# Wind damage vulnerability analysis of narrow base tower for distribution line based on probabilistic reliability

Chaoying Fang [1], Jun Xu [1], Yanhui Zhang [1], Zhaoqi Wu [2,*], Long Li [2], Jiceng Han [1], Jian Qian [1]

[1] State Grid Fujian Electric Power Research Institute, Fuzhou, Fujian, 35000, China

[2] College of Civil Engineering, Fuzhou University, Fuzhou, Fujian, 35018, China

* Corresponding Author Email: zhaoqi_wu@163.com

**Abstract.** Steel narrowbase tower has been widely used in distribution network in recent years because that it covers an area smaller than the conventional tower, and has stronger wind resistance than concrete pole. In order to fully understand the wind resistance performance of narrow base tower, a vulnerability performance of narrow base tower under different wind speeds was analyzed based on probabilistic reliability theory. According to the damage characteristics of narrow base tower and the corresponding tall structure specification, wind performance level indexes of narrow base tower were established. When calculating the effect of wind load on narrow base tower, the randomness of wind load, material properties and dimensions were considered. The probability of the narrow base tower appearing different degrees of damage under different wind speeds was calculated, and subsequently a wind vulnerability curve of the narrow base tower was drawn. It is found that the severe damage probability of narrow base tower is about 5% when the wind speed is 23.6m/s. And in the case of severe damage probability is 95%, the wind speed reaches 80m/s. Narrow base tower has good resistance to wind disaster.

**Keywords:** Narrow base tower system, Pulsating wind, Wind-vibration response, vulnerability analysis.

## 1. Introduction

Power grid lines have been serving in natural environment for a long time, and are frequently affected by wind, rain and other complex conditions. Among them, wind damage is one of the main factors leading to line failure [1-2]. The narrow base tower is a kind of new structure with small root opening and sensitive to wind load. It is of great theoretical and practical significance to understand the overall wind resistance of the narrow base tower line coupling system under wind load.

As one of the important infrastructure of power grid lines, the reliable operation of the tower is crucial to the safety of the power system [3-4]. Because of the complex structure of the circuit, it shows strong nonlinearity. Therefore, it is difficult to determine the limit state of transmission lines under the action of fluctuating wind, and the analysis of wind response and wind resistance of corresponding structures is relatively complicated compared with that of general structures. For example, Han Feng et al. [5-6] obtained the collapse mode of power grid lines caused by wind damage through statistical analysis of the cases of wind damage of Chinese transmission lines. Based on the tests and specifications, a performance leveling and quantization model with displacement and stress as indexes is proposed. Finally, the reliability of transmission tower performance of different tower types is analyzed systematically. Ge Yijiao [7] used Monte Carlo simulation method to conduct random sampling of structural parameters to consider the uncertainty of structural parameters, and completed the wind disaster vulnerability of the transmission tower according to the results of random wind load time history analysis and structural nonlinear buckling analysis. Fu Xing et al. [8-9] established mechanical models of multiple transmission towers considering the influence of structural materials and randomness of section size. The collapse displacement and wind speed of the structure are determined by the static elastoplastic analysis method, and the vulnerability of the transmission tower under the combined action of wind and rain is analyzed.

This paper takes the new narrow base tower as an example, according to the research results of the quantitative model of the transmission tower in the relevant literature, puts forward the quantitative model which takes the vertex displacement as the control standard and conforms to the structural characteristics of the narrow base tower, and analyzes its vulnerability to wind disaster based on the probabilistic reliability research method.

## 2. ANALYSIS method

### 2.1 Principle and procedure of vulnerability analysis

Wind disaster vulnerability analysis can establish the correlation between wind speed and structural damage degree, that is, the failure probability of structures reaching different damage degrees under different wind speed [10]. The vulnerability analysis is mainly divided into two parts: one is the random wind load effect analysis of the structure, from which the wind load effect function can be obtained; The second is the probabilistic statistical analysis of the wind resistance of the structure to obtain the different failure states of the structure and determine the corresponding critical control values. Vulnerability analysis Uncertainty of structural parameters and wind loads.

Vulnerability is usually expressed by lognormal cumulative distribution function, and the failure probability of wind load effect SD exceeding structural bearing capacity RC can be expressed by formula (1) [11].

$$P_f = P_r\left(\frac{R_C}{S_D} \le 1\right) \tag{1}$$

In the formula, $S_D$ and $R_C$ obey normal distribution.

