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Failure Analysis and Safety De-Icing Strategy of Local Transmission Tower-Line Structure System Based on Orthogonal Method in Power System

Li Zhang [1,2], Xueming Zhou [1], Jiangjun Ruan [2,3,*], Zhiqiang Feng [1], Yu Shen [1] and Yao Yao [1]

[1] State Grid Hubei Electric Power Research Institute, Wuhan 430077, China; zhangliwhu@whu.edu.cn (L.Z.); 13720183473@163.com (X.Z.); fresh_2005@163.com (Z.F.); toshenyu@126.com (Y.S.); jefferson_yao@163.com (Y.Y.)
[2] School of Electrical Engineering and Automation, Wuhan University, Wuhan 430072, China
[3] Hubei Engineering and Technology Research Center for AC/DC Intelligent Distribution Network, School of Electrical Engineering and Automation, Wuhan University, Wuhan 430072, China
* Correspondence: ruan308@126.com

Abstract: The development of lightweight de-icing equipment for partial transmission lines in a microtopography area has become a hot research topic. However, the existing local line de-icing methods pay less attention to the mechanical damage caused by unequal tension on the tower, and there is a lack of safe de-icing strategies. This study has proposed a methodology integrating an orthogonal experimental design and finite element mechanical analysis to assess the impact of localized line de-icing on the structural stability of transmission tower-line systems. Taking the ±800 kV transmission line as an example, the refined finite element model of the transmission tower-line system has been established, the influence of each conductor and ground wire defrosting on the tower has been analyzed, and a scientific de-icing strategy has been formulated. Thus, the critical ice thickness and wind speed curves for tower failure have been calculated. The research results show that the de-icing of conductor 1, 5, 6, and ground wires 11 and 12 has a higher impact on the failure of the entire tower-line system. Ice melting on the windward side and ice covering on the leeward side will cause the unbalanced tension of the tower to be greater. The findings provide actionable guidelines for the formulation of a transmission line de-icing strategy and reduce the damage caused by ice.

Keywords: de-icing; transmission tower; finite element; orthogonal method; unequal tension

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1. Introduction

Power transmission line icing poses a significant threat to the safe and stable operation of the transmission lines [1]. Experience has shown that line icing risk exhibits distinct local characteristics, influenced by micro-topographical factors. The severe icing sections that pose a genuine threat to the fundamental safety of tens of kilometers of lines are generally at the kilometer scale, with 90% being less than 2 km in length. Focusing on melting ice in these kilometer-scale micro-topographical line sections can effectively prevent tower collapses and line breaks caused by ice disasters, thereby reducing the impact on the safe operation of the power grid [2,3].

Hence, portable de-icing technologies for specific line sections have emerged as a research hotspot [4]. Based on the intermediate frequency voltage-regulated rectification inverter topology [5], the State Grid Corporation of China has developed a man-portable

DC de-icing device equipped with a built-in generator to address the challenge of obtaining power sources in the field [6]. This device weighs only 80 kg, with a rated power of 12 kW, a maximum de-icing current of 400 A, and an output voltage range of 15–30 V. Refs. [7,8] introduced a vehicle-based mobile DC de-icing device (MDID) that uses a 6-pulse rectifier to rectify 50 Hz of AC power, adjusting the de-icing current through the control of the triggering angle. In Refs. [9,10], a lightweight DC de-icing power source based on a coaxial modular motor design has been proposed, with a single unit weighing 85 kg, a rated power of 25 kW, capable of dual parallel operation, and a maximum output current of 600 A. Additionally, there are localized de-icing methods for conductors and ground wires, such as blank shell detonation [11,12], robot vibration de-icing [13], and drone-mounted iron rod vibration de-icing [14]. Existing de-icing methods can effectively remove severe icing on conductors and ground wires in icing-affected sections, addressing the challenge of obtaining power sources in the field. However, they seldom consider the mechanical destabilization and damage to the transmission tower structure during the de-icing process. After de-icing a single span of conductors and ground wires, the tower may experience increased unbalanced tension, potentially leading to tower damage [15,16]. Thus, it is very important to study the mechanical effect of melting ice on a transmission tower for the local de-icing of micro-terrain.

