Reliability Evaluation Model of Power Grid Considering the Structural Reliability of Tower under Earthquake Conditions

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Abstract. The seismic disaster will cause serious damage to the power system. At present, the reliability evaluation of the power grid under earthquake conditions is mainly subjected to the approximate analysis of seismic performance, and the approximate analysis results cannot meet the actual needs. In this paper, a reliability evaluation model of Power Grid considering the structural reliability of tower under earthquake conditions is proposed. The structural problems of tower and cable are analyzed directly by finite element simulation. The failure rate of transmission line is calculated by the structural reliability of tower and cable. After obtaining the reliability data of transmission line, the reliability of the power system under various seismic intensities is evaluated. Finally, the influence of the location of seismic source on the reliability of power system is analyzed. The results of the example analysis verify the accuracy and practicability of the proposed model and provide a reference for improving the seismic performance of the power system.

1. Introduction
The seismic disaster will cause great impact on transmission towers and lines, causing adverse effects such as collapse of transmission towers, line disconnection, and grid disconnection. In severe cases, the power grid will be greatly smashed, seriously affecting the national economy and the normal life of the people. In the recent earthquake disasters, such as the Tangshan earthquake in 1976, the Loma Prieta earthquake [1] in 1989, the Hanshin earthquake [2] in 1995, the Taiwan earthquake in 1999, and the Wenchuan earthquake [3] in 2008, the power system was severely affected. On May 12, 2008, the Wenchuan M8.0 earthquake caused direct economic losses of more than 10.6 billion yuan. Due to the earthquake, 2.46 million users were blacked out. Therefore, research on the reliability of power grid under earthquake conditions has become a crucial issue.

At present, the seismic research of power system is mainly divided into seismic equipment reliability research [4], substation seismic reliability research [5-6], and power grid seismic reliability [7-8] research. Among them, the seismic reliability research of electrical equipment level and substation level is relatively mature, and the seismic reliability research of power network level is in the preliminary stage and has not yet reached engineering application. There are three common ways to calculate the failure rate of transmission line: first, establish one-to-one correspondence or fuzzy correspondence between climatic conditions and line outage rate based on statistical data [9]; the second is to directly establish the approximation mathematical model of transmission lines and different loads [10]; the third is to directly analyze the structural mechanics of the tower and the transmission line by Finite Element Analysis [11-12]. Under the seismic conditions, due to the large geographical difference of each region and the different seismic intensity distribution, sufficient
historical data cannot be collected to reflect the relationship between seismic intensity and line outage rate; secondly, the line outage rate obtained by approximate analysis using mathematical model is not very accurate. Therefore, this paper proposes a reliability evaluation model of Power Grid considering the structural reliability of tower under earthquake conditions. Based on the Finite Element Method, the ANSYS software is used to calculate the seismic loads of the tower components and cable segments under various seismic intensities. The structural reliability of tower and cable is used to calculate the failure rate of transmission lines. Finally, use the obtained transmission line reliability data to evaluate the reliability of the power system.

2. Seismic load of transmission tower and cable

2.1. Load effect
The load effect [13] includes the dead load effect $S_0$ and the live load effect $S_q$. For the transmission tower, the dead load effects $S_0$ mainly include the gravity load of conductors, ground wires, insulators, their accessories, tower structure and various fixtures. Live load effects $S_q$ include wind, ice and snow, seismic intensity, component tension, etc.

2.2. Seismic load
In this paper, based on the Finite Element Method, ANSYS software is used to calculate the seismic loads of tower and cable under various seismic intensities. In ANSYS, modal analysis is used to study the vibrational properties of an object, i.e., the natural frequency and mode shape of the structure; spectral analysis is to correlate the results of modal analysis with a known response spectrum to calculate the displacement and stress of the structure. Through modal analysis and spectral analysis, the seismic loads $S_q$ of tower and cable can be obtained under the seismic response spectrum.

2.2.1 Seismic loads of transmission tower. In this paper, the transmission tower is selected from 2C3-J2-1 type in the 'General Design of 220KV Transmission Lines of State Grid Corporation'. Beam188 and link180 are selected as basic components. The elastic modulus is 2.06E11, the poisson’s ratio is 0.3, the density is 7.85E3, and the g is 9.80665. The constraint type of the four tower legs and the ground contact point is full constraint. The specific model is shown in Figure 1.