Under the action of wind load, the deformation of the tower presents an overall bending state. Based on Equation (1), the wind disaster vulnerability function equation (2) can be established with the maximum displacement of tower top as the performance level.

$$P_f = \Phi\left[\frac{\ln\left(m_D/m_C\right)}{\sqrt{\beta_C^2+\beta_D^2}}\right] \tag{2}$$

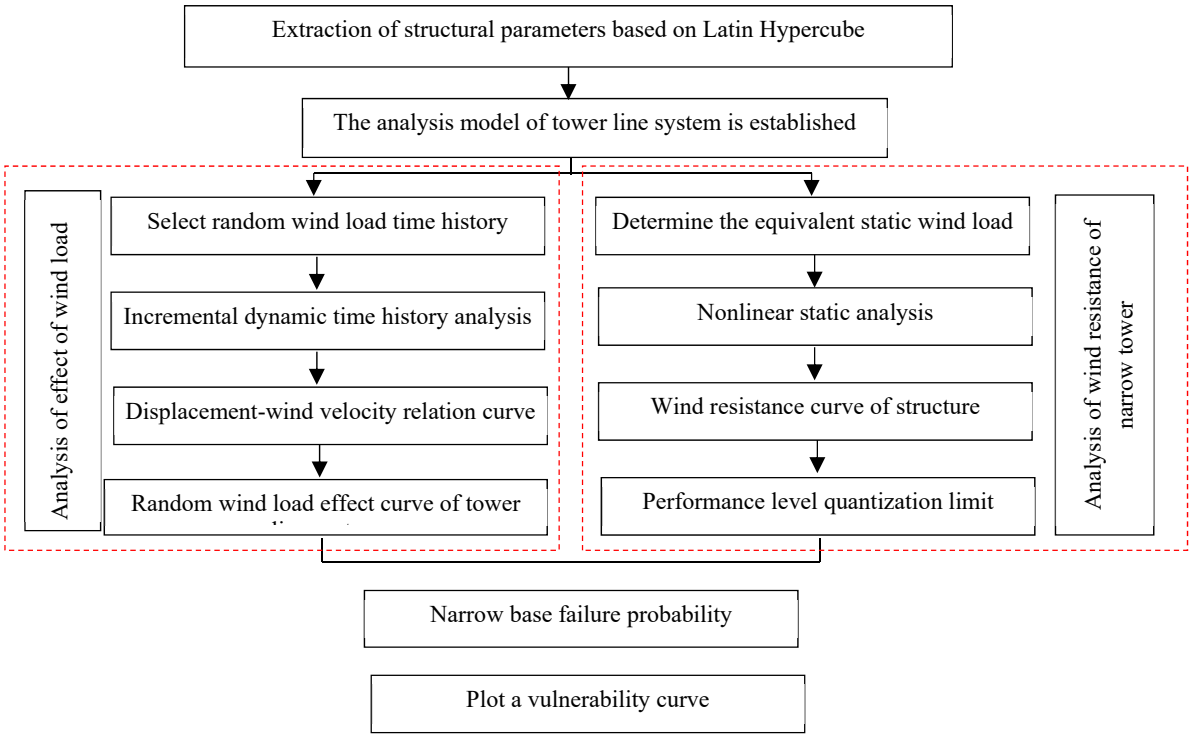


**Fig. 1** Wind disaster vulnerability analysis process

Where, $m_D$ is the maximum displacement of tower top under a given wind load; Wind resistance limit value of $m_C$ structure.

The main flow of wind vulnerability analysis of narrow base tower is shown in Figure 1.

### 2.2 Finite element model building

A typical 10kV distribution line linear narrow base tower ZJT-Z is taken as an example to analyze. The main body of the tower is made of Q345 steel, the auxiliary and oblique materials are made of Q235 steel, and all the rods are Angle steel. The size of the base is 0.773m×0.773m, the height of the tower is 18m, and the height of the call is 16.9m. The beam element beam188 was used to simulate the tower structure, and the four main materials of the tower foot and the ground were fixed constraints. The finite element model of the narrow base tower line system is shown in Figure 2, and the material parameters of the model are shown in Table 1.