For research on the mechanical failure of the transmission tower, numerous scholars have systematically investigated the mechanical characteristics of transmission towers under various loads based on beam element finite element models [17,18]. Rao N. Prasad et al. [19] employed the finite element software MSC-NASTRAN for the nonlinear analysis of transmission towers, and proposed a nonlinear finite element analysis model considering the effects of member eccentricity, beam-column effects, and material nonlinearity. Ref. [20] conducted in-depth research on the mechanical characteristics of tower-line systems with uneven icing, exploring the mechanical characteristics of the tower-line system under uneven icing conditions such as short-span and long-span heavy icing, and central heavy icing in the span. It has been observed that the excessive limit load and unbalanced tension borne by the tower-line system are the primary causes of tower collapses. However, the analysis of how various loads combine and their impact on the unbalanced tension of the tower-line system is not sufficiently in-depth. There is a lack of quantitative research on the mechanical characteristics of the tower-line system under uneven wind and ice loads during the local line section de-icing process [21].

Aiming at the problems existing in the local ice-melting technology of transmission lines, this paper proposed a method for analyzing the impact of local line section de-icing on tower failure based on orthogonal analysis and mechanical finite element calculations. Taking an actual ±800 kV power transmission line as a case study, the 1:1 refined finite element model of the tower-line system was established, and appropriate indicators for tower instability were selected. Using the orthogonal method, the impact of de-icing on each span of conductors and ground wires on tower instability was analyzed. A scientific de-icing strategy has been formulated. Thus, the critical ice thickness and wind speed curves for tower failure have been calculated. The research findings hold significant engineering practical value for safe de-icing decisions and the development of local line section de-icing technologies, as shown in Table 1.

Table 1. Comparison table of the proposed work with the existing work.

Aspect	Existing Work	Inadequacy	References	Proposed Work
Local Line De-icing Technologies	Effectively removes the ice, overcomes the problems of inconvenient transportation in mountainous areas and difficulty in obtain-ing power supply.	Lack of ice-melting strategy.	[4–14]	Research on the de-icing strategy for local line de-icing.
Mechanical Analysis	The mechanical characteristics of the tower under various loads based on beam element finite element models have been studied.	Lack of research on the impact of local ice melting on the unbalanced tension of the tower.	[15–22]	Analyzed based on FEM and orthogonal design.
Optimization Strategy	Heuristic or single-factor approaches.	Lack of criteria for transmission tower failure, and the considerations are also very limited.	[17–19,22]	Considers both the tower displacement and the element stress.
Computational Efficiency	Finite element calculations can analyze the impact of ice melting on the mechanical properties of the tower.	The number of ice-melting combinations for the wires is large, resulting in low cal-culation efficiency.	[20,21]	Orthogonal tests to re-duce the calculation time.

2. Transmission Tower-Line System Model

Take a strain section of a ±800 kV DC transmission line in China as the research object. The section is located on a plateau with an altitude of 2000 m and harsh climatic conditions. The maximum design wind speed is 30 m/s. Each tower consists of three different types of angled steel elements, Q420, Q345, and Q235, respectively. The tension section is composed of two tangent towers and two tension towers. The relevant parameters of the towers and spans are shown in Table 2.

Table 2. Related parameters of the towers and spans.

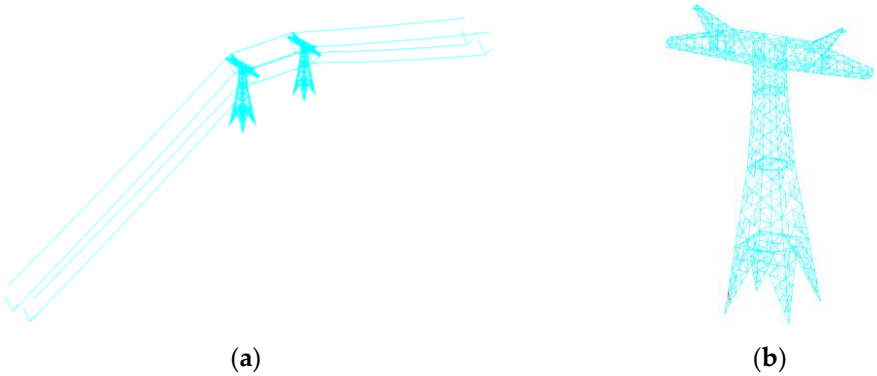
No.	Type	Nominal Height/m	Total Height/m	Altitude/m	Span/m
397	Tension tower	JT61	46.5	64.5	249
398	Tangent tower	Z30601	60	69.8	89
399	Tangent tower	Z30601	72	81.8	320
400	Tension tower	JT61	48	66	/

