_h - h) + \int_R^{H_t} \frac{1}{2} \rho V_i(z)^2 C_{DT} d(z)(z - h) dz \tag{11}
\]

Where,
- \( G_{Di} \): Wind gust coefficient during power generation corresponding to each wind speed level
- \( \rho \): Air density
- \( C_{Ti} \): Thrust coefficient during power generation corresponding to wind speed class \( V_{Hi} \)
- \( C_{DN} \): Average drag coefficient of the cabin
- \( A_N \): Visible area of the cabin
- \( H_t \): Height of tower
- \( h \): Evaluation height
- \( C_{DT} \): Average drag coefficient of the tower
- \( d(z) \): Tower diameter at height \( z \)
- \( V_i(z) \): Wind speed at height \( z \) of wind speed level \( V_{Hi} \)
- \( H_h \): Hub height
- \( a \): Vertical distribution index of wind speed

From the cut-in wind speed to the cut-out wind speed varying by 1 m/s, the expected value of the 50-year recurrence period of the peak shear force at the bottom of each section of the tower and the expected value of the 50-year recurrence period of the peak bending moment are calculated. As shown in Figure 4 and Figure 5, when the wind speed \( V_{Hi} = 12 \) m/s, the maximum shear force of the wind turbine is 717 kN, the maximum bending moment is 55247 kNm, and the maximum shear force and bending moment during power generation are both produced on the basis of a generator.

![Figure 4. Expected value of 50-year return period of peak shear force at the bottom of each section of the tower during power generation](image1)

![Figure 5. Expected value of 50-year return period of peak bending moment at the bottom of each section of the tower during power generation](image2)

For wind loads with extreme wind conditions, consider the state where yaw cannot be controlled during a power outage, and evaluate according to the state of the wind turbine shown in Figure 6. The yaw angle at maximum load is 90° and the azimuth 30°. For IA level standard wind turbines, the storm wind load is calculated according to the design wind speed of 50 m/s.
Figure 6. Posture of variable pitch control wind turbine during maximum wind load during a storm

Table 4. JG2010 wind load calculation results

| Numbering | Bottom height (m) | Bottom outer diameter (m) | Design wind speed (m/s) | Power generation | Torque (kNm) |
|-----------|------------------|---------------------------|-------------------------|------------------|--------------|
| Rotor+Nacelle | 77.261 | 3.005 | 50 | 686 | 1028 | 506 | 759 | 1661 |
| 1 | 75.54 | 3.03 | 49.85 | 686 | 2209 | 516 | 1639 | 1661 |
| 2 | 73.119 | 3.068 | 49.71 | 687 | 3872 | 530 | 2905 | 1661 |
| 3 | 70.699 | 3.105 | 49.55 | 688 | 2209 | 537 | 4420 | 1661 |
| 4 | 68.279 | 3.143 | 49.38 | 689 | 7204 | 558 | 5539 | 1661 |
| 5 | 65.86 | 3.181 | 49.20 | 690 | 8872 | 573 | 6907 | 1661 |
| 6 | 63.442 | 3.219 | 49.02 | 691 | 10543 | 588 | 8311 | 1661 |
| 7 | 61.025 | 3.256 | 48.84 | 692 | 12215 | 603 | 9749 | 1661 |
| 8 | 58.609 | 3.294 | 48.64 | 693 | 13889 | 618 | 11224 | 1661 |
| 9 | 56.193 | 3.332 | 48.44 | 694 | 15566 | 633 | 12735 | 1661 |
| 10 | 53.778 | 3.369 | 48.24 | 695 | 17244 | 649 | 14283 | 1661 |
| 11 | 51.363 | 3.407 | 48.02 | 696 | 18925 | 664 | 15868 | 1661 |
| 12 | 48.949 | 3.444 | 47.79 | 698 | 20607 | 680 | 17491 | 1661 |
| 13 | 46.537 | 3.482 | 47.55 | 699 | 22361 | 697 | 19221 | 1661 |
| 14 | 43.294 | 3.52 | 47.30 | 700 | 24117 | 714 | 20993 | 1661 |
| 15 | 41.013 | 3.557 | 47.03 | 701 | 25806 | 730 | 22734 | 1661 |
| 16 | 39.712 | 3.595 | 46.76 | 702 | 27496 | 747 | 24514 | 1661 |
| 17 | 36.693 | 3.633 | 46.47 | 703 | 29188 | 763 | 26333 | 1661 |
| 18 | 34.284 | 3.67 | 46.17 | 704 | 30882 | 780 | 28191 | 1661 |
| 19 | 31.875 | 3.708 | 45.85 | 705 | 32579 | 796 | 30089 | 1661 |
| 20 | 29.468 | 3.746 | 45.50 | 706 | 34277 | 813 | 32026 | 1661 |
| 21 | 27.061 | 3.783 | 45.13 | 707 | 35977 | 830 | 34004 | 1661 |
| 22 | 24.535 | 3.821 | 44.72 | 708 | 37764 | 848 | 36123 | 1661 |
| 23 | 22.009 | 3.858 | 44.26 | 709 | 39553 | 865 | 38286 | 1661 |
| 24 | 19.605 | 3.894 | 43.77 | 710 | 41258 | 882 | 40386 | 1661 |
| 25 | 17.201 | 3.931 | 43.23 | 711 | 42966 | 898 | 42526 | 1661 |
| 26 | 14.798 | 3.968 | 42.63 | 712 | 44675 | 915 | 44704 | 1661 |
| 27 | 12.395 | 4.004 | 41.95 | 713 | 46387 | 930 | 46921 | 1661 |
| 28 | 9.864 | 4.047 | 41.11 | 714 | 48192 | 947 | 49297 | 1661 |
| 29 | 7.334 | 4.085 | 40.07 | 715 | 49999 | 962 | 51712 | 1661 |
| 30 | 4.935 | 4.124 | 38.74 | 715 | 51714 | 976 | 54037 | 1661 |
| 31 | 2.537 | 4.162 | 36.86 | 716 | 53430 | 989 | 56394 | 1661 |
| 32 | 0 | 4.2 | 33.09 | 717 | 55247 | 1000 | 58917 | 1661 |
The shearing force acting on the tower evaluation height \( h \), the bending moment and torque are given by formulas (12)-(14) respectively.