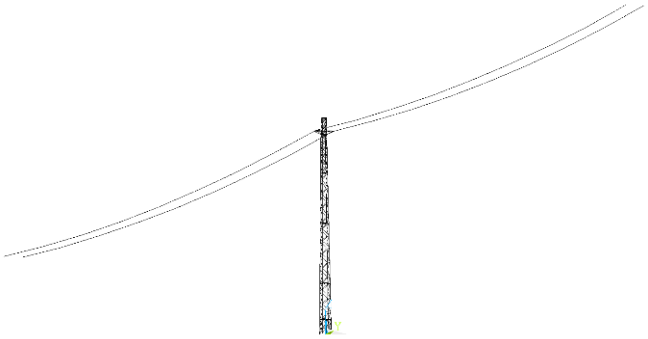

**Fig. 2** Finite element model of narrow base tower line system

## 3. Probabilistic wind resistance analysis of structure

### 3.1 Randomness of structural parameters

The wind resistance of the structure is affected by many random factors, which are mainly reflected in the structural parameters and load. For the mechanical model of narrow base tower, the randomness of structural parameters includes the material properties of Angle steel and section size, while the randomness of wind load is considered in the load aspect. On the premise that the uncertainty parameters obey normal distribution and the material parameters are based on the theoretical values at design time, the elastic modulus, yield strength, Poisson's ratio, density and component section size of the material are selected for random sampling. Table 1 lists the specific parameters.

**Table 1.** Statistical distribution Table of structural parameters

| Structural parameter | Average value | Coefficient of variation |
|---|---|---|
| Modulus of elasticity/GPa | 206 | 0.03 |
| Q235 yield strength/MPa | 215 | 0.07 |
| Q345 yield strength/MPa | 310 | 0.07 |
| Poisson's ratio | 0.3 | 0.03 |
| Density/kg·m$^{-3}$ | 7850 | 0.05 |
| Section size/mm | ∟40, ∟50, ∟45, ∟56, ∟75, ∟80, ∟50 | 0.008 |

Since Monte Carlo sampling method may lead to too much concentration of data in the case of insufficient sample quantity, this paper uses Latin hypercube sampling method to randomly extract structural parameters. The advantages of applying Latin Hypercube sampling method to sampling include: high reliability of sampling results, effective combination of multidimensional random variables, etc., so it is often used in practical projects [12]. The key of Latin hypercube sampling method is to divide statistical interval [0,1] into n equal parts, randomly select samples in each interval of n equal parts, and shuffle them in order to avoid data aggregation.

The lhsnorm function in MATLAB is used to compile a sampling program and carry out Latin hypercube sampling. Limited by space, only the sampling results of material parameters and partial section parameters are listed here, as shown in Table 2.

### 3.2 Selection and quantification of wind resistance

The key of performance-based design method is to select a reasonable performance level. For transmission tower, representative Yu Dengke et al. [5], based on a large number of research and analysis, considered the stress ratio and tower vertex displacement as quantification standards, and then defined its performance level quantification model combined with specifications. The effectiveness of the proposed performance level framework is verified by an engineering example, which has certain guiding significance for engineering design and practice. As shown in Table 3.

**Table 2.** Sample combinations

| No. | E /GPa | Q235 yield strength/Mpa | Q345 yield strength/MPa | $\upsilon$ | $\rho$ /kg.m$^{-3}$ | Angle limb width /mm |
|---|---|---|---|---|---|---|
| 1 | 201 | 183 | 335 | 0.31 | 7471 | 39.9 |
| 2 | 212 | 197 | 321 | 0.31 | 7907 | 40.4 |
| 3 | 205 | 222 | 281 | 0.29 | 8144 | 39.7 |
| 4 | 215 | 204 | 328 | 0.29 | 7730 | 39.0 |
| 5 | 199 | 217 | 302 | 0.30 | 8396 | 40.5 |
| 6 | 208 | 230 | 308 | 0.29 | 7594 | 40.2 |
| 7 | 195 | 235 | 296 | 0.30 | 8196 | 39.7 |
| 8 | 203 | 214 | 311 | 0.30 | 8013 | 40.1 |
| 9 | 207 | 226 | 286 | 0.32 | 7774 | 39.9 |
| 10 | 210 | 211 | 341 | 0.30 | 7241 | 40.1 |