To calculate the tower stress and deformation caused by uneven loading on the high-voltage transmission tower-line system accurately, the beam element is used to simulate the three types of angled steel used in transmission towers. The link element with nonlinear, stress-stiffening, and large deformation capabilities is used to simulate the conductor and ground wire. For the modeling of the conductor and ground wire, under normal conditions, the conductor and ground wire of overhead transmission lines are in a suspension line structure under the action of gravity, and various forces have reached equilibrium. The 6-split conductor can be equivalent to a single conductor to simplify the model, and the equivalent must ensure that the initial strain, conductor-specific load, and unit cross-section tension are still consistent with the single conductor. The catenary equation of the transmission line is as follows [22]:

$$\begin{cases} y = \frac{\sigma_0 h}{\gamma L_{h=0}}\left(\sinh\frac{\gamma l}{2\sigma_0} + \sinh\frac{\gamma(2x-l)}{2\sigma_0}\right) - \\ \left(\frac{2\sigma_0}{\gamma}\sinh\frac{\gamma x}{2\sigma_0}\sinh\frac{\gamma(l-x)}{2\sigma_0}\right)\sqrt{1+\left(\frac{h}{L_{h=0}}\right)^2} \\ L_{h=0} = \frac{2\sigma_0}{\gamma}\sinh\frac{\gamma l}{2\sigma_0} \end{cases} \quad (1)$$

where l and h are the horizontal distance and vertical distance of the line, respectively. γ is the ratio of gravity per unit length to the cross-section of the wire; σ_0 is the horizontal stress of the wire.

The tower takes each steel element and each string of insulators as a separate unit, and the conductor and ground wire between each segment are divided into 300 units. The 1:1 refined simulation model of the tower-line system is shown in Figure 1.



(**a**) (**b**)

Figure 1. Simulation model of the tower-line system. (**a**) Tower-line system; (**b**) Enlarged view of Tower 398.

3. Orthogonal Test Design of De-Icing for Each Wire

Mechanical failure of the transmission tower is mainly caused by an excessive load and unbalanced tension. When part of the conductors or ground wires melt ice due to natural de-icing or artificial de-icing, the unbalanced tension borne by the tower increases. Therefore, it is necessary to analyze the influence of different ice-covering combinations of the conductors and ground wires on the stress distribution of the transmission tower. By sequencing the effect of the conductors' and ground wires' ice covering on the mechanics of the tower, the optimal de-icing strategy can be obtained.

3.1. Design of the Orthogonal Array

The DC ± 800 kV transmission tower-line system contains 6 conductors and 6 ground wires, as shown in Figure 2. Considering the ice covering of each conductor and ground wire between the three spacing, there are 2^{12} cases of combination, and 4096 finite element simulation calculations are needed to determine the worst de-icing combination, which takes too long. Therefore, the orthogonal design method can be used for analysis [23], which will greatly reduce the workload of simulation calculation and improve the efficiency of analysis.

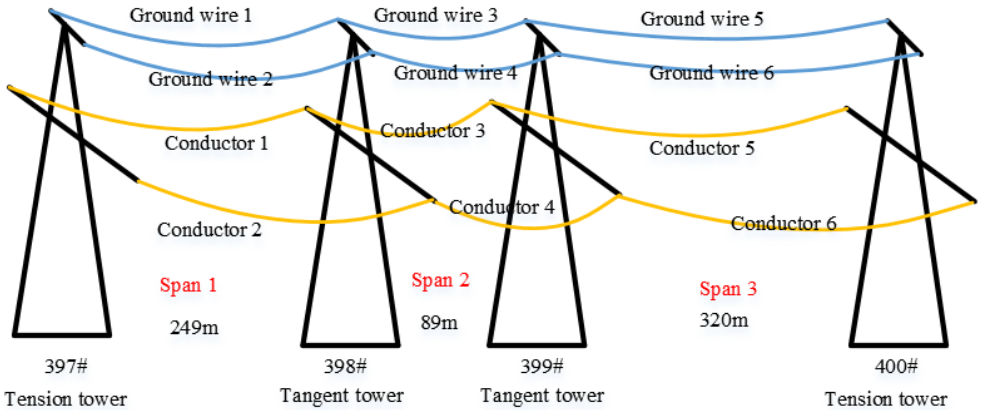


Figure 2. Diagram of tower-line system numbering.

