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Research Article

A Real-Time Reliable Condition Assessment System for 500kV Transmission Towers Based on Stress Measurement

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Transmission power towers play an important role in power delivery systems. In recent years, some important results on reliability of transmission towers have been obtained based on theoretical analysis, but there are very few practical application systems of real-time condition monitoring. This paper proposes a new real-time reliable condition assessment system for 500kV transmission power towers based on stress measurement. The necessity of such systems and the architecture of the online monitoring system will first be presented. Through calculating the stress distribution condition of different components of the transmission tower under typical working conditions, those positions with relatively high failure probability in the transmission tower can be identified monitored for installing the stress sensors on them. A new method is presented for calculating the reliability index of the transmission tower structure is also developed based on the mechanical structure of the tower. In particular, the tower structure is simplified to a series system, and the *Ditlevsen's bounds* is used to estimate the reliability of the tower system. Finally, a designed example for the online reliable condition assessment procedure is given using a 500kV oxytropis tower as an illustration.

1. Introduction

Transmission power towers are important parts of power transmission and distribution systems. Their failure would lead to severe consequences. In recent years, accidents in power grid caused by adverse weather conditions and climate are increasing. For example, many transmission towers were wrecked in South China in 2008 due to a large-scale ice disaster, which caused catastrophic damages to China power grid. Preventing the occurrence of such incidents has been research focus on transmission lines safety in recent years [1–3]. In the transmission tower-line system, towers should bear its weight and those of the lines, by producing a certain tension load for hanging the lines. Consequently, the stress distribution in transmission towers reflects not only the mechanical load of the transmission towers, but also the resistance tension of the lead wires and ground wires. Therefore, reliability assessment of power tower structures under various conditions has important theoretical as well as practical significance.

Considerable works have been devoted to the system reliability assessment of structures. In [2], the safety of power transmission line structures under wind and ice storms was evaluated. In [3], the reliability of a 1000kV UHV transmission tower considering icing was analyzed. In [4], the reliability analysis of a 75m tall steel microwave tower under wind load was presented. Reliability theory was also used to analyze 500 kV transmission towers considering wind and ice loads in [5]. In [6], the idea of equivalent extreme-value event was used to evaluate of the structural system reliability. A hybrid experimental/analytical framework for condition assessment and life prediction of existing structures was also developed in [7]. The durability of natural-draught cooling towers was investigated using finite element reliability analysis in [8]. To solve the computational complexity of structure function, two algorithms for calculating Direct Partial Boolean Derivative based on BDD of structure function are proposed in [9].

All these aforementioned works on reliability assessment of structure are theoretical analysis or simulations which are carried out by theoretical calculation. With the development of modern measurement technologies, novel online health monitoring systems of steel structures have been developed and employed for safety inspection in the last few years [10–12]. However, there are very few practical systems for real-time monitoring or condition assessment of transmission power towers structure currently.

Under different loads, the steel structures of the transmission tower will subject to certain degree of deformation. Generally, this deformation is so slight that it is difficult to be observed directly by human. However, it can be measured by stress (strain) sensors. In fact, the real-time reliable condition assessment of transmission tower has both theoretical and practical significance. It can provide online monitoring of stress at critical positions of the transmission tower and hence real-time reliability assessment of the tower.

In this paper, a real-time reliable condition assessment system for transmission power tower based on stress measurement is proposed. In particular, measured stress data from strain/stress sensors installed in the tower is used to evaluate the reliability of the structure. To this end, the positions of stress sensors need to be determined and a method based on finite element analysis is proposed in our previous work [1]. It calculates the stress distribution of different components of transmission tower under typical working condition, and finds the positions with relatively higher failure probability. The stress sensors are hence installed in these positions to better monitor and evaluate the condition of transmission tower. The next important issue is how to evaluate the reliable condition of the structure given these measured data. Transmission tower has a complicated structure made up of thousands of pole members, and hence its reliability is difficult to calculate directly. In this paper, the reliability of the whole tower structure is simplified to the reliability of a series system which consisted of main bars. Consequently, the *Ditlevsen's bounds* is used to calculate the reliability of the structure.