**Table 3.** Classification of wind performance levels of transmission towers

| Performance level | | Basically sound | Minor damage | Moderate failure | Severe damage and collapse |
|---|---|---|---|---|---|
| Tower stress | phenomenon | No damage, all components are in the elastic stage | The secondary inclined material produces plastic deformation or deflection, and the main material is in an elastic state | Plastic deformation or deflection of the main material | The main material has large plastic deformation or deflection and cannot continue to bear or collapse |
| | Maintenance standard | No repair required | Simple repair and continue to use | Use after regular repair | Basically irreparable |
| Apex displacement of tower | | Allowable value in literature [13] | Less than the empirical design value | Greater than the empirical design value | Design experience value or finite element calculation value |

Han Feng [6], on the basis of the performance-considering aseismic design theory, obtained the collapse mode of power grid lines caused by wind damage through statistical analysis of the cases of wind disaster of Chinese transmission lines. Finally, based on the tests and specifications, a performance leveling and quantitative model with displacement and stress ratio as indexes is proposed. See Table 4 for details. In addition, on the basis of considering specifications and design experience values, the author gives another quantitative model, which is detailed in Table 5.

**Table 4.** Performance leveling model based on test values and specifications

| Performance level | | Basically sound | Minor damage | Moderate failure | Severe damage and collapse |
|---|---|---|---|---|---|
| Stress ratio | Inclined wood | $\xi<1$ | $1\leq\xi<1.15$ | $1.15\leq\xi$ | — |
| | Main wood | — | $\xi<1$ | $1\leq\xi<1.15$ | $1.15\leq\xi$ |
| Top displacement | | $l<3h/1000$ | $3h/1000\leq l<h/80$ | $h/80\leq l<h/50$ | $h/50\leq l$ |

**Table 5.** Performance level quantization model based on specifications and empirical values

| Performance level | | Basically sound | Minor damage | Moderate failure | Severe damage and collapse |
|---|---|---|---|---|---|
| Stress ratio | Inclined wood | $\xi<1$ | $1\leq\xi<1.15$ | $1.15\leq\xi$ | — |
| | Main wood | — | $\xi<1$ | $1\leq\xi<1.15$ | $1.15\leq\xi$ |
| Top displacement | | | - | $3h/1000\leq l<h/100$ | $h/100\leq l$ |

On the basis of Han Feng's research, Ge Yijiao [7] evaluated the wind disaster vulnerability of the transmission tower through time history analysis of random wind load and nonlinear buckling analysis of the structure based on probabilistic reliability method. It is proposed to take the top displacement Angle RDA as the control standard, and the specific quantitative standard is shown in Table 6. Among them, RDAma and RDAmo are the limit control values of severe damage and collapse state of transmission tower respectively.

**Table 6.** Definition of failure state

| Failure state | Displacement limit |
|---|---|
| Minor damage | $0.5RDA_{ma}\leq RDA<RDA_{ma}$ |
| Severe damage | $RDA_{ma}\leq RDA<RDA_{mo}$ |
| Collapse failure | $RDA_{mo}\leq RDA$ |

By comparing Table 4 and 5, it can be seen that the quantification of performance level is mainly caused by the vertex displacement of the tower. Therefore, this paper carries out nonlinear analysis of the tower line system, takes the top displacement as the performance level, and quantifies the wind resistance performance of the tower line system on the basis of referring to Table 3, 4, 5 and 6.

### 3.3 Nonlinear static analysis of narrow base tower line system

Ten random structural samples were selected considering the uncertainty of structural material properties and section size. Through the nonlinear static buckling analysis of the 10 structural samples, the influence of the randomness of the structural parameters on the wind resistance of the tower line system is considered. When the wind direction is 90 degrees, the analysis object is the narrow base tower line system. A series of nonlinear static buckling analysis is carried out by gradually increasing the load until the calculation of tower line system fails to converge, and the dislocation-wind speed wind resistance curve of the structure is obtained.

As can be seen from the wind-displacement wind resistance curves of 10 samples of narrow pin-line system in FIG. 3, when the wind speed increases gradually, the top displacement of the narrow pin-line system also increases gradually, which shows that there is a positive correlation between the two. Sun Tiange [14] verified the accuracy of the analysis model on the basis of the true type test of the narrow base tower, and gave the whole process of the collapse of the narrow base tower through simulation. Based on the simulation analysis of narrow base tower collapse conducted by the authors of this paper, it can be seen in Figure 3 that the narrow base tower line system is in the elastic stage when it is near 0~0.2m. When the top displacement of the narrow base tower is about 0.45m~0.56m, the displacement of the tower line system increases significantly one after another, which leads to the failure of the calculation, and the structure can be considered to have collapsed.

