Quantitative assessment method of power grid disaster response capability based on fuzzy comprehensive evaluation and comprehensive weight

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Abstract. To study the objective assessment of power grid disaster response capacity under extreme natural disasters, a quantitative assessment method of power grid disaster response capacity based on fuzzy comprehensive evaluation and weight is proposed. Firstly, a pre-disaster endurance and post-disaster resilience evaluation index system is established by analyzing the comprehensive data of the power grid system. Then, the analytic hierarchy process and the entropy weight method to obtain the subjective and objective weights of the indicators are used and combined into comprehensive weight determination indicators. Fuzzy comprehensive evaluation to quantitatively evaluate the disaster response capability of the power grid is used. Finally, the proposed evaluation method is verified through a calculation example. The results show that the method is reasonable and effective, and has a certain guiding role for the grid to respond to extreme natural disasters.

1. Introduction

Extreme natural disasters happened frequently because of the abnormal global climate changes for the last 10 years, various small-probability and high-risk extreme natural disasters also have significantly increased the impact of power grids [1]. Every year, typhoon disasters have a huge effect on the normal operation of the power system of coastal cities in southeast my country [2-3]. Due to a large number of electrical equipment and the complex network structure, the power grid disaster response capability assessment is a multi-attribute comprehensive assessment problem [4-6]. As the power system continues to develop, it will become more complex, and society will continue to rely on it. When the power grid is damaged by natural disasters, it will not only cause huge losses to the economy but also have a direct impact on the normal production order of society. Therefore, it is of great significance to study the power grid's ability to withstand extreme natural disasters and recover from disasters.

The current research on the impact of extreme natural disasters on power grids mainly focuses on two aspects: evaluation model and index system evaluation. Billinton et.al evaluated the meteorological disasters of power systems by establishing and using multi-level weather models. It was also used of HAZUS software to establish a meteorological probability model to evaluate the impact on the power grid infrastructure[7-8]. Gu Minghong et.al focused on the resilience of the...
distribution network and established an evaluation index system, but they did not quantitatively analyze and evaluate the disaster response capacity of the grid[9]. Xu Mingming et al. used the analytic hierarchy process and fuzzy comprehensive evaluation to evaluate the power grid emergency system by establishing an evaluation system, but the evaluation method has certain subjective assumptions and has certain limitations[10]. Wang Di et al. focused on the assessment of power grid emergency capabilities but did not consider the dynamic and complex correlations between grid indicators[11]. At the same time, it also uses quantitative power grid disaster assessment data for in-depth analysis[12].

The main structure of this paper should be composed of three parts: the establishment of the power grid evaluation system, the selection of evaluation methods and the fuzzy quantitative evaluation results. This paper divides the power grid’s response to extreme natural disasters according to time, and constructs an electricity evaluation system from both pre-disaster endurance and post-disaster resilience, the pre-disaster index system considers the power grid’s transmission, transformation, distribution, grid, and personnel factors. Post-disaster resilience from the grid Racks, grid loads, and emergency repairs. The combined weight is used to reduce the weight deviation, and the fuzzy comprehensive evaluation is used to quantify the evaluation. Finally, an example is used to verify the effectiveness and feasibility of the method. Through this method, a scientific guidance is provided to the power grid to help the power grid system to make improvements in response to extreme natural disasters.

2. Evaluation index system of power grid's disaster response ability to cope with extreme natural disasters

2.1. Power grid response to extreme natural disasters stage division

To improve the power grid's ability to respond to disasters, corresponding strategies and plans must be adopted at different stages of disasters. When the power grid is subjected to extreme natural disasters, it will do great harm to the power system [13-14]. The damage and impact of extreme natural disasters on the power grid are carried out in the dimension of time and space [15]. From the perspective of improving the resilience of the power grid, the process of disaster prevention is divided into the planning measures phase, the pre-disaster prevention phase, and the disaster and post-disaster recovery phase according to time [16]. There are also studies divided into four time periods from the perspective of defense: disaster warning, disaster arrival, disaster continuation, and disaster end [17]. Taking into account the relatively limited disaster response measures of the power grid during the disaster phase and consideration of personal safety and other factors. The paper divides the disaster response process of the power grid into the pre-disaster bearing stage and the post-disaster recovery stage in the time dimension.