![Figure 1. The ANSYS model of tower](image)

After ANSYS modal analysis and spectral analysis, the seismic loads $S_q$ (unit: N) of tower components under the three seismic intensities of 6, 7 and 8 are obtained in Table 1.
Table 1. The seismic loads of the tower components under various seismic intensities.

| Component | $S_q$ (6) | $S_q$ (7) | $S_q$ (8) |
|-----------|-----------|-----------|-----------|
| 3916      | 3099200   | 8746000   | 17492000  |
| 3895      | 3301300   | 9316500   | 18633000  |
| 3413      | 1869600   | 5276200   | 10552000  |
| 3958      | 3294500   | 9297100   | 18594000  |
| 3850      | 3336500   | 9415600   | 18831000  |
| 3826      | 3346000   | 9442400   | 18885000  |

2.2.2 Seismic loads of cable. High-voltage transmission cables are mainly laid in power tunnels. Since the cable tunnel is an underground structure and the cable is fixed to the bracket, a cable segment between the two joints can be taken as a research object. YJLW02 64/110 1×630 cable is used. According to the cable’s dead weight, the seismic loads $S_q$ (unit: N) of cable segments under 6, 7 and 8 seismic intensity are obtained as shown in Table 2.

Table 2. The seismic loads of the cable segments under various seismic intensities.

| Seismic intensity | $S_q$ |
|-------------------|------|
| 6                 | 5271 |
| 7                 | 10104|
| 8                 | 19769|

3. Structural reliability of transmission tower and cable

3.1. Performance function of tower component

In order to ensure the reliability and safety of the transmission tower structure, the limit state design method [14] based on probability theory should be adopted in the design process. The structural components are evaluated and designed with quantifiable reliability index. The limit state of the structure [15] refers to the critical state that the structure or the component meet the safe operation of the line under the specified combination of various loads or under the limits of various deformations and cracks. The performance function of transmission tower component can be expressed as follows:

$$Z = G(R, S_G, S_Q) = R - S_G - S_Q$$

(1)

Where $Z=0$ means that the structure reaches the limit state, $Z>0$ indicates that the structure is in a reliable state, $Z<0$ indicates that the structure is in a failure state. $R$ is the structural resistance; $S_G$ is the dead load effect; $S_Q$ is the live load effect.

3.2. Structural reliability of tower and cable

The structural reliability [16] refers to the ability of a structure to perform a predetermined function under predetermined conditions within a predetermined time. Structural reliability is a concept obtained by quantifying reliability. The structural reliability of the tower components can be expressed as follows:

$$\beta = \frac{H_{S_G}}{\sigma_Z} = \frac{\mu_R - \mu_{S_G} - \mu_{S_Q}}{\sqrt{\sigma_R^2 + \sigma_{S_G}^2 + \sigma_{S_Q}^2}}$$

(2)
Where \( \beta \) is the structural reliability of tower; \( \mu_Z, \mu_R, \mu_{S_G}, \mu_{S_Q} \) is the expected value of \( Z, R \), \( S_G, S_Q \); \( \sigma_Z, \sigma_R, \sigma_{S_G}, \sigma_{S_Q} \) is the standard deviation of \( Z, R, S_G, S_Q \).

And the failure rate of tower is:

\[
p_f = \Phi(-\beta)
\]

Where \( \Phi(.) \) is the Standard normal distribution function; \( p_f \) is the failure rate of tower; \( \beta \) is the structural reliability of tower.

From the above, the structural reliability and failure rate of the tower components and the cable segments under 6, 7 and 8 seismic intensities can be obtained as shown in table 3 and table 4.

**Table 3** The structural reliability and failure rate of the tower components under various seismic intensities.

| Component | \( \beta \) (6) | \( \beta \) (7) | \( \beta \) (8) | \( p_f \) (6) | \( p_f \) (7) | \( p_f \) (8) |
|-----------|----------------|----------------|----------------|--------------|--------------|--------------|
| 3916      | 6.22691        | 6.12483        | 5.96612        | 2.38E-10     | 4.54E-10     | 1.21E-09     |
| 3895      | 4.0887         | 3.98723        | 3.82971        | 2.17E-05     | 3.34E-05     | 6.41E-05     |
| 3413      | 6.38674        | 6.32505        | 6.22927        | 8.47E-11     | 1.27E-10     | 2.34E-10     |
| 3958      | 5.19544        | 5.08996        | 4.92607        | 1.02E-07     | 1.79E-07     | 4.20E-07     |
| 3850      | 5.51467        | 5.40678        | 5.23909        | 1.75E-08     | 3.21E-08     | 8.07E-08     |
| 3826      | 3.85736        | 3.75553        | 3.59746        | 5.73E-05     | 8.65E-05     | 0.000161     |