The rest of the paper is organized as follows: Section 2 introduces the proposed system architecture and method to determine the installation positions of the stress sensors on the tower, which are our previous work[1]. Section 3 discusses the proposed approach to assess the reliability of transmission tower structure based on the sensor measurements. In Section 4, a 500kV oxytropis tower is used as an example to present the procedure for evaluating the reliability of the structure. Finally, conclusions are drawn in Section 5.

2. System Architecture and Stress Sensors' Installing Positions

The system architecture of the real-time reliable condition assessment system has been introduced in our previous work [1]. Particularly, the monitoring system works in the field and must consider communication, power supply, and waterproofing of equipments. The real-time monitoring system is composed of stress sensors installed on the tower, data acquisition-communication equipment in field, and a backend server in control center, as shown in Figure 1. The acquisition-communication equipment is responsible for acquiring and processing data from sensors, correcting the data based on temperature, encapsulating them after stress calculation and sending them to the server. The front-end acquisition-communication equipment is integrated with a communication module, which communicates using GPRS/CDMA.

The method to determine the installation positions of the stress sensors on the tower is based on finite element analysis. By calculating and comparing the force of the tower the force of the tower, those positions with relatively high failure probability in the transmission tower can be identified for installing the stress sensors. The procedure has been described in our previous work in detailed [1].

3. Reliability of Transmission Tower Structure

In the reliable condition assessment of the transmission tower, the main task is to evaluate the reliability index of the tower structure. Conventionally, the reliability index of complicate system can be obtained by two steps: (1) calculating reliability index of each component and (2) obtaining system reliability index based on (1) by system reliability theory.

3.1. Reliability Analysis of Structure Components. For a structure component, its reliability is decided by several random factors, such as load types, material strength, and geometry. Usually, these random factors are called basic variables, expressed by $x_i, i = 1, 2, \ldots, n$. In general, the limit state function of structure is given by

$$Z = g(x_1, x_2, \ldots, x_n) = 0. \tag{1}$$

The limit state is reached when

$$Z = g(x_1, x_2, \ldots, x_n) \leq 0. \tag{2}$$

The limit state function can be expressed using Taylors series, and if the first-order terms are retained, then it can be simplified as follows:

$$g(x_1, x_2, \ldots, x_n) \approx g(x_1{}^*, x_2{}^*, \ldots, x_n{}^*) + \sum_{i=1}^{n} (x_i - x_i{}^*) \left(\frac{\partial g}{\partial x_i}\right)_{x_i{}^*}, \tag{3}$$

where $x_1{}^*$ is the linearization point and the partial derivatives are evaluated at this point, where it can be set as the mean value $(E(x_1), E(x_2), \ldots, E(x_n))$.

The mean and variance of Z are then approximated by

$$u_z \approx g(u_1, u_2, \ldots, u_n), \tag{4}$$

$$\sigma_z^2 \approx \sum_i \sum_j^n (x_i - x_i{}^*) \left(\frac{\partial g}{\partial x_i}\right)_{\overline{x}^*} \left(\frac{\partial g}{\partial x_j}\right)_{\overline{x}_j} \rho_{x_i x_j} \sigma_{x_i} \sigma_{x_j} \tag{5}$$

where $u_i = E(x_i) = \overline{x_i}$ is the mean point, $\rho_{x_i x_j}$ is the correlation coefficient between x_i and x_j, $(\partial g/\partial x_i)_{\overline{x}^*}$, and $(\partial g/\partial x_j)_{\overline{x}_j}$ denote the partial derivatives at the mean point.