2.2. The pre-disaster endurance index system

The pre-disaster endurance index mainly considers whether the grid can withstand the disaster or weaken the related indexes affected by it.

The relationship between extreme natural disasters and the power grid is composed of disaster-causing factors, disaster-pregnant environment, and disaster-bearing bodies [18]. Among them, the power grid is composed of multiple system equipment. The power grid is directly affected or even damaged in the disaster, and the power grid continues to maintain the normal operation of the entire system when it is affected by natural disasters, reflecting its bearing capacity. According to the division of disaster response, the pre-disaster endurance index of the power grid is constructed, and it is composed of multiple equipment systems [19]. So the disaster response capacity of the power grid can be studied from the three aspects of transmission, transformation and distribution, and the research and prevention of power grid disaster resistance are also Research on important combinations of disaster response capabilities [17,20]. Figure 1 shows the index system of the power grid's capacity before a disaster.
3. Quantitative assessment method of power grid disaster response capability based on fuzzy comprehensive evaluation and comprehensive weight

2.3. The post-disaster resilience index system

According to the division of the power grid in the disaster response stage, the power grid will operate from the pre-disaster stage to the post-disaster stage. The post-disaster stage focuses on taking into account the rapid repair of the power grid to restore the system to normal operation after being affected by the disaster [21-23]. It is divided into three parts to construct the power grid resilience index after a disaster, including the grid restoration capability index, the grid load recovery capability index, and the emergency resource control capability index, as shown in Figure 2.

Figure 1. Pre-disaster endurance index system of power.

Figure 2. Power grid resilience index system after a disaster.

Figure 3. Quantitative assessment process of power grid disaster response capacity.
To study the ability of the power grid to withstand extreme natural disasters, it is necessary to conduct a scientific and reasonable analysis of the impact of the power grid on disasters through indicator weights and evaluation results. At the same time, it can reflect the disaster response capability of the power grid in a quantitative way. Figure 3 shows the quantification process of the power grid disaster response capability assessment proposed in the article.

4. Fuzzy comprehensive evaluation method of evaluation index before and after the disaster in power grid

4.1. Standardization of evaluation indicators
Since the indicator selections in the two types of indicator systems are different, and the dimensions of the indicators are also different, to achieve a reasonable and scientific comparative analysis, the corresponding disaster capacity indicators are standardized before the evaluation. Then the comprehensive weight is calculated after the processing. The calculation formula is formula (1):

\[
r_{ij} = \frac{r_{ij} - \min r_{ij}'}{\max r_{ij} - \min r_{ij}'}
\]

\[
r_{ij} = \frac{\max r_{ij}' - r_{ij}'}{\max r_{ij}'}
\]

In the formula, \( r_{ij} \) is the standardized value of the \( j \) index of the \( i \) expert, and \( r_{ij}' \) is the original data before standardization. \( \max r_{ij}' \) and \( \min r_{ij}' \) represent the maximum and minimum values of \( r_{ij}' \) respectively.

Sorting out the pre-disaster and post-disaster indicators, the corresponding indicators are divided as shown in Table 1:

| Indicator type | Corresponding indicators |
|----------------|--------------------------|
| Benefit type   | A11, A12, A13, A14, A17, A19, A21, A22, A23, A24, A25, A26, A27, A28, A29, A31, A32, A33, A34, A41, A42, A43, A44, A45, A46, A47, A51, A52, A53, A54, B11, B12, B13, B14, B21, B22, B23, B24, B25, B27, B31, B32 |
| Cost type      | A15, A16, A18, A210, A211, A55, B26, B33 |

After standardization, the evaluation index matrix \( R \) can be obtained:

\[
R = \begin{bmatrix}
r_{11} & \cdots & r_{1n} \\
\vdots & & \vdots \\
r_{m1} & \cdots & r_{mn}
\end{bmatrix}
\]

Among them, \( m \) is the number of experts, and \( n \) is the number of comprehensive evaluation indicators.

