Reliability Study of Important Cross-Over Transmission Line System Based on Series System

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Abstract. Transmission lines inevitably cross railroads, highways, and other facilities, and in order to ensure the safety and reliability of the cross-crossing section, the influence of various random factors on important cross-crossing transmission lines needs to be fully considered. In this paper, the transmission line crossing section is treated as a tandem system according to the force transmission route, and the reliability calculation method of the cross-crossing transmission line system based on the tandem system is proposed. The reliability calculation method of each component and the reliability calculation method of the tandem system are given. Finally, an example of the reliability calculation of a 220kV cross-crossing transmission line system is given, and the results show that the cross-crossing section has the highest reliability of tower FSJ404, with a reliability index of 8.61, the second highest reliability of insulators, with a reliability index of 7.22, and the lowest reliability of tower FSJ302, with a reliability index of 4.28. The failure probability of the cross-crossing section is 0.000009245, and the reliability index is 4.28.

1. Introduction

Transmission line corridors and various traffic corridors cross each other, resulting in an increasing number of intersections between power lines and traffic lines, also making various accidents and potential risks particularly prominent at the crossover points. For example, in 2016, the ground line of a 220kV transmission line broke and fell on the contact network of high-speed railway, resulting in abnormal railroad operation and causing a large impact. Therefore, it is urgent to improve the reliability of important cross-crossing lines, and it is of profound significance to ensure the reliability of important cross-crossing lines for the safe operation of railroads, highways and power grids.

A great deal of research has been done on the reliability of transmission lines at home and abroad, especially with the application of ultra-high voltage (UHV) and ultra-high voltage (UHV) in practical projects. Chen Haibo[3] used JC method to calculate the reliability of 500 kV transmission tower components in China, and got the failure probability of transmission tower system. Also in the study of large-span steel tube towers. Li Maohua[4] has studied the reliability level of 500 kV transmission line towers under various standards by counting the failure probability of 500 kV transmission line towers in recent years, and by using FOSM, the results show that the level of reliability is gradually improved. Li Feng[5] statistics the random distribution types of wind and ice loads, and uses FOSM to analyze the design reliability of transmission tower. The conclusion shows that the current reliability level of transmission tower in China can meet the corresponding demand. In the study of the reliability of...
transmission line insulators and fittings, Feng Yunfen et al. [6-10] used FOSM to study the reliability of the insulators, conductors and insulators Xu Bin Wang Songtao et al. [11] also uses FOSM to analyze the reliability of line components, and gets the load and resistance statistical parameters of line components. The analysis shows that the current design method of line components is safe. Zhang Haiwei[14] used the JC method to analyze the structural reliability of ultra and extra high voltage transmission tower with multi-Circuit lines and studied the design criteria.

The dependability of cross-crossing transmission lines is investigated in this article, and the cross-crossing section of transmission lines is treated as a tandem system based on the force transmission route, completely evaluates the impact of numerous random elements on critical cross-crossing transmission lines, and presents a tandem system-based reliability calculation technique for cross-crossing transmission lines. The reliability calculation methods for each component and the series system are provided in conjunction with current design codes such as "Unified standard for reliability design of building structures"[1] and "Code for design of 110kV-750kV overhead transmission lines"[2]. Finally, an example of a 220kV cross-crossing transmission line system reliability estimate is provided, The results demonstrate that the tension-resistant tower FSJ404 has the highest cross-crossing section dependability, with an 8.61 reliability index, the next highest for the tension-resistant insulator, with a reliability index of 7.22, and the lowest for the tension-resistant tower FSJ302, with a reliability index of 4.29. The failure probability of the cross-crossing section is 0.000009245, and the reliability index is 4.28.

2. Calculation method of line system reliability

2.1. Transmission line system division

A transmission line is a system consisting of several units. Different system compositions can be obtained from different levels of division. For a transmission line, each tension-resistant section constitutes a system. For a tension-resistant section, tension-resistant towers, straight-line towers, gold tools, insulator strings and conductive ground lines constitute a system. For a pole tower, metal tool strings, insulator strings, ground wires, several components constitute a system. Therefore, analyzing the reliability of the system at different levels will have different analysis results. To analyze the reliability of a large system, it is necessary to first analyze the reliability of the subsystems that constitute it, and on the basis of obtaining the reliability of the subsystems, gradually recur to the reliability of the large system.
2.2. Calculation of component reliability

Suppose that there are \( n \) non-normal random variables \( X_i (i = 1, 2, \ldots, n) \) in the structural design, the mean value is \( \mu_{X_i} \), the standard deviation is \( \sigma_{X_i} \), the probability density function is \( f_{X_i}(x_i) \), and the cumulative distribution function is \( F_{X_i}(x_i) \). The function composed of these random variables is \( Z = g(X_1, X_2, \ldots, X_n) \).