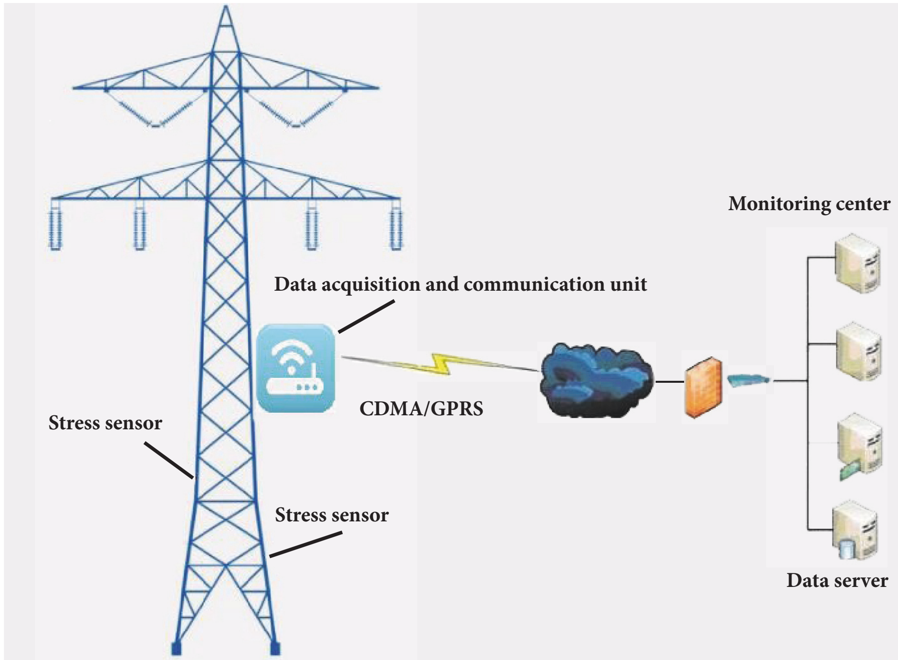

Figure 1: Block diagram of System Structure.

If the variables x_i are statistically independent, (5) can be simplified to

$$\sigma_z^2 \approx \sum_i \left(\frac{\partial g}{\partial x_j}\right)_{\overline{x}_j} {\sigma_{x_i}}^2. \tag{6}$$

The standardized margin G_Z, which has a zero mean and a unit standard deviation, can be written as

$$G_Z = \frac{Z - u_z}{\sigma_z} \tag{7}$$

Failure occurs when $Z \leq 0$ so that the probability of failure can be written as $P_f = P[Z \leq 0]$.

$$P_f = P[Z \leq 0] = F_Z(0) = F_{G_Z}\left(\frac{-u_z}{\sigma_z}\right) = F_{G_Z}(-\beta) \tag{8}$$

where $\beta = u_z/\sigma_z$ is the reliability (or safety index), which is the inverse of the coefficient of variation of safety margin.

Considering a steel rod under pure tension loading, the rod will fail if the applied stress on the rod cross-sectional area exceeds the steel yield stress. The yield stress R of the rod and the loading stress on the rod S are assumed to be uncertain, and they are modeled by uncorrelated normal distributed variables. The system function of the structure in terms of R and S can be expressed as follows:

$$Z = g(S, R) = R - S. \tag{9}$$

Then Z is also fitting normal distribution. According to (4) and (6), the following results are obtained:

$$\begin{aligned} u_Z &= u_R - u_S, \\ \sigma_Z &= \sqrt{\sigma_R^2 + \sigma_S^2}. \end{aligned} \tag{10}$$

The reliability of the structure is thus given by

$$\beta = \frac{u_Z}{\sigma_Z} = \frac{u_R - u_S}{\sqrt{\sigma_R^2 + \sigma_S^2}}. \tag{11}$$