Considering the number of ice melting combinations of each conductor and ground wire, the 15 factors and 2 levels the orthogonal table are selected, and its first 12 columns are taken to correspond to the conductors and ground lines (12 factors) in Figure 2. The last 3 empty columns in the orthogonal table that are orthogonal to the other factors are regarded as the influence of random error on the test index. A total of 16 simulation calculations are required for a given ice thickness and wind speed. The orthogonal table is shown in Table 3. Level 1 indicates that the conductor or ground wire corresponding to the factor has not melted ice, and level 0 indicates that the ice covering the surface of the wire has fallen off. Abbreviate "Condutor 1" as shown in Figure 2 to "C1", "Ground wire 1" to "G1", and so on. For example, the ice combination "111111111111" in Table 3 means that all conductors and ground wires are fully covered with ice.

Table 3. Orthogonal trial plan.

Test No.	Ice Combination											
	C1	C2	C3	C4	C5	C6	G1	G2	G3	G4	G5	G6
1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	0	0	0	0	0
3	1	1	1	0	0	0	0	1	1	1	1	0
4	1	1	1	0	0	0	0	0	0	0	0	1
5	1	0	0	1	1	0	0	1	1	0	0	1
6	1	0	0	1	1	0	0	0	0	1	1	0
7	1	0	0	0	0	1	1	1	1	0	0	0
8	1	0	0	0	0	1	1	0	0	1	1	1
9	0	1	0	1	0	1	0	1	0	1	0	1
10	0	1	0	1	0	1	0	0	1	0	1	0
11	0	1	0	0	1	0	1	1	0	1	0	0
12	0	1	0	0	1	0	1	0	1	0	1	1
13	0	0	1	1	0	0	1	1	0	0	1	1
14	0	0	1	1	0	0	1	0	1	1	0	0
15	0	0	1	0	1	1	0	1	0	0	1	0
16	0	0	1	0	1	1	0	0	1	1	0	1

The wind speed and ice thickness will affect the wind load and ice load of the line, so the analysis results under different wind speed and ice thicknesses may be different. Therefore, based on the transmission line section design wind speed of 30 m/s and ice thickness of 30 mm, a variety of typical wind speeds and ice thicknesses are comprehensively selected for simulation calculation in the test, which will make the final analysis conclusion not affected by the external environment and cover realistic combinations observed in plateau regions.

3.2. Apply Loads and Calculations According to the Orthogonal Table

3.2.1. Calculation of Load

The load applied to the transmission tower-line system includes the ice load and the wind load.

Usually, the ice covering of various types and different surface shapes attached to the transmission line is translated into a circular rime section with a density of 0.9×10^3 kg/m^3. If the ice thickness of the wire is δ mm, the unit ice covering load is shown as Equation (2).

$$g_0 = 9.8 \times 0.9\pi\delta(d + \delta) \times 10^{-3} \quad (2)$$

where d is the calculated outside diameter of the conductor or ground wire.

According to Ref. [9], the ice covering thickness of the ground wire is set to be 5 mm larger than the ice covering thickness of the conductor, and the conductor ice load must be multiplied by the number of splits when calculating.

When the wire is covered with ice, the wind load per unit length of wire generated by horizontal wind is calculated using the following Equation (3).

$$g_1 = 0.625n\alpha\mu_z\mu_{sc}\beta_c B v^2 (d + 2\delta) \sin^2\theta \times 10^{-3} \quad (3)$$

where n is the number of wire splits; α is the uneven factor of wind speed; μ_z is the wind pressure height variation coefficient; μ_{sc} is the type coefficient of the wire; β_c is the wind load adjustment factor; l_H is the horizontal span; B is the increasing coefficient of wind load during ice covering; θ is the angle between the wind direction and the wire.

The ice load on the transmission tower node is equivalent to half of the algebraic sum of the ice load on all the members connected to it, as shown below:

$$F_i = \frac{1}{2}\sum_{j=1}^{m} \rho g (\frac{\pi}{4} h_z D^2) l_j \quad (4)$$

where m is the number of members connected at the tower node; ρ is the density of covered ice; h_z is the coefficient of ice diameter change with height; l_j is the length of the tower element. Considering that there is no heat generated for the tower, the ice thickness of the tower is consistent with the ice thickness of the ground wire.