The \( X_i \) equivalent is normalized to a random variable \( X_i' \) with mean \( \mu_{X_i'} \), standard deviation \( \sigma_{X_i'} \), probability density function \( f_{X_i'}(x_i') \), and probability distribution function \( F_{X_i'}(x_i') \). The condition of equivalent normalization is that the cumulative distribution function value and the probability density function value of the equivalent normal random variable \( X_i' \) are equal to the cumulative distribution function value and the probability density function value of the non-normal random variable \( X_i \) respectively, at the Check Point \( x_i^* \), i.e.

\[
F_{X_i}(x_i^*) = F_{X_i'}(x_i^*) \quad (1)
\]

\[
f_{X_i}(x_i^*) = f_{X_i'}(x_i^*) \quad (2)
\]

The mean and standard deviation of the equivalent normalized random variable \( X_i' \) can be expressed as:

\[
\mu_{X_i'} = x_i^* - \Phi^{-1} \left[ F_{X_i}(x_i^*) \right] \sigma_{X_i'} \quad (3)
\]

\[
\sigma_{X_i'} = \frac{\Phi^{-1} \left[ f_{X_i}(x_i^*) \right]}{f_{X_i'}(x_i^*)} \quad (4)
\]
After equivalent normalization, the reliability index can be expressed as:

$$\beta = \frac{g(x_1^*, x_2^*, \cdots, x_n^*) + \sum_{i=1}^{n} \left( \frac{\partial g}{\partial X_i} \right)_p \left( \mu_{X_i} - x_i^* \right)}{\sqrt{\sum_{i=1}^{n} \left\{ \left( \frac{\partial g}{\partial X_i} \right)_p \sigma_{X_i} \right\}^2}}$$  \hspace{1cm} (5)

The sensitivity coefficient can be expressed as:

$$\alpha_{X_i} = -\frac{\partial g}{\partial X_i} \left( \frac{\sigma_{X_i}}{\sum_{i=1}^{n} \left( \frac{\partial g}{\partial X_i} \right)_p \sigma_{X_i}^2} \right)$$  \hspace{1cm} (6)

Check Point coordinates:

$$x_i^* = \mu_{X_i} + \alpha_{X_i} \sigma_{X_i} \beta \hspace{1cm} (i = 1, 2, \ldots, n)$$  \hspace{1cm} (7)

In summary, it can be seen that the mean, standard deviation, reliability index and sensitivity coefficient of the equivalent normal random variables are functions of the test point values and need to be determined by iterative calculations.

2.3. Reliability calculation of tower, hardware, insulator and ground conductor subsystem

The following introduces the reliability calculation of the tower system. The reliability calculation principle of the subsystem of the metal, insulator and guide wire is the same as the reliability calculation of the tower system.

Based on the probabilistic approach, the failure probability of a series system can generally be expressed as follows:

$$P_f = P(G_1 < 0 \cup G_2 < 0 \cup \cdots \cup G_n < 0)$$  \hspace{1cm} (8)

In the formula: $G_i < 0$ means the failure of unit $I$ or failure mode $I$ occurs; $\cup$ is the sum of the events.

The tower system can be regarded as a series system of multiple members. In the failure mode of the tower, the failure of one member usually leads to the failure of the whole tower system. That is, the failure probability of the whole tower system is controlled by the component element with the highest probability, then the failure probability of the tower is:

$$P_f = \max \{ P_{f_i} \}$$  \hspace{1cm} (9)

Then the reliability index of the whole tower system can be calculated by the following formula:

$$\beta = \varphi^{-1}(P_f) = \varphi^{-1}(1 - P_f) = -\varphi^{-1}(P_f)$$  \hspace{1cm} (10)

2.4. Reliability calculation of tensile section system

For a tension-resistant section, tension-resistant towers, linear towers, fixtures, insulator strings, Ground wires constitute a system, the failure probability and reliability index of the system represents the degree of safety of a transmission line, and its failure probability and reliability index are calculated with the following method.