\[
Q = F_{rD} + F_{nD} + \int_{h}^{H} F_{tD}(z) \, dz
\]  

\[
M = (F_{rD} + F_{nD}) \times (H - h) + \int_{h}^{H} F_{tD}(z)(z - h) \, dz
\]  

\[
M_T = -\sin(y_r) F_{rD} L_r - \sin(y_n) F_{nD} L_n
\]

In the formula, \( F_{rD}, F_{nD}, F_{tD} \) are the wind loads acting on the blades, nacelle and tower, respectively.

\( y_r \): \( y \) coordinate of the wind load center acting on the rotor

\( y_n \): \( y \) coordinate of the wind load center acting on the nacelle

\( \sin(y_r) \): when the \( y \) coordinate is positive, it is equal to 1, when it is negative, it is equal to -1

\( L_r, L_n \): the distance from the wind load center acting on the rotor and the nacelle to the central axis of the tower (m)

The wind load design values calculated according to JG2010 during power generation and storms are shown in Table 4.

3.3. IEC2019 Wind Load Design Value

For DLC1.1, there are two methods to obtain the characteristic value on the tower in IEC2019.

1) First, for each wind speed, the 99% quantile of the 10-minute simulated extreme value sequence is obtained, and then the maximum value of the quantile is multiplied by 1.2 as the characteristic value of load.

2) Determine the characteristic value of the load according to the statistical extrapolated value \([7]\) and the corresponding override probability.

In order to ensure the accuracy of the obtained load characteristic value, the wind speed step in the simulation is 2 m / s, a total of 11 wind speeds are generated, each wind speed will be simulated more than 99 times, each simulation for 10 minutes. Because the amount of data generated by the simulation calculation is large, about 125G, in order to extract the extreme value of the simulation data more quickly and accurately, first save the Bladed output as ASCII code, and then use the inhouse C++ data processing program to extract the extreme value of each section of tower.

Meanwhile, for comparison, only the main shear component (\( F_x \)) and bending moment component (\( M_y \)) corresponding to the JG2010 results during power generation are listed. The simulation extreme value obtained by processing the simulation data of DLC 1.1 through method 1, the characteristic value and the design value are shown in Fig. 7.

![Figure 7](image1.png)

(a)Shear force at the bottom of each section  (b)ending moment at the bottom of each section

**Figure 7.** Simulation values, characteristic values and design values of the bottom load of each section of the tower obtained by method 1
Bladed's post-processing uses three parameter estimation methods for statistical extrapolation, namely the moment estimation method (MOM), maximum likelihood method (MLE) and least squares method (MOLS). Figure 8 shows the 50-year extrapolation results of the tipping moment at the bottom of the tower with an average wind speed of 12 m/s. In this paper, the moment estimation method is used to extrapolate each wind speed, and the simulation extreme value, eigenvalue and design value obtained by processing the simulation data of DLC1.1 through method 2 are shown in Figure 9.