For the wind load borne by the tower, the wind load acting on the vertical structure surface can be calculated using the following Equation (5).

$$F_t = k k_z k_T A_c \frac{v^2}{1.6} \quad (5)$$

where k is the shape coefficient; k_z is the variation coefficient of wind pressure, which is calculated by interpolation method. k_T is the adjustment factor of wind load. A_c is the wind blocking area of the tower element.

3.2.2. Load Application and Calculation

In the simulation, the self-weights of the conductors, ground wires, and towers are first set, and then the ice load and wind load as described above are, respectively, applied to them, and the loads are all loaded to the nodes of the tower-line system in the form of concentrated force. The tower base is deeply buried in soil, and the displacement of the foundation needs to be considered only when the foundation of the transmission tower experiences settlement. This paper aims to study the stability of the tower during the ice-melting process. Therefore, the connection nodes between the tower foundation and the ground can be regarded as fixed points in the calculation. At the same time, considering that the offset of the tension tower under unbalanced tension is relatively small, it is assumed that the conductor and ground suspension points of the two tension towers will not move. Therefore, zero displacement constraints are applied to all degrees of freedom of each tower foundation node and the wire suspension points of the two tension towers.

Taking orthogonal test 6 as an example, the corresponding levels of conductors 1, 4, and 5 and ground wire 4 and 5 in Table 2 are 1, and the others are 0. Therefore, ice load and wind load are applied to wires 1, 4, and 5 and ground wires 4 and 5 when loading, while other conductors and ground wires only load wind load. When loading, the wind speed is 30 m/s and the ice thickness is 40 mm. The geometric nonlinearity of the transmission tower-line system is considered in the calculation. After the calculation is completed, the node displacements of transmission tower No. 398 and 399 are extracted, as shown in

Figure 3, and the stress values of each element of the towers are extracted, as shown in Figure 4.

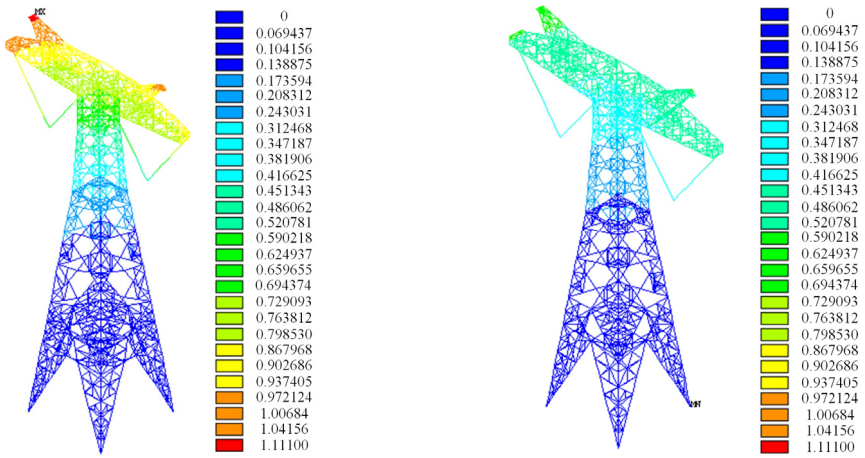


Figure 3. Node displacement nephogram of the transmission tower. (**a**) Tower 398; (**b**) Tower 399.

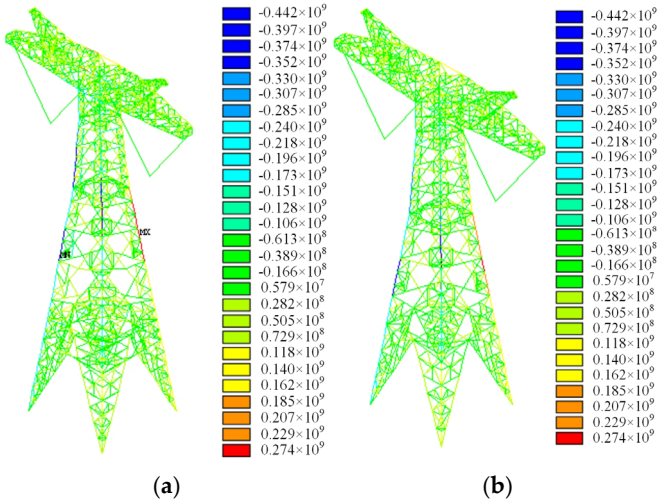


Figure 4. Element stress nephogram of the transmission tower. (**a**) Tower 398; (**b**) Tower 399.

