Comprehensive evaluation system of transmission tower foundation safety

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Abstract: With the expansion of power grid construction scale, the upgrading of transmission current level and the innovation of current transmission technology, we are forced to pay close attention to the safety management of transmission projects, which is very important for social security and development. As an important part of the power grid, the stability and security of the transmission tower are closely related to the safe operation of the whole power grid. Therefore, the construction and maintenance of transmission towers need a set of scientific, quantitative and systematic safety evaluation methods. This paper will sort out the influencing factors that affect the safety of transmission towers, and then introduce a variety of mathematical models and methods to establish a perfect safety evaluation system.

1. Introduction

With the increasing power demand in China, the shortage of land resources and the improvement of environmental protection requirements in China, the problems of route selection and demolition of houses along the line are becoming more and more serious, which promotes the rapid development of large-capacity and high-voltage transmission lines, and the high-voltage AC 750, 1000kV and DC ±800kV transmission lines gradually appear. The tower tends to be large, and the design load of the tower gradually increases, which greatly enhances the requirements for the safety performance of the transmission tower.

The transmission tower has been in the wild for a long time, and it often works in harsh environment. The frequent occurrence of extreme weather and natural disasters increases the safety risk of the transmission tower. Its stability and safety are closely related to the power operation safety and social impact, and once destroyed, it will cause incalculable losses and adverse social impacts. Therefore, it is of great social significance and economic value to establish a complete safety evaluation system for transmission towers.

Scholars at home and abroad have done some research on the establishment of safety evaluation system: the commonly used qualitative safety evaluation methods mainly include expert argumentation method, Delphi method, brainstorming method, safety checklist method, operation condition risk evaluation method, WBS method and system analysis method, etc. For example, after studying and analyzing the risk factors affecting safety, M.Osama conducts safety evaluation on the construction site through actual site inspection and with the help of standard checklist [1]; Zhao Tingsheng and others used expert assessment and safety risk checklist to track and monitor the safety
risks in the construction process, and established the dynamic management theory of safety risks in the construction process from the aspects of dynamic monitoring operation mode, organization and procedure, and dynamic safety risk assessment grade standard. Based on the existing research results of scholars at home and abroad, this paper innovates and constructs a unique and perfect safety evaluation system. After collecting the research literature at home and abroad and the historical accident records of the power tower, we summarize the main safety problems existing in the power transmission tower itself, and finally decide to analyze the safety of the power transmission tower from four aspects: its own structure, material influence, geological condition and working environment. After comprehensively comparing various safety evaluation methods, this paper decided to introduce GI method and expert evaluation method to determine the subjective and objective weight ratio of each influencing factor, and then established a multi-level index system of influencing factors of transmission tower by using AHP combined with fuzzy comprehensive analysis.

2. Establish the safety evaluation index system of transmission tower
We have preliminarily summarized the safety evaluation indexes of the transmission tower, which are as follows:

1) stable structure
   The safety of the transmission tower itself is characterized by the stress of the tower and the actual strength of the tower material [3]. As the main support point of overhead lines, the transmission tower is a high-rise tower structure widely used in transmission line engineering. Due to the high-rise structural characteristics of the transmission tower, it is very sensitive to tilt deformation and has high requirements for uneven settlement of the foundation. It is a lattice structure composed of steel members connected by joint plates and bolts. The horizontal section of the tower is generally quadrilateral, which is mainly composed of top frame, tower head, lightning wire, conductor, tower body and tower legs, and is a spatial truss structure. There are many classification methods for transmission towers. According to its different structural forms, it can be divided into two types: pull-line type and self-supporting type; According to its different positions in the line, it can be divided into straight tower, tension tower and corner tower; According to the cross-section form of transmission tower components, it can be divided into steel pipe transmission tower (as shown in Figure 1.1) and angle steel transmission tower (as shown in Figure 1.2); According to different shapes, it can be divided into dry-shaped tower, cat head tower, wine glass tower and so on. With the rapid development of China's electric power industry, the structure of transmission tower is becoming more and more complex, and different structures have a significant impact on the stress distribution and mechanical performance of the tower.

![Figure 1. Steel Tube Transmission Tower](image1)

![Figure 2. Corner Transmission Tower](image2)

2) Material condition
   When the transmission tower is in actual service, it works in the natural environment where fatigue corrosion and fatigue alternate, so the tower will be affected by acid rain and wind, which will easily
lead to serious problems such as corrosion, aging and concrete cracks. Moreover, the nodes of the transmission tower are numerous and extremely important in the whole structure. As the weak link of the power tower structure, the nodes are easy to be destroyed, which will have an indelible adverse impact on safety.