In order to be able to use (11) approximately, in the case of nonnormal variables, a transformation of these variables into equivalent normal variables is necessary. By requiring that the cumulative distributions and the probability density functions of both the actual distribution and the normal distribution be equal at the linearization point, one can determine the mean u_x' and standard deviation σ_x' of the equivalent normal variable, that is,

$$F_x(x^*) = \Phi\left(\frac{x^* - u_x'}{\sigma_x'}\right) \tag{12}$$

and

$$f_x(x^*) = \frac{1}{\sigma_x'}\varphi\left\{\Phi^{-1}\left[F_x(x^*)\right]\right\} \tag{13}$$

where $\varphi(.)$ is the standard normal probability density, $\Phi(.)$ is the standard normal distribution function, and u_x' and σ_x' are the unknown mean value and standard deviation of the approximating normal distribution. Solving (12) and (13) with respect to u_x' and σ_x', we obtain

$$\sigma_x' = \frac{\varphi\left\{\Phi^{-1}\left[F_x(x^*)\right]\right\}}{f_x(x^*)} \tag{14}$$

$$u_x{}' = x^* - \Phi^{-1}\left[F_x(x^*)\right]\sigma_x'. \tag{15}$$

3.2. The System Reliability of Series System. The system reliability is determined based on the failure probability of its components. The reliability assessment of the structural system requires analysis of the various possible failure modes. Generally, two types of systems are commonly used: (1) series systems or the "weakest-link" system and (2) parallel systems. A series system fails if any of its components fails, and a parallel system fails only if all of its components fail. In practical situations, there are also some structural systems, which are combination of series and parallel systems.

The general structure function of a series system with n components is

$$\phi(X) = X_1 X_2 \cdots X_n \tag{16}$$

All of these success indicators for the components must be equal to 1 for the structure function to equal 1. The reliability of a series system is the probability that all the components in the system are successful.

For the system in series with n mutually independent components, the failure probability of system P_f is

$$P_f = 1 - P\left(\prod_{i=1}^{n} X_i\right) = 1 - \prod_{i=1}^{n}\left(1 - P_{fi}\right), \tag{17}$$

where P_{fi} is the failure probability of the i^{th} component. If each component of the series system is fully correlated, the failure probability of system P_f is

$$\begin{aligned} P_f &= 1 - P\left(\min_{i\in(1,n)} X_i\right) = 1 - \min_{i\in(1,n)}\left(1 - P_{fi}\right) \\ &= \max_{i\in(1,n)} P_{fi}. \end{aligned} \tag{18}$$

Generally, for a series system, the failure probability lies within the about two limits

$$\max_{i\in(1,n)} P_{fi} \le P_f \le 1 - \prod_{i=1}^{n}\left(1 - P_{fi}\right) \tag{19}$$

The failure probability bound obtained by (19) usually has a big interval. In application, the *Ditlevsen's bounds* [13] are often used for assessing the reliability of series systems. Ditlevsen derived a smaller interval for the probability of failure of a structural system using all single-mode probabilities of failure and all two-mode joint failure probabilities, the so-called *two-order bounds (Ditlevsen's bounds)*.

For a series system, if E_i $(i = 1, 2, \ldots, n)$ is the event of the i^{th} failure mode, according to *Ditlevsen's bounds*, the bound of the series system can be expressed as

$$\begin{aligned} &P(E_1) + \sum_{i=2}^{n} \max\left\{P(E_i) - \sum_{j=1}^{i-1} P\left(E_i \cap E_j\right); 0\right\} \le P_f \\ &\quad \le \sum_{i=1}^{n} P(E_i) - \sum_{i=2}^{n} \max_{j<i} P\left(E_i \cap E_j\right), \end{aligned} \tag{20}$$

and in terms of the FORM approximation in reliability indices [13]

$$\begin{aligned} &\Phi\left(-\beta^S\right) \\ &\quad \ge \Phi(-\beta_1) \\ &\qquad + \sum_{i=2}^{n} \max\left\{\Phi(-\beta_i) - \sum_{j=1}^{i-1} \Phi_2\left(-\beta_i, -\beta_j; \rho_{ij}\right), 0\right\}, \end{aligned} \tag{21a}$$

$$\begin{aligned} &\Phi\left(-\beta^S\right) \\ &\quad \le \sum_{i=1}^{n} \Phi(-\beta_i) - \sum_{i=2}^{n} \max_{j<i}\left\{\Phi_2\left(-\beta_i, -\beta_j; \rho_{ij}\right)\right\}, \end{aligned} \tag{21b}$$

where ρ_{ij} is the correlation coefficient of E_i and E_j.