The transmission line is a complex engineering system connected by multiple tower systems in series, and any damage or failure of the tower system will directly affect the normal operation of the entire transmission system. Therefore, the entire transmission line can be considered as a series system with
each individual tower line system as a functional subunit. In addition, in the case of a single tower line system, in addition to the tower itself, it also includes components such as guide wires, insulators and fixtures, and damage to each of these components can also affect the normal operation of the line. Each tower-line system can also be simulated by a series system composed of various components. Therefore, the whole line can represent the series model in Figure 2. Where the $i$th single tower, the conductor and ground wire on one side along the forward direction of the single tower line and the insulators and fittings on the single tower line are called the $i$th unit, and the components in the unit are called the elements $A(i, j)$ of the unit.

Figure 2 Series system model

It is assumed that each element is independent of each other for the whole series system of tensile section. The failure probability of the whole system can be calculated as follows:

$$P_{f} = P(G_{1} \geq 0 \cap G_{2} \geq 0 \cap \cdots \cap G_{n} \geq 0)$$

$$= P(G_{1} \geq 0)P(G_{2} \geq 0) \cdots P(G_{n} \geq 0) = \prod_{i=1}^{n} P_{a}$$  \hspace{1cm} (11)

In the formula, $P_{f}$ is the failure probability of the $i$th unit of the system, $P_{a}$ is the reliable probability of the system, and $\cap$ is the product of the events.

There is a correspondence between the system reliability and the failure probability, so the failure probability of the system is:

$$P_{r} = 1 - P_{f} = 1 - \prod_{i=1}^{n} (1 - P_{a})$$  \hspace{1cm} (12)

Then the reliability index of the whole tower line system can be calculated by the following formula:

$$\beta = \varphi^{-1}(P_{f}) = \varphi^{-1}(1 - P_{r}) = -\varphi^{-1}(P_{r})$$  \hspace{1cm} (13)

3. Analysis of finite element simulation example

3.1. Tower-line system modeling

Based on a 220 kV transmission line crossing a high speed railway line, the crossing section is composed of two tension towers, conductor, ground wire connecting two base towers and metal tool string. The wind speed is 31 m/s. The tower type is FSJ404 and FSJ302, and the height is 18 m and the whole height is 36 m. It is a combination structure of a typical space beam and truss. The conductor type of the spanning line is LGJ-300/40, the ground wire type is LBJ-150-40AC, the insulator string type is LXHY-100, and the insulator type is U100BLP-1. In Ansys, the beam element (BEAM188) is used to simulate the main material and the cross material components of the tower. The Link element (LINK180) is used to simulate the oblique material components of the tower to establish the finite element model of the tower. The Link Unit (LINK180) is used to simulate ground wire and metal tools. Combined with the tower to establish a finite element model of the line system across the section. The results are shown in Figure 3.
3.2. Variable statistical parameter

The statistical parameters (mean coefficient and coefficient of variation) and the probability distribution of each variable are shown in table 1.

Table 1. Summary of variable statistical parameters

| Load effect and tensile breaking force | Statistical parameters | Probability distribution |
|----------------------------------------|-------------------------|-------------------------|
| Load                                   | k(mean/standard value), δ(coefficient variation) | Normal distribution, Extreme type I distribution, Log-normal distribution |
| Load dead weight                       | 1.060, 0.070            | Normal distribution     |
| Wind load (31m/s)                      | 0.908, 0.193            | Extreme type I distribution |
| Axial Force on the member of the tower | 1.134, 0.117            | Log-normal distribution |
| Resistance                             | Axial compression of tower member |                     |
| Insulator                              | 1.185, 0.150            |                         |
| Metal fittings                         | 1.500, 0.122            |                         |
| Ground wires                           | 1.394, 0.166            |                         |
|                                         | 1.081, 0.093            |                         |

Figure 3 Tower-line system model of 220 kV transmission line in span section
3.3. Calculation of line reliability

1) Reliability calculation of single component

Taking “Dead weight + high wind” as an example, the reliability index of a single member is calculated by the JC method, as shown in Table 2 and 3.

**Table 2: ‘Dead weight + Gale’, FSJ302 Angle Tower Reliability Index**

| Serial number | Member number | Cross section type | Permanent load reference value (kN) | Wind load reference value (kN) | Resistance standard value (kN) | Bar Reliability Index |
|---------------|---------------|--------------------|------------------------------------|-------------------------------|-------------------------------|---------------------|
| 1             | 872           | L160×16            | -127.67                            | -113.59                       | -613.76                       | 4.29                |
| 2             | 560           | L160×16            | -243.21                            | -210.65                       | -1347.56                      | 4.97                |
| 3             | 600           | L160×16            | -237.23                            | -208.71                       | -1422.05                      | 5.25                |
| 4             | 601           | L160×16            | -228.53                            | -202.49                       | -1422.05                      | 5.39                |
| 5             | 873           | L125×10            | -98.65                             | -86.89                        | -613.76                       | 5.41                |
| 6             | 404           | L200×16            | -304.23                            | -252.32                       | -1835.56                      | 5.46                |
| 7             | 402           | L200×16            | -302.29                            | -249.33                       | -1835.56                      | 5.5                 |
| 8             | 403           | L200×16            | -300.60                            | -248.71                       | -1835.56                      | 5.52                |
| 9             | 878           | L125×10            | 96.10                              | 135.00                        | 840.77                        | 5.55                |
| 10            | 405           | L200×16            | -278.72                            | -234.68                       | -1835.56                      | 5.78                |