4.2. Weight calculation method

4.2.1. Analytic hierarchy process. Based on the actual situation of the power grid, the decision-makers' subjective thinking of the power grid disaster response capability assessment is modeled separately and the abstract turned into a concrete method. The general steps of the Analytical Hierarchy Process are based on the previously established index system, constructing a judgment matrix, hierarchical ordering, and consistency testing [24].

The power grid evaluation index system is established as the endurance before the disaster and the resilience after the disaster.
Assign values to the index weights at all levels according to experts and construct a judgment matrix by comparing them in pairs according to the nine-scale method.

Hierarchical ranking and consistency check.

According to the judgment matrix, the corresponding maximum eigenvalue $\lambda_{\text{max}}$ and its eigenvector $\theta$ can be calculated. The consistency index $CI$ of the judgment matrix is shown in formula (2):

$$CI = \frac{\lambda_{\text{max}} - n}{n - 1}$$

(2)

Where: $n$ is the order of the matrix, and $\lambda_{\text{max}}$ is the maximum eigenvalue of the matrix.

At the same time, the consistency ratio $CR$ can be calculated as shown in formula (3):

$$CR = \frac{CI}{RI}$$

(3)

Where: $CI$ is the consistency index of the judgment matrix. $RI$ is the average consistency index of the corresponding judgment matrix.

When $CR<0.10$, the consistency test is passed, and the eigenvector of the judgment matrix is the index weight. Otherwise, $CR>0.10$ requires the reconstruction of the judgment matrix.

4.2.2. Entropy method. Analyze the amount of information carried by each indicator of the power grid and the importance of the evaluation indicator in decision-making, so the entropy weight method is used to calculate the objective weight of the indicator. The amount of useful decision-making information for each indicator in the evaluation system is different. The calculation steps are as follows:

The evaluation indicators of the power grid disaster response capacity by multiple experts rely on the judgment matrix $X = (x_{ij})_{m \times n}$ composed of expert experience assignment. The $X$ judgment matrix is standardized, and its formula is shown in formula (4):

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}$$

(4)

In the formula: $r_{ij}$ is the standardized index value.

Calculate the entropy value of the standardized indicator data. The entropy value of the $i$ expert for the $j$ indicator is shown in formula (5):

$$H_j = -\frac{1}{\ln m} \sum_{i=1}^{m} u_{ij} \ln u_{ij}$$

$$u_{ij} = \frac{r_{ij}}{\sum_{j=1}^{n} r_{ij}}$$

(5)

In the formula: $H_j$ is the entropy $j = 1, 2 \cdots n$.

When $u_{ij} = 0$, then let $u_{ij} \ln u_{ij} = 0$, calculate the entropy weight of the $j$ index as follows (6):

$$\omega_j = \frac{1 - H_j}{n - \sum_{j=1}^{n} H_j}$$

(6)
4.2.3. Comprehensive subjective and objective weights. Because AHP has subjective factors and the entropy weight method lacks expert experience, the two types of weights will be merged to obtain a more balanced comprehensive weight, as shown in the following formula (7):

\[ \lambda = \left[ \lambda_1, \lambda_2, \ldots, \lambda_n \right] = \left[ \frac{\theta_1 \omega_1}{\sum_{j=1}^{n} \theta_j \omega_j}, \frac{\theta_2 \omega_2}{\sum_{j=1}^{n} \theta_j \omega_j}, \ldots, \frac{\theta_n \omega_n}{\sum_{j=1}^{n} \theta_j \omega_j} \right] \]  

In the formula: \( \theta_j \) and \( \omega_j \) (\( j = 1, 2, \ldots, n \)) respectively represent the subjective weight value and objective weight value of the evaluation index.