The *Ditlevsen's bounds* are usually much more precise than the simple bounds in (19), but they require the estimation of $\Phi_2(-\beta_i, -\beta_j; \rho_{ij})$ in (21a) and (21b).

Define

$$\begin{aligned} \gamma_i &= \frac{\beta_i - \rho_{ij}\beta_j}{\sqrt{1 - \rho_{ij}{}^2}}, \\ \gamma_j &= \frac{\beta_j - \rho_{ij}\beta_i}{\sqrt{1 - \rho_{ij}{}^2}}, \\ p_i &= \Phi(-\beta_i)\,\Phi\left(-\gamma_j\right) \\ \text{and } p_j &= \Phi\left(-\beta_j\right)\Phi(-\gamma_i), \end{aligned} \tag{22}$$

The following bounds exist [14]:

$$\max\left(p_i, p_j\right) \le \Phi_2\left(-\beta_i, -\beta_j; \rho_{ij}\right) \le p_i + p_j \tag{23}$$

These bounds are easy to use and P_{ij} can be approximated as the average of the lower and the upper bounds:

$$\begin{aligned} \mathrm{P}_{ij} &= P\left(E_i \cap E_j\right) = \Phi_2\left(-\beta_i, -\beta_j; \rho_{ij}\right) \\ &\approx \frac{1}{2}\left(\max\left(p_i, p_j\right) + p_i + p_j\right). \end{aligned} \tag{24}$$

3.3. The Proposed Method to Calculate Reliability of Transmission Power Tower Structure

3.3.1. Structure System Analysis and Modeling. Transmission power tower has complex towering structure, and its reliability is greatly influenced by wind load and ice load. Meanwhile, it consists of a large number of main bars, helical rods, diagonal braces and other components. Therefore, it is very difficult to determine its structural reliability directly. Since main bars account for a large proportion of the weight of the tower in the structural design, they are the main load-bearing structures of the tower. For the sake of simplicity, a tower can be considered as damaged when any main load-bearing bar yielding occurred. So, we can use the reliability of main bars instead of the reliability of whole transmission tower to access its reliability in practice. We now proposed a method to model the reliability of high-voltage transmission tower in form of a series system based on its mechanical structure.

The length of the each main bar in high-voltage transmission tower does not exceed 10 ~ 12 m. For example, the height of 500 kV transimission power towers are mostly 30 ~ 60 m; main bars of tower structure can be divided into 4 to 8 sections; the numbers of main load-bearing sections (called main section) are 3 to 5 [15]. Each section composes four main bars which are controlled by the same limit state equation and are thus considered to have same failure mode. Therefore, for the transmission power tower structure, the number of failure modes is 3 to 5 under normal operating conditions. The failure of each main section will led to the failure of whole tower strcucture. In other words, the total power tower structure can be seen as a series system model with 3 to 5 failure modes (components). The failure of any component will lead to the failure of system. The word "series" does not imply the physical arrangement of the components. Instead, it describes the response of the system to the failure of one of its components.

3.3.2. Reliability Index of the Main Bar Section. As mentioned above, a main bar section composes of four main bars, which are controlled by the same limit state equation and each of them is considered to have same failure mode. Therefore, a section can also be considered as a series system which composes of four bars. Each bar of the same section is working under same condition, as they are made of same material and has same structure, so, they can be seen to fully correlate with each other. In [4], for a section of microwave tower, if at least two legs have failed, the section would be considered as failed. But the transmission tower is very important to power system, and its failure would cause serious accidents; hence if any of the four main bars has been yielded under compressive stress load, the whole main bar section will be considered failed.