**Table 3: ‘Dead weight + Gale’, FSJ404 Angle Tower Reliability Index**

| Serial number | Member number | Cross section type | Permanent load reference value (kN) | Wind load reference value (kN) | Resistance standard value (kN) | Bar Reliability Index |
|---------------|---------------|--------------------|------------------------------------|-------------------------------|-------------------------------|---------------------|
| 1             | 3121          | L200×20            | -232.99                            | -136.29                       | -2254.21                      | 8.61                |
| 2             | 2391          | L200×20            | -232.35                            | -134.30                       | -2254.21                      | 8.66                |
| 3             | 2395          | L200×20            | -231.28                            | -134.27                       | -2254.21                      | 8.67                |
| 4             | 2549          | L200×18            | -193.42                            | -118.14                       | -1970.06                      | 8.69                |
| 5             | 2553          | L200×18            | -185.04                            | -116.89                       | -2041.79                      | 8.93                |
| 6             | 2399          | L200×20            | -214.31                            | -126.96                       | -2254.21                      | 8.94                |
| 7             | 2403          | L200×20            | -212.97                            | -126.92                       | -2254.21                      | 8.95                |
| 8             | 2557          | L200×18            | -177.55                            | -113.98                       | -2041.79                      | 9.06                |
| 9             | 2175          | L200×24            | -255.55                            | -144.38                       | -2708.65                      | 9.13                |
| 10            | 2171          | L200×24            | -255.74                            | -143.81                       | -2708.65                      | 9.15                |

2) Reliability calculation of tower, insulator, metal fittings and ground conductor system, as shown in Table 4.

**Table 4: tower, fixture, insulator, Ground wires system reliability**

| Parts                | Reliability of “Dead weight + gale” working condition |
|----------------------|------------------------------------------------------|
| FSJ302 Tower         | 4.29                                                 |
| FSJ302 Insulator     | 7.22                                                 |
| FSJ302 Metal Fittings| 5.37                                                 |
| Ground wires         | 5.67                                                 |
| FSJ404 Metal Fittings| 5.37                                                 |
| FSJ404 Insulator     | 7.22                                                 |
| FSJ404 Tower         | 8.61                                                 |
4. Conclusion

4.1. Conclusions

The equivalent normalization method (JC method) and the series system reliability calculation method, which can be obtained by combining with usual calculation case analysis, are used to examine the reliability of a cross-crossing transmission line system at three levels in this work:

(1) In this paper, the transmission line crossing section is considered as a tandem system based on the transmission route in this research, and a method for calculating the dependability of the cross-crossing transmission line system based on the tandem system is proposed. Each component's reliability calculation technique is described, as well as the tandem system's reliability calculation approach.

(2) As an example of reliability calculation, the 220kV crossover transmission line system in high wind conditions is used in this study. With a reliability value of 8.61, the crossover portion of the tensioning tower FSJ404 has the best reliability, the tensioning insulator has the second highest dependability, with a reliability index of 7.22, while the tensioning tower FSJ302 has the lowest reliability, with a reliability value of 4.29. The crossover section has a failure probability of 0.000009245 and a dependability index of 4.28.

(3) The findings of the analysis reveal that the 220kV crossover transmission line system is reliable under high wind circumstances, and this reliability analysis only looks at the situation from a mechanical standpoint, ignoring the influence of other aspects like electrical considerations.

4.2. Suggestions for future research

(1) This paper only examines the reliability of the spanning section using the "Tensile-Tensile" tension-resistant section as an example; in future research, the spanning section can be divided into "Tensile-Tensile," "Tensile-Straight," and "Straight-Straight" three spanning modes to investigate the influence of the spanning mode on the reliability of the spanning section and even the entire tower-line system.
(2) In future reliability studies, the reliability of cross-crossing transmission lines can be thoroughly analyzed by combining the effects of other factors such as electrical and mechanical factors to obtain a more accurate system reliability.

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