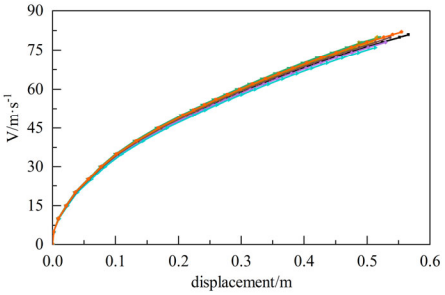


**Fig. 3** Wind-displacement curves of 10 structural samples

# 4. Effect analysis of random wind load

## 4.1 Principle and procedure of random wind load effect analysis

On the basis of considering the randomness of wind load, the wind vibration response of the narrow base tower line system is analyzed in this section. The basic steps of random wind load time history analysis are as follows:

(1) Based on the randomness of structural parameters, the finite element model of the tower line system is established;

(2) The wind load time history curve at the representative node of the tower line system was simulated by AR method. Based on the incremental dynamic analysis method, the amplitude modulation principle of wind speed was determined. Starting from the wind speed of 20m/s, the wind speed was adjusted increments and the dynamic response was analyzed;

(3) Step (2) was repeated for 9 times to generate 9 groups of random wind load time history samples, which were combined with the 10 structural samples extracted in consideration of the uncertainty of structural parameters as mentioned above to form random "wind velocity-structure" samples, respectively, for structural dynamic response analysis;

(4)A series of random time-history analysis results generated in step 3 are analyzed by linear regression, and the functional relationship between wind speed and structure effect is obtained.

At a 90 degree wind direction Angle, the relationship between the maximum displacement $m_D$ at the top of the tower and wind speed v usually follows the power exponential relationship shown in Equation (3).

$$m_D=\alpha\cdot v^{\beta} \tag{3}$$

Logarithm of both sides of equation (3) can be obtained:

$$\ln m_D=b\ln(v)+a \tag{4}$$

In the formula (4), $a=\ln\alpha$ and $b=\beta$, the specific values of $a$ and $b$ can be obtained by regression analysis of the calculation results of the incremental dynamic time history analysis of the structure.

## 4.2 Random wind load time history analysis

According to the random wind load time history analysis results of 90 wind-speed structure samples, logarithms of the maximum displacement response $m_D$ of wind speed and tower line system were respectively taken to draw a scatter diagram. As can be seen from Equation 2, taking wind speed as variable, the stochastic wind load effect model of tower line system can be obtained by linear regression analysis of the time history analysis results of stochastic wind load. Fig. 4 shows the scatter plot and the regression curve obtained by fitting.

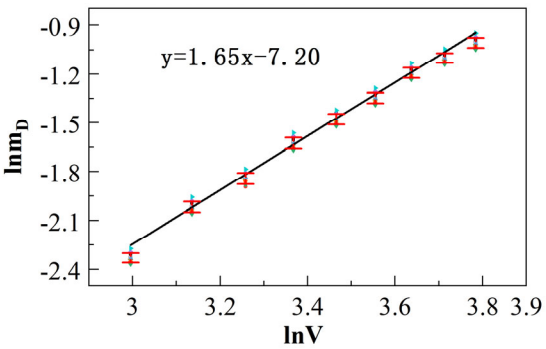


**Fig. 4** ln(V) -ln (mD) regression curve of narrow base line system

The equation of trend line obtained by linear regression fitting is:

$$y=1.65x-7.20 \tag{5}$$

## 5. Wind disaster vulnerability analysis

In order to accurately obtain the wind disaster vulnerability results of the narrow base tower line system, the quantitative index limits and vulnerability curves of each limit state in different literatures were compared and analyzed in this section. On this basis, the control value of the top displacement limit conforming to the narrow base tower structure was obtained, and then the vulnerability curve of the structure was drawn with Equation 2. Table 4, Table 5 and Table 6 in FIG. 5, FIG. 6 and FIG. 7 respectively represent the table contents in Section 3.2 above, namely the quantitative standard of wind resistance performance and the displacement limit value.