As shown in Figure 3, under the combined conditions of the conductor and ground wire ice covering corresponding to test 6, the maximum displacement of the transmission tower appears at the top of the tower, and the displacement of tower 398 is much larger than that of tower 399. From Figure 4, the greatest stress of the two transmission towers is located at their waists under the current calculation conditions. And the maximum stress of the main element of the No. 398 transmission tower reached 274 MPa.

4. Analysis of Orthogonal Test Results

The purpose of the orthogonal test is to analyze the effect of different wires' ice melting on the mechanical failure of the transmission tower. In general, when the stress of part of the main beams and diagonal beams exceeds its yield strength, the tower has the risk of mechanical failure. In addition, the standard [24] stipulates that the top displacement of the high-voltage transmission tangent tower shall not exceed 3/1000 of its tower height. Thus, considering the influence factors of the mechanical failure of the transmission tower comprehensively, the following two calculation indexes are selected as the indexes of orthogonal test analysis:

(1) The first test index is the stress ratio of the beam, which is calculated as follows:

$$\gamma = \left| \frac{\sigma_{eq}}{[\sigma]} \right| \tag{6}$$

where $[\sigma]$ is the allowable stress of the beam element, σ_{eq} is the absolute value of the beam stress. If $\gamma > 1$, it indicates that the equivalent stress of the bar exceeds the allowable stress value, and the beam element has failed.

(2) The second test index is the horizontal displacement of the top node of the transmission tower.

The orthogonal test results have been analyzed using the above two test indexes. Firstly, the range analysis method is used to determine the conditions in which the different melting combinations lead to the maximum test index value. The test indexes' sum k of each factor are calculated at different levels.

$$k_i(j) = \frac{\sum_{1}^{n(i)} \Omega(i,j)}{n(i)} \tag{7}$$

i is level 0 or 1, j is the factor, $n(i)$ is the number of occurrences of level i in the j column of the orthogonal table, and $\Omega(i, j)$ is the total value of indexes of the corresponding test with level i.

According to the value of k, the most severe combination can be obtained. The advantages of this method are simple, and the disadvantage is that the confidence coefficient of the optimal level of each factor cannot be determined, and the influence of random error on the test results cannot be considered. Then, by using the method of the experiment and mathematical statistics, this paper analyses the results of the 16 orthogonal experiments and obtains the variance ratio F of each factor. The corresponding F of a factor is the variance of each corresponding column divided by the variance of the error. F represents the confidence coefficient of a factor, and the influence degree of each factor can be obtained. The most severe combination determined by the range analysis method is shown in Table 4.

Table 4. Most severe combination under different weather conditions.

Wind Speed	Ice Thickness	Most Severe Combination Index 1	Most Severe Combination Index 2	Wind Speed	Ice Thickness	Most Severe Combination Index 1	Most Severe Combination Index 2
22 m/s	20 mm	110111010011	101010101010	26 m/s	40 mm	101011001011	101010101010
22 m/s	30 mm	110111000111	101010111010	26 m/s	50 mm	100011011011	101010101010
22 m/s	40 mm	110011000111	101010111010	30 m/s	20 mm	100011011011	101010111010
26 m/s	20 mm	110011000111	100010111010	30 m/s	30 mm	100011010011	101010111010
26 m/s	30 mm	101011001011	101010101110	30 m/s	40 mm	101011001011	101010101110

From Table 3, the most severe combination of different wind speeds and ice thicknesses can be changed slightly, and the selected test indexes influence the results of orthogonal analysis. But under the same index, most of the factors are basically unchanged. For example, when the displacement of the top of the tower is the index, the other factors will always be 0 or 1, except for factors 8 and 10. Therefore, in order to determine factor 8 and other uncertainties, the variance analysis method should be used. It can be seen from the distribution table of F that the factor with an F value greater than 10.13 has a more than 95% confidence coefficient, and the factor with an F value greater than 5.54 is a 90% confidence coefficient. And the greater the confidence coefficient, the greater the influence of this factor on the results. Due to different orthogonal groups in different weather conditions,

the variance ratio F of different orthogonal groups is tremendous. This paper gives the frequency of occurrence of F whose value is greater than 5.54, as shown in Table 5.