![Graph showing extrapolation results of overturning moments at the bottom of each tower (V = 12 m/s)](image)

**Figure 8.** Extrapolation results of overturning moments at the bottom of each tower (V = 12 m/s)

(a) Shear force at the bottom of each section  (b) Bending moment at the bottom of each section

![Graph showing simulation value, characteristic value and design value of the bottom load of each section of the tower obtained by method 2](image)

**Figure 9.** Simulation value, characteristic value and design value of the bottom load of each section of the tower obtained by method 2

It can be seen from figure 10 and 12 that the characteristic values of shear force and bending moment obtained by method 2 are relatively large. The bottom shear characteristic value and bending moment characteristic value obtained by method 2 are 15.8% and 10.7% greater than method 1, respectively.

It can be seen that method 2 is more conservative than method 1, and IEC2019 adds method 1, mainly because it is more convenient to use.

Corresponding to the storm conditions of JG2010 are the extreme wind speed models of DLC6.1 and DLC6.2. Which can be simulated by the steady-state wind speed model or the turbulent wind speed model. In this paper, a turbulent wind speed model is used. For the normal state of DLC6.1, the average yaw error in the simulation process is allowed to be +/- 8°, and 48 working states are simulated within 10 minutes, including the shutdown and idling states. For the abnormal state of DLC6.2, assuming the extreme situation of grid power outage and yaw system failure, 40 simulations and 10 minutes simulation of the working conditions, including shutdown and idling state. The maximum load appears when the yaw angle is +/- 90°. The design values of the shear force, bending moment and torque of each section of the tower are shown in table 5 after comprehensive power generation, startup, power off and shutdown.
### Table 5. IEC2019 wind load calculation results

| No. | Height (m) | Power generation | Storm | Shear force(kN) | moment(kN) | torque(kNm) | Shear force(kN) | moment(kN) | torque(kNm) |
|-----|------------|------------------|-------|-----------------|------------|-------------|----------------|------------|-------------|
| Wind blade+ nacelle | 77.261 | 723 | 4548 | 3907 | 491 | 1901 | 1668 |
| 1 | 75.54 | 726 | 4779 | 3907 | 500 | 2718 | 1669 |
| 2 | 73.119 | 727 | 5038 | 3909 | 512 | 3888 | 1670 |
| 3 | 70.699 | 727 | 6257 | 3910 | 527 | 5084 | 1671 |
| 4 | 68.279 | 725 | 7714 | 3911 | 540 | 6303 | 1672 |
| 5 | 65.86 | 724 | 9063 | 3912 | 553 | 7546 | 1673 |
| 6 | 63.442 | 721 | 10279 | 3913 | 564 | 8822 | 1673 |
| 7 | 61.025 | 715 | 11448 | 3914 | 577 | 10208 | 1674 |
| 8 | 58.609 | 708 | 12741 | 3915 | 589 | 11624 | 1675 |
| 9 | 56.193 | 701 | 14655 | 3916 | 602 | 13066 | 1676 |
| 10 | 53.778 | 694 | 16486 | 3917 | 614 | 14533 | 1676 |
| 11 | 51.363 | 691 | 18213 | 3918 | 628 | 16025 | 1677 |
| 12 | 48.949 | 702 | 20861 | 3919 | 641 | 17541 | 1678 |
| 13 | 46.437 | 711 | 22578 | 3920 | 655 | 19149 | 1678 |
| 14 | 43.925 | 725 | 24250 | 3921 | 669 | 20796 | 1679 |
| 15 | 41.513 | 736 | 25999 | 3922 | 683 | 22458 | 1680 |
| 16 | 39.103 | 748 | 27636 | 3923 | 696 | 24152 | 1680 |
| 17 | 36.693 | 759 | 29296 | 3924 | 710 | 25879 | 1681 |
| 18 | 34.284 | 766 | 30956 | 3925 | 730 | 27631 | 1682 |
| 19 | 31.875 | 771 | 32269 | 3926 | 750 | 29409 | 1682 |
| 20 | 29.468 | 778 | 33731 | 3927 | 769 | 31210 | 1683 |
| 21 | 27.061 | 785 | 35378 | 3928 | 787 | 33042 | 1683 |
| 22 | 24.535 | 791 | 36402 | 3929 | 804 | 35010 | 1684 |
| 23 | 22.009 | 798 | 38436 | 3930 | 823 | 37010 | 1684 |
| 24 | 19.605 | 801 | 40384 | 3931 | 837 | 38939 | 1684 |
| 25 | 17.201 | 805 | 42318 | 3932 | 851 | 40893 | 1685 |
| 26 | 14.798 | 808 | 44241 | 3933 | 864 | 42868 | 1685 |
| 27 | 12.395 | 810 | 46158 | 3934 | 875 | 44868 | 1685 |
| 28 | 9.864 | 812 | 48176 | 3935 | 886 | 46996 | 1685 |
| 29 | 7.334 | 813 | 50217 | 3936 | 895 | 49147 | 1685 |
| 30 | 4.935 | 814 | 52142 | 3937 | 903 | 51203 | 1686 |
| 31 | 2.537 | 814 | 54050 | 3938 | 910 | 53270 | 1686 |
| 32 | 0 | 814 | 56067 | 3939 | 914 | 55473 | 1686 |