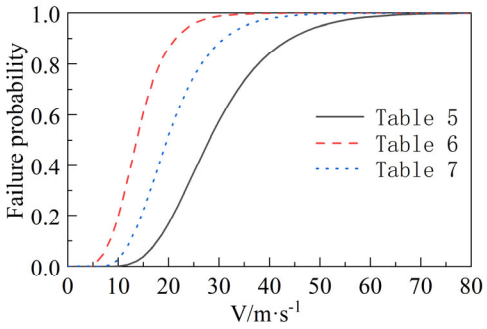


**Fig. 5** Comparison of the vulnerability curve of the limit value of minor damage displacement

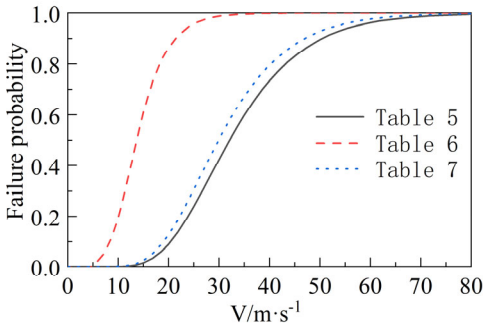


**Fig 6.** Comparison of vulnerability curves of moderate failure displacement limits

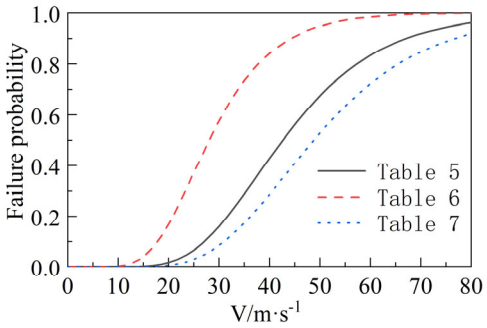


**Fig. 7** Comparison of vulnerability curves of displacement limits of severe failure and collapse

By comparing the vulnerability curve of moderate failure state in FIG. 6 and the definitions of minor and moderate failure in Table 3, it can be seen that the displacement corresponding to the elastic-plastic junction of the narrow base tower is a more appropriate control criterion for minor and moderate failure, i.e. h/90. The displacement limit also has a certain safety margin compared with the displacement control value of moderate failure in Table 4.

Similarly, for the displacement boundary value of basic integrity and minor damage, 3h/1000 is given under the condition that the specification is limited to wind speed of 5m/s, which is conservative.

Therefore, in summary, the control value of displacement in this state takes minor damage in Table 6 as the quantitative standard, namely h/180.

As can be seen from FIG. 7, considering the small root opening of a narrow base tower, a large lateral displacement will be generated under wind load, and when the top displacement is h/100, the tower is still in the elastic stage. Comparing with Table 3, it can be seen that the safety margin of the control value is large, which fails to give full play to the performance of the structure. In Table 6, the displacement value when the tower collapses is taken as the control value of serious damage and collapse. Considering the importance of line safety and the regulation of the horizontal displacement limit of tall structure design standard [15], it can be seen that it is more appropriate to take the tower top displacement h/50 as the control value of serious damage and collapse.

To sum up, it is suggested in this paper that the control values of wind resistance performance level and top displacement limit of the narrow base tower line system are shown in Table 7.

**Table 7.** Level division and quantification of wind resistance performance of narrow base tower line system

| Performance level | Basically sound | Minor damage | Moderate failure | Severe damage and collapse |
|---|---|---|---|---|
| Top displacement | $m_c < h/180$ | $h/180 \le m_c < h/90$ | $h/90 \le m_c < h/50$ | $h/50 \le m_c$ |

Based on the quantitative index limit values of each limit state determined in Table 7 and the random wind load effect function of Equation 5 structure, wind disaster vulnerability results of narrow base tower line system are obtained, as shown in Figure 8.