Assume the failure probabilities of the main bars in a section is P_{f1}, P_{f2}, P_{f3}, and P_{f4} respectively. According to (18), the failure probability of the section P_f^s can be obtained as follows:

$$P_f^s = \max_{i\in(1,4)} P_{fi} \tag{25}$$

If the value of measured compressive stress is D_{ti} at time t, for the main bar where the sensor is located, its structure system function is

$$Z = g\left(S_G, S_Q, R\right) = R - K\left(S_G + S_Q\right) = R - KD_{ti} \tag{26}$$

where K is the safety coefficient, which is equal to 1.5 generally; S_G is the permanent load and S_Q is the variable load. R is the yielding strength of main bar. It is a random variable, which is lognormal distributed [3, 5], with a mean of u_R and a variation of σ_R.

By (14) and (15), R can be transformed to be a normal variable R' with its mean $u_R{}'$ and variation $\sigma_R{}'$ given by

$$\sigma_R{}' = r^* \sigma_{\ln R} \tag{27}$$

$$u_R{}' = r^*\left(1 - \ln r^* + u_{\ln R}\right), \tag{28}$$

where $\sigma_{\ln R} = \sqrt{\ln[1+(\sigma_R/u_R)^2]}$, $u_{\ln R} = u_R/\sqrt{\ln[1+(\sigma_R/u_R)^2]}$, r^* is the linearization point, and $r^* = u_R$.

Then, using (11) and (26)-(28), we can obtain

$$u_Z = u_R\left(1 - \ln u_R + \frac{u_R}{\sqrt{\ln\left[1+\left(\sigma_R/u_R\right)^2\right]}}\right) - KD_{ti}, \tag{29}$$

$$\sigma_Z = u_R\sqrt{\ln\left[1+\left(\frac{\sigma_R}{u_R}\right)^2\right]}. \tag{30}$$

The reliability index of the i^{th} main bar at time t is thus given by

$$\beta_i = \frac{u_Z}{\sigma_Z}. \tag{31}$$

Since four sensors are installed symmetrically in the main bar section, the corresponding measured values D_{t1}, D_{t2}, D_{t3}, and D_{t4} often contain two compressive stresses and two tensile stresses under the wind load at time t. Compressive stresses are indicated by a negative value and tensile stresses are positive. According to (25), the reliability index of the section can be represented by that of its main bar with biggest compressive stress as follows:

$$\beta^S = \beta_i\big|_{D_{ti}=\max\limits_{i\in(1,4)}(-D_{ti})}. \tag{32}$$

3.3.3. Procedure for Real-Time Reliable Condition Assessment of Tower Structure. Assuming the transmission tower structure is a series system composed of N ($3 < N < 5$) main sections, there are $4\times N$ main bars in total and each of them is installed with a stress sensor. So, at time t, we obtain N sets of measurement data from sensors and each set has four units of data from the same section, which are

$$\begin{gathered}\left(D_{11}, D_{12}, D_{13}, D_{14}\right), \left(D_{21}, D_{22}, D_{23}, D_{24}\right), \ldots, \\ \left(D_{N1}, D_{N2}, D_{N3}, D_{N4}\right).\end{gathered} \tag{33}$$

The procedure for calculating the reliability index of tower structure at time t can be summarized as follows:

(I) Calculate the reliability index of each section according (29)-(32). The parameters u_R and σ_R used in (29) and (30) depend mainly on the type of main bar steel and the size of main bar, and both parameters can be calculated by the relevant specifications. Suppose that these reliability indices of main sections obtained are

$$\beta_1, \beta_2, \ldots, \beta_N \tag{34}$$

(II) After obtaining the above reliability indices of main sections, the reliability index of tower structure can be evaluated by (21a), (21b), (23), and (24).