4.3. Quantitative analysis of evaluation index of power network disaster response ability

4.3.1. Fuzzy comprehensive evaluation of power grid. There are certain fuzziness, dynamics, and other factors in the evaluation index of power grid disaster response capability. Fuzzy theory can balance this problem.

To quantify the fuzzy classification of the evaluation object, the evaluation results are divided into 5 different levels of fuzzy judgment set \( V = \{ V_1, V_2, V_3, V_4, V_5 \} \).

The fuzzy subset of each indicator corresponding to different reviews can be described by the membership function, as shown in the following formula (8):

\[ f(x, \sigma, c) = e^{-\frac{(x-c)^2}{2\sigma^2}} \]  

In the formula: \( x \) is the decision index, \( \sigma \) and \( c \) are the two parameters of the Gauss membership function, \( \sigma \) is generally a positive number, and \( \sigma = 0.3 \) in the text. The value \( c \) represents the center position of the membership function.

To ensure that each index has 5 comment membership degrees, 5 \( c \) values are adopted in the article: Substituting into equation (8) to obtain 5 corresponding membership functions. Substituting the index \( r_{ij} \) in the judgment matrix \( R \) into each membership function, the following formula (9) is obtained:

\[ F = \left[ \begin{array}{ccc} f_{V_1}(r_{i1}) & \cdots & f_{V_1}(r_{i1}) \\ \vdots & \ddots & \vdots \\ f_{V_5}(r_{in}) & \cdots & f_{V_5}(r_{in}) \end{array} \right] \]  

In the formula: \( f_{V_k}(r_{ij}) (k = 1, 2, \ldots, 5; j = 1, 2, \ldots, n) \) is the degree of subordination of index \( r_{ij} \) to evaluation level \( V_k \).

4.3.2. Quantify the level of grid evaluation indicators. There are four types of operators in the fuzzy comprehensive evaluation, which are \( M(\land, \lor), M(\ast, \lor), M(\land, \oplus), M(\ast, \oplus) \). Among them, the \( M(\ast, \oplus) \) operator has a strong degree of comprehensiveness, the \( M(\ast, \oplus) \) operator (replaced by "\( \circ \)") is used. At the same time, the principle of average weighting is combined with comprehensive weights to obtain the grid disaster response assessment results, as shown in the following formula (10):

\[ P = \lambda \circ F = \left[ p_1(V_1) \quad p_1(V_2) \quad p_1(V_3) \quad p_1(V_4) \quad p_1(V_5) \right] \]  

In the formula: \( p_1(V_k) \) represents the degree of membership of each index relative to \( V_k \), which is the degree described by \( V_k \).

Quantify the evaluation index of formula (10) and quantify it through the fuzzy evaluation set, and obtain the quantified level of disaster response capability. \( V_1 \) is a stronger disaster response-ability, the score interval is (85,100), and the quantitative score is 95. \( V_2 \) is strong, the interval is (70,85], and the
quantitative score is 80. \( V_3 \) in general, and the interval is (70,85), the quantitative score is 65. \( V_4 \) is weak, the interval is (55,70], and the quantitative score is 50. \( V_5 \) is weaker, the interval is (0,55], and the quantitative score is 35.

The quantitative calculation method of the evaluation result is shown in formula (11):

\[
Z_i = \sum_{k=1}^{5} P_i(V_k) \times V_k
\]

5. Case study
A city-level power grid was used as the research object to carry out an extreme natural disaster response capacity assessment. The city’s extreme natural disasters are mainly wind disasters and icing disasters. The wind disasters are particularly serious and mainly occur in the winter and spring phases each year.

The power grid disaster response capacity system is divided into the pre-disaster endurance and post-disaster resilience index systems. Experts use the nine-scale method to assign the evaluation index system to obtain the judgment matrix of each criterion level index.

According to formula (3), it is checked whether the judgment matrix passes the consistency test, and the subjective weights of the index layer before and after the disaster are obtained through the test.