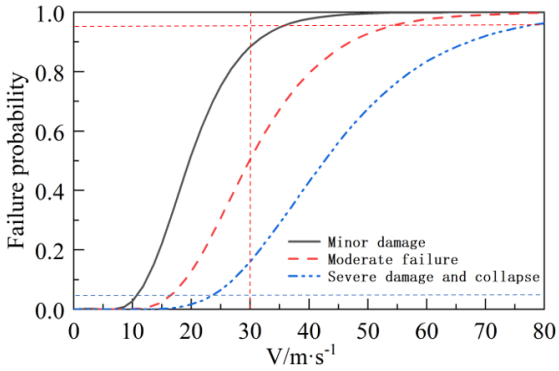


**Fig. 8** Wind disaster vulnerability curve of narrow base tower line system

As can be seen from FIG. 8, with the increase of wind speed, the failure probability of each failure state of the narrow base tower line system presents an expanding trend. For example, when the wind speed reaches 45m/s, the probability of minor damage is 99.05%, the probability of moderate damage is 87.71%, and the probability of serious damage and collapse is 56.19%. It can be seen that the tower line system is prone to slight and moderate damage when encountering strong winds, which should be taken into account in the design of structural wind resistance.

## 6. Conclusions

(1) Through the nonlinear static buckling analysis of several samples, the wind speed - displacement wind resistance curve of the tower line system is obtained. According to the wind-displacement curve, when the top displacement is near 0~0.2m, the narrow base tower line system is in the elastic stage. When the displacement of the tower top is about 0.45m~0.56m, the displacement of the tower line system increases significantly, which leads to the failure of the calculation. At this time, the structure can be considered to have collapsed.

(2) Based on the comparative analysis of the quantitative index limit values and their vulnerability curves of each limit state in different literatures, and combined with the wind-displacement resistance curves of several random tower line system samples, the quantitative displacement limit values of different limit states of narrow base tower line system were proposed in this paper.

(3) According to the results of vulnerability analysis, when the wind speed is small, the rods of the narrow base tower line system are in the elastic state, and the performance is good. But under the action of strong wind, the probability of slight damage and moderate damage of the tower line system is high, and enough attention should be paid to the wind-resistant design of the structure.

## Acknowledgments

This research was funded by the Science and Technology project of China State Grid Fujian Electric Power Company (Grant No.521304210001), which are gratefully acknowledged.

## References

[1] Xie Q, Li J. Current situation and countermeasures of natural disasters in power system [J]. Journal of Natural Disasters, 2006, 15(4): 126-131.

[2] Zhang X T. Structural wind engineering [M]. Beijing: China Architecture and Building Press, 2006.

[3] Liu S T. Transmission tower structure and foundation design [M]. Beijing: China Water Resources and Hydropower Press, 2005.

[4] Yang B, An L Q, Cao M. Durability life prediction and economic evaluation of transmission tower foundation [J]. Electric Power Science and Engineering, 2015, 31(2): 55-59.

[5] Yu D K, Li Z L, Han F, et al. Wind reliability analysis of UHV transmission tower based on performance objective [J]. Journal of Disaster Prevention and Mitigation Engineering, 2013, 33(6): 657-662.

[6] Han F. Study on wind reliability of UHV transmission tower line system [D]. Chongqing: Chongqing University, 2012.

[7] Ge Y J. Study on wind disaster vulnerability of transmission tower structure [D]. Suzhou: Suzhou University of Science and Technology, 2014.

[8] Fu X, Li H N. Fragility analysis and estimation of collapse status for transmission tower subjected to wind and rain loads [J]. Structural Safety, 2016, 58: 1-10.

[9] Fu X, Li H N. Uncertainty analysis of the strength capacity and failure path for a transmission tower under a wind load [J]. Journal of Wind Engineering and Industrial Aerodynamics, 2018, 173: 147-155.

[10] An S J. Study on wind disaster vulnerability of single column billboard structure [D]. Harbin: Harbin Institute of Technology, 2009.

[11] Cao X J. Research and application of elastoplastic analysis method for high-rise building structures [D]. Hunan: Hunan University, 2008.

[12] Jiang W. Seismic vulnerability analysis of continuous girder bridge [D]. Wuhan: Huazhong University of Science and Technology, 2012.

[13] Power Industry standard of the People's Republic of China. DL/T 5154-2012. Technical regulations for tower structure design of overhead transmission lines [S]. Beijing: China Planning Publishing House, 2012.

[14] Sun T G. Mechanical analysis and collapse simulation of narrow base angle steel tower [D]. Hefei: Hefei University of Technology, 2019.

[15] Ministry of Housing and Urban-Rural Development of the People's Republic of China. GB 50135-2019. Design standard for high-rise structures [S]. Beijing: China Planning Press, 2019.