3) Geological disasters
Because the northwest region of China is mostly plateau, and the south, central and eastern regions are mostly hills and mountains, which have complex topography and meteorological conditions, as the main carrier of power network, overhead transmission lines inevitably have to cross these plateaus, hills and mountainous areas, which are distributed in the wilderness, with many points, long lines and wide areas. The geographical, geomorphological, surrounding environment and meteorological conditions of the lines are complex, so they are easily covered. It will inevitably be built in various extremely harsh geographical environments, including areas with high earthquake intensity or frequent earthquakes. Compared with conventional structures, the transmission tower-line system has the characteristics of high tower body, large span and strong flexibility of the whole structure, which is extremely sensitive to earthquake action. Transmission towers are prone to vibration fatigue damage and dynamic collapse, which will have a serious impact and change on the stable development of society and people's lives. As the medium of power transportation, the normal and stable operation of transmission tower is related to the normal implementation of national security strategy and the rapid development of social economy. It is very important to incorporate geological conditions into the safety evaluation system of transmission tower.

4) Environmental impact
The geographical environment of the transmission tower is complex, which often passes through complex terrain such as mountains, dense forests, rivers. The transmission tower is often built on the top of a mountain or a hillside, which is easily affected by extreme weather such as lightning strikes, heavy rains, freezing and thawing. Compared with the above-ground engineering structure, the foundation environment of the transmission tower is hidden and the service environment is complex. In the underground environment, the transmission tower is not only eroded by corrosive ions in groundwater and rock and soil particles, but also the parts close to or exposed to the ground are exposed to CO₂ or Cl in the air. And the transmission tower is a wind-sensitive structure. Because of its large windward area, the transmission tower-line system has strong tower-line coupling effect under the action of strong wind, and the wind-induced vibration response and stress situation of the transmission tower are more complex. The environmental impact on the evaluation framework of transmission tower safety structure design cannot be ignored.

To sum up, we divide the structural stability, material condition, geological disaster and environmental impact of the transmission tower in detail, and get the safety evaluation index system of the transmission tower foundation.

3. Safety assessment method of transmission tower

3.1 Determine the index weight

3.1.1 GI Method to Determine Weight
Invite experts to sort the determined index sets according to their importance, assuming that the sorting result is S₁>S₂>S₃>S₄>S₅>S₆, and then scientifically compare the importance between adjacent indexes Sj-1 and Sj, and get Rj=Sj-1/Sj, where j = 1, 2, and z. (1 < Rj < 2, the importance of Sj-1 over Sj increases with the increase of rj) [5].

1) calculate the weight of the first-level index to the target layer, calculate the weight Uz of the z-th first-level index to the target layer according to G1 weighting method,

2) In the same way, the weight Uj of each secondary index (Sj1, Sj2, Sj3) (j=1, 2, 3 ...) to the primary index is calculated by the same method. Then, calculate the weight of the secondary index to the target layer, and the calculation formula is as follows:
\[ W_j = U_s \times U_j \]  

(1)

(3) Blindness analysis

In order to reduce the influence of the degree of uncertainty in the scoring process of different indicators by various experts, we will conduct blind analysis on the scoring process of experts.

Firstly, \( D_{ij} \) (i.e., the information entropy of the \( i \)-th expert to the \( j \)-th index) is calculated by using the information entropy formula, and then the average recognition degree \( D_j \) (i.e., the "consistent views" of all experts on the importance of the \( j \)-th index) is obtained by using the average method

\[ D_j = \frac{D_{1j} + D_{2j} + \ldots + D_{mj}}{M} \]  

(2)

Experts' cognition of safety evaluation system will produce uncertainty. This objective cognitive uncertainty is called cognitive blindness \( T_j \), which can be quantified by fuzzy analysis of uncertainty.

According to the average cognition degree \( D_j \) and cognition blindness \( T_j \) of experts on a certain index calculated above, the overall cognition degree of \( M \) experts on index \( J \) is \( P_j \), and the revised information entropy \( Q_j \) is obtained by modifying it at the same time.

According to the calculated \( Q_j \), an expert evaluation vector set \( Q = \{Q_1, Q_2, Q_3, Q_4 \ldots Q_J\} \) is formed.