Five experts were selected to score various indicators of the power grid's disaster response capacity, and the pre-disaster bearing capacity and post-disaster recovery capacity indicators were divided into Table 1 using formula (1), and the standard evaluation matrix for each indicator was calculated. At the same time, the entropy method is used to obtain the objective weight of disaster response-ability before and after the disaster.

Combining subjective weights and objective weights, the final comprehensive weights \( \lambda_1 = [0.0161, 0.0333, 0.0268, 0.0372, 0.0147, 0.0190, 0.0040, 0.0247, 0.0141, 0.0410, 0.0240, 0.0167, 0.0178, 0.0120, 0.0411, 0.0085, 0.0134, 0.0058, 0.0131, 0.0177, 0.0236, 0.0510, 0.0602, 0.0654, 0.0252, 0.0101, 0.0302, 0.0347, 0.0138, 0.0621, 0.0324, 0.0475, 0.0565, 0.0486, 0.0230, 0.0208] \) and \( \lambda_2 = [0.1526, 0.0800, 0.0593, 0.0867, 0.0599, 0.0225, 0.0475, 0.0877, 0.0567, 0.0172, 0.0471, 0.0377, 0.0377, 0.0621, 0.1831] \) can be obtained through formula (7). The comprehensive weights of the pre-disaster and post-disaster criterion layers are [0.1899, 0.2051, 0.2003, 0.2083, 0.1964] and [0.3785, 0.3386, 0.2829].

Among the pre-disaster capacity of the power grid, the overall weight of the distribution network's disaster response capacity is the highest, among which the black start capacity weight is the largest to 0.0411, indicating that the distribution network has a strong ability to recover its system after a disaster, outage. Besides, the overall weight of the disaster response capacity of the transmission grid is the lowest, and the lowest insulation rate in the indicator layer is 0.004, reflecting the low insulation capacity of the city's transmission lines. In the evaluation results of the power grid resilience after a disaster, the comprehensive weights between the criterion levels are relatively balanced, which indirectly reflects the relatively balanced power grid recovery capacity of the city. The comprehensive weight reflects that the recovery speed of the backbone grid after the disaster is faster, and the speed of power grid rescue is faster, which provides a guarantee for the recovery of the power grid after the disaster, but it also reflects the need to improve the ability of the emergency organization.

Substituting the standard evaluation matrix \( R \) into equation (8) to obtain equation (9), and using equation (10) to calculate the fuzzy comprehensive evaluation of the power grid's disaster response capacity, using equation (11) to quantify the evaluation result, and obtaining the pre-disaster and post-disaster according to the principle of maximum subordination. The fuzzy comprehensive evaluation results of the index evaluation are 69.4116 and 78.1841 respectively. According to the quantitative classification, the city's power grid capacity before the disaster is at a general level, the power grid resilience after the disaster is at a relatively strong level.

In 2018, extreme natural disasters occurred. Due to insufficient insulation of transmission lines, foreign bodies tripped under strong wind disasters. The city's power supply company immediately organized and coordinated emergency repair work and issued a grid risk warning before the disaster.
The deployment of emergency resources is rapid and accurate, and the emergency repair of equipment is time to reduce the impact and damage to the power grid caused by strong wind disasters and improve the power grid recovery capacity after disasters.

Through the analysis of actual cases, it is verified that the quantitative assessment method of the power grid's disaster response capacity proposed in the article can meet the needs of the power grid disaster response capacity assessment. It can reflect the shortcomings of the power grid in the disaster response and recovery process, and provide reasonable guidance.

6. Conclusions
In terms of the time dimension of grid disaster response under extreme natural disasters, this paper divides the grid disaster response into two indicator evaluation stages: before and after disasters. The subjective and objective weights are used to form a comprehensive weight to reduce the weight deviation, and the comprehensive weight and fuzzy comprehensive evaluation method are used to carry out the quantitative assessment of the power grid disaster response capability.

The calculation example uses a certain power grid's disaster response capability as an evaluation. The evaluation results are consistent with the facts, verifying the validity and rationality of the proposed method. This method has certain guiding significance for the power grid's disaster response capability.

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