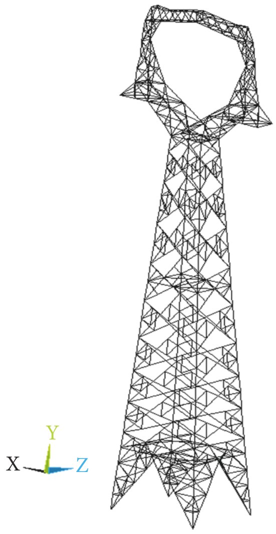

Figure 2: Finite element model of a 500kV oxytropis tower.

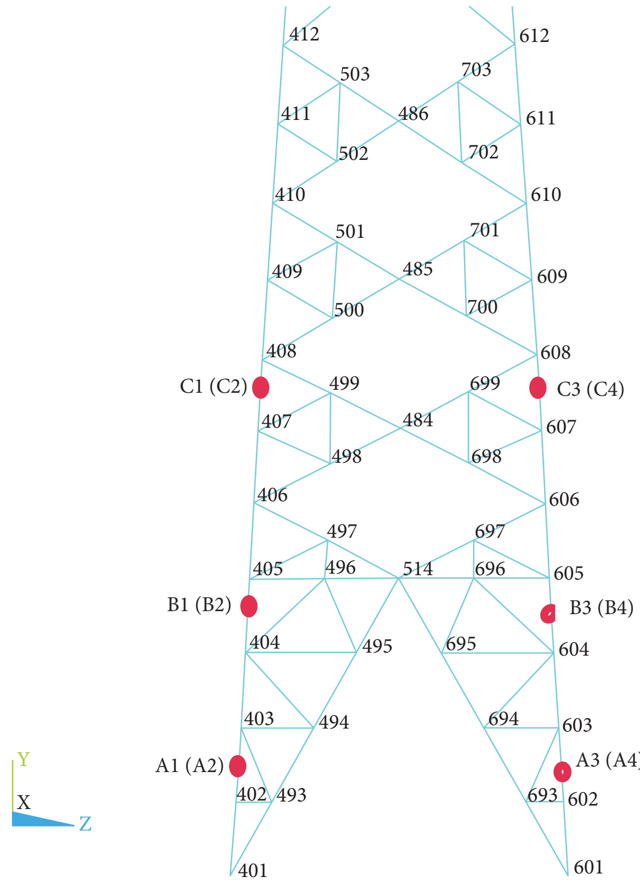

Figure 3: Positions of stress sensors installed on the transmission tower.

4. Experimental Results

A 500kV oxytropis tower is employed to illustrate the method suggested in the paper. This transmission tower is erecting in Yunnan Power Grid, located in southwest China. Of course, other types of transmission power towers can also be calculated accordingly.

4.1. Installation Positions for Stress Sensors. Positions where the sensors are installed must be decided firstly. So, the finite element model of transmission tower is established and then analyzes its stress in various extreme conditions. The finite element model is shown in Figure 2 [1].

Through the stress analysis in the finite element model, it is possible to select the points at which the stress is relatively strong and thus determine the installation position of the stress sensor. The specific process can be seen in our preliminary work [1]. The positions of stress sensors installed on the transmission tower are shown in Figure 3.

4.2. Reliability Assessment Procedure of System. According to the above design procedure, 12 stress sensors have been installed in 12 main bars in this real-time assessment system of the 500kV oxytropis power structure, which belong to three sections, respectively, as shown in Figure 3. Suppose the data sever in Figure 1 has received 12 data samples at time t, as shown in Table 1; then, using the procedure described in the Section 3.3.3, the reliability index of tower structure at time t can be evaluated as follows:

(1) The steel strength of main bar is assumed to be log-normal distributed. The mean coefficient u_K and the coefficient of variation V_R can be obtained from specifications [15–17]. So, according to (29)-(30), the reliability index of each section can be obtained. The result is also shown in Table 1.