Then, the normalized equation is used to process the data of the evaluation vector, and the weight \( W_j \) of each index is obtained. The calculation formula is as follows:

\[ W_j = \frac{Q_j}{\sum_{j=1}^{n} Q_j} (j = 1, 2, \ldots, n) \]  

(3)

3.1.2. Structural entropy modified G1 method to determine comprehensive weight

First of all, when G1 method judges the importance of indicators, experts directly judge and sort them, which is quite subjective. The structural entropy weight method can be used to find the revised information entropy to judge the importance of indicators, which can eliminate the uncertainty of expert judgment and objectively rank the importance of indicators.

Then, using two different methods, the weights of the indicators are calculated respectively. At this time, the same indicator has two weights, which need to be calculated and reorganized, and the result after reorganization is the final comprehensive weight. After literature review, there are many researches on the related combination weighting. In this paper, Lagrange extremum method is used to determine the undetermined coefficients of the two weights.

3.2. Safety Fuzzy Comprehensive Evaluation

Firstly, the index factor set of fuzzy comprehensive evaluation is established [6], and the related index set \( A = (A_1, A_2, A_3, A_4) = \) (structural stability, material condition, geological disaster, environmental impact) is established according to the previous article. Then, a fuzzy comprehensive evaluation comment set \( B = (B_1, B_2, B_3, B_4, B_5) = \) (very safe, very safe, safe, unsafe and extremely unsafe) is constructed. Then, according to the above weight calculation process, the final weight set \( W = (W_1, W_2, \ldots, WM) \) of transmission tower safety evaluation index is obtained.

M experts are invited to make fuzzy evaluation on each single index in the comment set \( B \) respectively, and a evaluation result of each index is obtained to construct the evaluation matrix \( C \). The formula is as follows:

\[ C = (C_{ij})_{m \times n} = \begin{bmatrix} C_{11} & C_{12} & \ldots & C_{1n} \\ C_{21} & C_{22} & \ldots & C_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ C_{m1} & C_{m2} & \ldots & C_{mn} \end{bmatrix} \]  

(4)

In which \( m \) is the number of experts; \( N \) is the number of indicators (\( n = 4 \)).

Then, according to the evaluation results, the frequency of each index is calculated, and the membership degree of each index is obtained, and finally the fuzzy evaluation matrix \( R \) is constructed, and the formula is as follows:
\[ R = R_{i5} = \begin{pmatrix} R_{11} & R_{12} & \cdots & R_{15} \\ R_{21} & R_{22} & \cdots & R_{25} \\ \vdots & \vdots & \ddots & \vdots \\ R_{i1} & R_{i2} & \cdots & R_{i5} \end{pmatrix} \] (5)

I is the number of indicators (i=4).

According to the analysis flow of fuzzy comprehensive evaluation, the final data is processed, and then the weight set \( w \) of safety evaluation index and the evaluation matrix \( r \) of safety evaluation index are obtained. According to the fuzzy comprehensive evaluation algorithm, the fuzzy comprehensive evaluation result \( I \) of transmission tower safety can be obtained by combining the two, and the formula is as follows:

\[ I = W \times R \] (6)

According to the principle of maximum membership degree, the final result \( I \) is judged. Select the evaluation in the fuzzy comment set corresponding to the maximum value in \( I \), and give the final evaluation result to determine the safety level of the transmission tower. In this method, GI method combined with structural entropy weight method is used to determine weights, which solves the problem of proportional distribution of subjective and objective weights. It not only ensures that the professional opinions of experts are reflected when determining weights, but also eliminates subjective errors of expert evaluation by using objective weighting method in structural entropy weight method. This method greatly increases the reliability of safety evaluation system of transmission towers. Finally, the fuzzy mathematics principle is adopted to construct a model and comprehensively evaluate all evaluation indexes. This method can quantitatively study the indexes with unclear boundary and difficulty in quantification in the process of safety assessment, and solve the problems of complex indexes and diversified evaluation standards.

4. Conclusion

According to the structural characteristics and historical safety accidents of the transmission tower structure, this paper analyzes and summarizes the literature related to the research, safety evaluation and related experts and scholars of the transmission tower structure, preliminarily sorts out the safety influencing factors, and after questionnaire investigation and analysis, screens out four factors with high correlation, namely, structural stability, material condition, geological disaster and environmental impact. We set out to establish the final safety evaluation index system from these four aspects. After comprehensive consideration of various safety evaluation methods, a complete safety evaluation model of transmission tower foundation is constructed by using analytic hierarchy process and fuzzy judgment matrix, which can accurately grade the safety influencing factors and determine the safety evaluation grade of transmission tower.

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