Table 5. Frequency of confidence coefficient greater than 90% of each factors.

Factor	Frequency of Occurrence		Factor	Most Severe Combination	
	Index 1	Index 2		Index 1	Index 2
1	6	10	7	0	0
2	4	10	8	0	0
3	0	5	9	0	5
4	3	10	10	0	0
5	10	10	11	9	10
6	7	10	12	8	9

According to Table 4 and the mean values of F of each factor to rank the importance of each factor, the most reliable factors include lines 1, 5, 6, 11, and 12, comparatively important factors are lines 2, 3, 4, and 9, and the least important factors are lines 7, 8, and 10, whose F values are close to F values of error obtained from the final three columns of the orthogonal table. The effect of conductors and ground wires corresponding to the least important factors on tower failure is negligible. Therefore, when reliable factors achieve an optimal value, the probability of tower failure is greatest. Combining with the most severe combination of different weather conditions, the worst combination can be obtained, index 1 corresponds to condition combination of ice cover 1000110x1011, index 2 corresponds to condition combination of ice cover 1010101x1010, and the level x can be 0 or 1, which does not make much difference to the tower failure. So, there are four of the worst combinations, the four kinds of combinations are verified in this paper, the results show that all the peak stress ratios of the main element or diagonal element of the former two combinations are bigger than the results of those combinations in the orthogonal table, and all the horizontal displacement of the tower top nodes of the latter two combinations are bigger than the results of those combinations in the orthogonal table. The reliability of the orthogonal test results is proven.

To analyze the actual terrain of the tower-line system, factors 5, 6, 11, and 12 correspond to the conductors and ground wires of the span 3, the length of span 3 is much larger than the other two spans, and the altitude of tower 399 and tower 400 is much different. Therefore, it has a great influence on the unbalanced tension of the transmission tower, which reflects the reliability of the orthogonal test results. From the results of the orthogonal analysis, generally when the conductors and ground wires of the windward side are covered with nothing, and the conductors and ground wires of the leeward side are covered with ice, the tower-line system is more likely to fail. Due to the high confidence coefficient of factors 1, 5, 6, 11, and 12, these lines must be much accounted for when developing ice-melting strategies.

Since the combination factors 1, 5, 6, 11, and 12 are determined with high confidence, and the values of these factors are all 1 in the worst combination for the tower failure, this means that whether the conductor and ground ice melt at these numbered places has the greatest influence on the unbalanced tension and load of the tower-line system. When formulating ice melt strategies or preventing tower tipping accidents, priority should be given to ensuring that these conductors and ground lines melt ice in time or make their ice thickness not too large to prevent excessive unbalanced tension caused by improper ice melting. According to the confidence degree of each factor and its value on the mechanical instability of the tower obtained by the orthogonal test, the optimal ice melting order is as follows: conductor 5 in span 3, ground wires 11 and 12 in span 3, conductor 6 in span 3, and conductor 1 in span 1. As for the ice melting order of other lines, it has little influence

on the mechanical characteristics of the towers, so the ice melting order can be formulated according to the distance of the span distance.

5. Tower Failure Analysis Under the Most Dangerous Ice Melting Condition

A transmission tower is a construction with a tall structure composed of angled steels, which belongs to the high-order super-static structure system. The failure of an individual structural component does not inevitably result in the collapse of the entire transmission tower system, but when the corresponding component's damage reaches a certain number, the local section of the tower fails gradually, then even the whole tower ultimately fails. At present, many experts and scholars have studied the failure of the tower structure system. In general, the failure criterion of a transmission tower structure system can be roughly classified into the following three kinds of circumstances [25,26]:

(1) The structure of the tower becomes a single mechanism. The criterion is that after the failure of some components, the total stiffness matrix of the residual components is singular.
(2) The structural deformation is greater than the allowable value. If the top displacement of the tower exceeds a certain value, the transmission tower will be considered a failure.
(3) The structure cannot bear the extra load or a lower structural bearing capacity occurs for the first time. Generally speaking, the transmission tower will be considered a failure when the stress ratio of the main components of the tower is too large.