**Table 4** The structural reliability and failure rate of the cable segments under various seismic intensities.

| \( \beta \) (6) | \( \beta \) (7) | \( \beta \) (8) | \( p_f \) (6) | \( p_f \) (7) | \( p_f \) (8) |
|----------------|----------------|----------------|--------------|--------------|--------------|
| 3.8492         | 3.5598         | 2.9735         | 5.93E-05     | 1.86E-04     | 1.50E-03     |

4. **Reliability evaluation model of power grid under earthquake conditions**

This paper established a reliability evaluation model of Power Grid considering the structural reliability of tower under seismic conditions. The model mainly focuses on the influence of earthquake on the structural reliability of transmission tower and cable. It calculates the failure rate of transmission line caused by the failure of tower and cable. And then analyses the influence of earthquake on the reliability of Power Grid. The basic steps of the model are as follows:

Step 1: Determine the seismic intensity distribution in the area where the power system is to be evaluated.

Step 2: Modeling the transmission tower and cable based on the Finite Element Method using ANSYS software. After the modeling is completed, the seismic loads \( S_Q \) of the transmission tower components and cable segments under various seismic intensities are calculated.

Step 3: After obtaining the seismic load \( S_Q \), the structural reliability \( \beta \) and failure rate \( p_f \) of transmission tower components and cable segments can be obtained.

Step 4: This paper focuses on the reliability of the tower and makes some simplifications. Assuming that the line is a series system consisting of several towers or cable segments. The line failure rate can be obtained: \( p = 1 - \prod_{i=1}^{n} (1 - p_{f_i}) \) where \( p_{f_i} \) is the failure rate of the tower \( i \); \( n \) represents the number of the tower.
Step 5: According to the obtained system reliability data, the Monte Carlo sampling method is used to evaluate the reliability of the power system. And the reliability index under each seismic intensity is calculated. The reliability index uses the EENS (Expected energy not supplied) and the LOLP (Loss of Load Probability).

Step 6: Considering that the seismic intensity is not evenly distributed in the region, divide the seismic intensity distribution of the region where the system is located. And the failure rate of transmission line is recalculated when the location of seismic source is different. Finally, analyze the impact of the different location of seismic source on power system reliability.

5. Case study
This section uses matlab programming to realize the reliability assessment of the power system. The model mentioned above is used to assess the reliability of the IEEE RTS-79 system. The iteration number is selected as 10000 as the Monte Carlo simulation is chosen and the results we get can satisfying the condition of convergence.

5.1. Power Grid reliability under various seismic intensities
Using the reliability data of transmission line calculated above, the reliability evaluation results of the power system can be obtained. The power system reliability index LOLP and EENS under various seismic intensities are given in figure 2.

![Figure 2](image)

**Figure 2.** The power system reliability index LOLP and EENS under various seismic intensities

5.2. Power Grid reliability under different location of seismic intensity
In practice, the seismic intensity is not evenly distributed in a region. Based on these considerations, we use the intensity distribution of the Wenchuan earthquake to divide the IEEE-RTS79 system, assuming that the seismic source is in the center, northwest, northeast, southwest and southeast of the power system region. The system area is divided into three seismic intensity areas of 6, 7, and 8. The failure rate of the transmission line at different location of seismic source was recalculated. And then the reliability of the system was comprehensively evaluated. Figure 3 shows the reliability index LOLP and EENS of the power system with different location of seismic source.

![Figure 3](image)

**Figure 3.** The power system reliability index LOLP and EENS under different location of seismic source

6. Conclusion
The earthquake will cause serious damage to the power system. Considering the seismic intensity distribution and the structural reliability of the tower, the reliability assessment of power system can effectively reduce the damage of earthquake. In this paper, a reliability evaluation model of power grid considering the structural reliability of the tower under earthquake conditions is proposed. The structural reliability of the tower and cable under various seismic intensities is calculated. Then the failure rate of the transmission line is calculated under various seismic intensities and different location of seismic source. Finally, the IEEE-RTS79 test system is used to analyze the impact of different seismic intensities on the reliability of power systems and the impact of different location of seismic source on power system reliability. The results show that the proposed model can effectively analyze the reliability of the system under seismic conditions and provide a reference for improving the seismic performance of the power system.

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