3.4. Load Design Value Comparison

In order to facilitate comparison, this paper classifies the power generation, start-up and power off conditions in IEC2019 as power generation conditions, and the shutdown conditions as storm conditions, and compares the shear and bending moments at the bottom of each section of tower under power generation conditions as shown in Figure 10.

The maximum shear force deviation is 12.1%. The bending moment deviation at the bottom of the top four parts of tower is large, while the bending moment deviation at other parts is within 10%.

The comparison of the shear force and bending moment at the bottom of each section of the tower in storm conditions is shown in Figure 11. The maximum shear deviation is 9.5%. Similarly, the bending moment deviation at the bottom of the top four sections of the tower is large, and the bending moments deviations at other parts is within 10%. The maximum shear force and bending moment design values appear at the bottom of the tower, but under power generation conditions, the shear
value of JG2010 is 12% smaller than the value calculated by IEC2019, and under storm conditions, it is 9.5% smaller than the maximum shear force of IEC2019. The deviation of the bending moment at the bottom of the tower is only 1.46% under power generation conditions, which is basically the same, but the bending moment value of JG2010 during storm conditions is 6.2% larger than that of IEC2019. In addition, under storm conditions, the maximum torque of the two is basically the same.

The main reason for the large deviation in the bending moment values of the four sections at the top of the tower is that JG2010 did not consider the influence of gravity and inertia force in the formula for calculating shear force and bending moment. The main reason may be that the influence of this part cannot be well reflected in the formula. Since the bending moment of several sections at the top of the tower is small and has limited influence, if necessary, it is suggested that the bending moment design value of several sections in the upper tower (about 10% of the tower height) should be multiplied by a gradient increasing amplification factor when calculating the bending moment design value with reference to the JG2010 evaluation formula.

![Graphs showing shear force and bending moment comparisons](Image)

**Figure 10.** Comparison of design values of shear force and bending moment of the load at the bottom of each section of the tower under the conditions of power generation (upper axis is the percentage deviation)

![Graphs showing shear force and bending moment comparisons](Image)

**Figure 11.** Comparison of design values of shear force and bending moment of the load at the bottom of each section of the tower under storm conditions (the upper axis is the percentage deviation)

4. Conclusion

1) Since the values of some necessary parameters and calculation methods for the evaluation of wind loads in various codes or guidelines are not completely consistent, it will inevitably lead to differences in calculation results. When using standard wind turbine or other types of wind turbine, a detailed onsite assessment of wind conditions would be necessary.
2) JG2010 directly evaluates the wind load of the pitch control wind turbine when the storm occurs according to the wind turbine position shown in Figure 9. However, IEC61400-1 did not stipulate until the third edition that unless it can provide backup power for the control and yaw system and has at least 6 hours of yaw adjustment capability, the impact of the wind direction shown in Figure 9 will not be analyzed. It can be seen that the conditions of JG2010 are stricter, and the coverage of the load conditions of IEC2019 is more comprehensive than that of JG2010.

3) From the comparison of the calculation results, it can be seen that the design values of the shear force and bending moment calculated according to the evaluation formula of JG2010 and the design values obtained by GH Bladed simulation calculation according to the load conditions of IEC2019 can be better fitted. The main reason is that JG2010's evaluation formula itself is derived based on the response spectrum method, so JG2010 has a good reference for the design of domestic wind turbines and the formulation of related specifications.