(2) After obtaining the reliability index of every section, we can use (21a), (21b), (23), and (24) to calculate the reliability index of tower structure system. According to [15], the relative coefficient ρ_{ij} in (21a) and (21b) between each failure mode could be considered the same in order to simplify calculations, and an approximate estimate value of ρ_{ij} for 500kV tower structure is proposed to be 0.39.

$$\begin{aligned}
\Phi\left(-\beta^S\right) \geq{} & \Phi\left(-\beta_1\right) + \max\left\{\Phi\left(-\beta_2\right)\right. \\
& \left.- \Phi_2\left(-\beta_2, -\beta_1; \rho_{12}\right), 0\right\} + \max\left\{\Phi\left(-\beta_3\right)\right. \\
& \left.- \left(\Phi_2\left(-\beta_3, -\beta_1; \rho_{31}\right) + \Phi_2\left(-\beta_3, -\beta_2; \rho_{32}\right)\right), 0\right\} \\
& = 4.53 \times 10^{-3} + \max\left\{1.81 \times 10^{-3} - 0.271\right. \\
& \left.\times 10^{-3}, 0\right\} + \max\left\{0.467 \times 10^{-3}\right. \\
& \left.- \left(0.05 \times 10^{-3} + 0.027 \times 10^{-3}\right), 0\right\} = 6.460 \\
& \times 10^{-3}
\end{aligned}$$

$$\begin{aligned}
\Phi\left(-\beta^S\right) \leq{} & \Phi\left(-\beta_1\right) + \Phi\left(-\beta_2\right) + \Phi\left(-\beta_3\right) - \Phi_2\left(-\beta_2,\right. \\
& \left.- \beta_1; \rho_{21}\right) \\
& - \max\left\{\Phi_2\left(-\beta_3, -\beta_1; \rho_{31}\right), \Phi_2\left(-\beta_3, -\beta_2; \rho_{32}\right)\right\} \\
& = 4.53 \times 10^{-3} + 1.81 \times 10^{-3} + 0.467 \times 10^{-3}
\end{aligned}$$

Table 1: Measurement stress data samples and corresponding reliability indices.

D_{ti}(MPa)	D_{t1}	D_{t2}	D_{t3}	D_{t4}	β_i	$\Phi(-\beta_i)$
Section A	127.20	127.20	-158.20	-158.20	2.61	$4.53*10^{-3}$
Section B	121.63	121.63	-146.80	-146.80	2.92	$1.81*10^{-3}$
Section C	103.32	103.32	-108.76	-132.26	3.32	$0.467*10^{-3}$

$$
\begin{aligned}
&- 0.271 \times 10^{-3} - \max\left\{0.05 \times 10^{-3}, 0.027 \times 10^{-3}\right\} \\
&= 6.486 \times 10^{-3}
\end{aligned}
\tag{35}
$$

corresponding to

$$2.48454 \leq \beta_S \leq 2.48597. \tag{36}$$

If the reliability of system is calculated exactly from (19)

$$
\begin{gathered}
4.53 \times 10^{-3} \leq P_f{}^S \leq 8.896 \times 10^{-3} \\
2.367 \leq \beta_S \leq 2.61
\end{gathered}
\tag{37}
$$

so, it is seen that the Ditlevsen bounds in this case are very narrow and the result is more accurate.

5. Conclusions

This study proposes a real-time reliability assessment system for transmission tower structure. It aims to address and evaluate the reliability index of tower structure system based on measurement stress data samples. By finite element analysis, main bars with large compressive stress will be selected for installing stress sensors. The main bars of tower structure are divided into 3 to 5 main sections. Therefore, the tower structure system can be seen as a series system model with 3 to 5 failure modes (components). In this project, 12 stress sensors will be installed; it means there are three failure modes in our simplified series system. Afterwards, *Ditlevsen's bounds* method is used to calculate the reliability index of structure system. The designed real-time assessment system will be installed later in Yunnan Province, China. As we mentioned before, there are very few practical application systems of real-time monitoring or condition assessment applied to steel structure of transmission tower and the current work serves a pilot study for practical deployment and application of this new approach.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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