Based on relevant literature and standards, the classification failure criterion of the tower-line system is shown in Table 6. There are three levels of failure: minor damage, moderate damage, and serious damage. ξ is the peak value of the stress ratio of elements, l is the horizontal displacement of nodes of the tower top, and h is the tower height.

Table 6. Grading failure criteria of tower-line system.

Category	Minor Damage	Moderate Damage	Serious Damage
Stress ratio of main beam	$\xi > 1.0$	$\xi > 1.15$	——
Stress ratio of diagonal beam	$0.8 < \xi < 1.0$	$1.0 < \xi < 1.15$	$\xi > 1.15$
Horizontal displacement of the tower top	——	$3h/1000 < l < h/100$	$l > h/100$
Convergence of program	——	——	Program cannot converge

Based on the most severe combination determined by the range analysis method, the wind speed and the ice thickness have been changed to study the failure of the tower-line system under different environmental loads, and we obtained the general trigger range of tower failure. Refer to Table 5, and the critical failure curves of the ±800 kV DC transmission tower-line system are shown in Figure 5.

From Figure 5, the minimum thickness of ice when the tower-line system fails is significantly reduced with the increase in wind speed. When the wind speed is less than 20 m/s, the minimum thickness of ice of failure curve at all levels is not much different with the increase in wind speed, mainly because the wind load is positively correlated with the squared wind speed, and the wind load is small when the wind speed is small. It is recommended that the tower-line system should be noticed when the ice thickness of the transmission lines is above 25 mm, and some ice melting measures should be taken in

a timely manner. When the wind speed exceeds 20 m/s, the ice thickness of the failure reduces evidently. When the wind speed exceeds 26 m/s, even if the ice thickness is smaller than about 10 mm, the tower still has a risk of mechanical failure. The calculated results are close to the designed wind speed and designed ice thickness of the tower, verifying the accuracy of the calculation results.

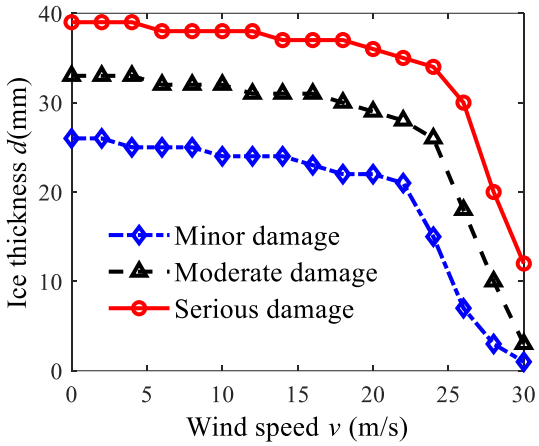


Figure 5. The critical failure curves of the tower-line system.

6. Conclusions

This paper proposed a method for failure analysis and a safety de-icing strategy of a local transmission tower-line system based on orthogonal analysis and mechanical finite element analysis. The research work helps to prevent the failure of transmission towers caused by ice melting. The following conclusions are made:

(1) Orthogonal test results show that conductors 1, 5, and 6 and ground lines 11 and 12 icing or not has a great impact on the mechanical failure situation of the whole tower-line system, and conductors and ground lines with large span lengths and large altitude differences in icing have a greater impact. Meanwhile, from the results of optimal combination, no icing at the windward side and icing at the leeward side can cause larger unbalanced tension on the tower, wherein the risk of tower collapse is significantly elevated. Therefore, the ice on these lines should be preferentially removed when melting ice.

(2) The ice thickness–wind speed critical failure curves of the tower-line system have been proposed. When the ice thickness of the transmission lines is above 25 mm, some ice melting measures should be taken in a timely manner. When the wind speed exceeds 20 m/s, the ice thickness of the tower failure reduces evidently. When the wind speed exceeds 26 m/s, even if the ice thickness is smaller than about 10 mm, the tower still has a risk of mechanical failure.

(3) Next, research on the real-time de-icing system can be carried out based on the work of this paper. The ice–wind critical failure curve is pre-input into the system, thereby enabling the prediction of ice disaster on transmission lines and the determination of the conditions for ice-melting initiation. Subsequently, based on the current situation of the ice-melting equipment, differentiated efforts will be made to conduct ice melting on specific sections of the conductors and ground wires. The application of the system will help reduce the hazards and losses caused by ice formation on transmission lines.

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