5. References

[1] World Wind Energy Association (WWEA). Wind Power Capacity Worldwide Reaches 597 GW, 50, 1 GW added in 2018[OL]. 2019. https://www.windea.org/blog/2019/02/25/wind-power-capacity-worldwide-reaches-600-gw-539-gw-added-in-2018/

[2] ZHANG Chen, GUO Sheng, GAO Wei, QIU Fengtao, YANG Tao, LI Youliang. Opportunity Maintenance Strategy for Wind Turbines Based on Reliability [J]. Guangdong Electric Power, 2016, 29 (02): 40-44.

[3] GUO Jiasheng, LIU Hanjiang. Calculation method of short-circuit current in wind farm considering voltage distribution [J]. Guangdong Electric Power, 2017, 30 (12): 55-61.

[4] CHEN X, Xu J. Structural failure analysis of wind turbines impacted by super typhoon Usagi[J]. Engineering Failure Analysis, 2016, 60:391-404.

[5] CHEN X, LI C, Xu J. Failure investigation on a coastal wind farm damaged by super typhoon: a forensic engineering study [J]. Journal of Wind Engineering and Industrial Aerodynamics, 2015, 147: 132-142.

[6] KATSANOS E I, THONS S, GEORGAKIS C T. Wind turbine and seismic hazard a state-of-the-art review [J]. Winde Energy, 2016, 19:2113-2133.

[7] DYRBREY C, HANSEN S O. Wind loads on structures [M]. UK:John Wiley& Sons,1997.

[8] MARDFEKRI M, GARDONI P. Multi-hazard reliability assessment of offshore wind turbine [J]. Wind Energy, 2015, 18:1433-1450.

[9] KE Shitang, WANG Tonguang, CHEN Shaolin, et al. Wind-induced responses and equivalent static wind load and large wind turbine system[J]. Journal of Zhejiang University: Engineering Science, 2014, 48 (4): 686—692

[10] TAN Dongmei, JIN Chao, QU Weilian, ZHAO Ziyi. Fatigue reliability analysis of high-strength bolts of wind power tower under combined action of wind and ice [J]. Journal of Building Science and Engineering, 2019, 36 (02): 92-100.

[11] GAO Qingshui, DENG Xiaowen, ZHANG Chu, TIAN Feng, LIU Shi. Collapse analysis of wind turbine tower under strong wind-near-field seismic coupling [J]. Special Structures, 2018, 35 (04): 60-68.

[12] PAN Fangshu, WANG Fawu, KE Shitang, TANG Gan. Buckling Analysis and Stability Design of Large Wind Turbine Tower Considering Defects [J]. Chinese Journal of Solar Energy, 2017, 38 (10): 2659-2664.

[13] World Wind Energy Association (WWEA). Wind Power Capacity Worldwide Reaches 597 GW, 50, 1 GW added in 2018[OL]. 2019. https://www.windea.org/blog/2019/02/25/wind-power-capacity-worldwide-reaches-600-gw-539-gw-added-in-2018/

[14] ZHANG Chen, GUO Sheng, GAO Wei, QIU Fengtao, YANG Tao, LI Youliang. Opportunity Maintenance Strategy for Wind Turbines Based on Reliability [J]. Guangdong Electric Power, 2016, 29 (02): 40-44.

[15] GUO Jiasheng, LIU Hanjiang. Calculation method of short-circuit current in wind farm considering voltage distribution [J]. Guangdong Electric Power, 2017, 30 (12): 55-61.
[16] CHEN X, XU J. Structural failure analysis of wind turbines impacted by super typhoon Usagi [J]. Engineering Failure Analysis, 2016, 60:391-404.

[17] CHEN X, LI C, XU J. Failure investigation on a coastal wind farm damaged by super typhoon: a forensic engineering study [J]. Journal of Wind Engineering and Industrial Aerodynamics, 2015, 147:132-142.

[18] KATSANOS E I, THONS S, GEORGAKIS C T. Wind turbine and seismic hazard a state-of-the-art review [J]. Wind Energy, 2016, 19:2113-2133.

[19] DYRBEY C, HANSEN S O. Wind loads on structures [M]. UK: John Wiley & Sons, 1997.

[20] MARDFEKRI M, GARDONI P. Multi-hazard reliability assessment of offshore wind turbine [J]. Wind Energy, 2015, 18:1433-1450.

[21] KE Shitang, WANG Tongguang, CHEN Shaolin, GE Yaojun. Large-scale wind turbine full-scale wind vibration response and equivalent static wind load [J].