Smart Grid Risk Warning Based on Multi-Level Fuzzy Analytic Hierarchy Process

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Abstract. Real-time control of the risks that may occur in the smart grid is of great significance for the safe and efficient operation of the smart grid. This paper establishes a risk early warning system for smart grids based on analytic hierarchy process and fuzzy theory. Firstly, the analytic hierarchy process is used to comprehensively consider the system line, load, system power supply capacity and environment and other factors to establish a smart grid evaluation index system. Then the comprehensive weights of each level of indicators are calculated, and then the evaluation matrix of the index is established by combining the membership function. Finally, the fuzzy theory is used to predict the system risk. The case study shows that the qualitative and quantitative early warning system for assessing smart grid risk has good practicability.

1. Introduction
In recent years, frequent smart grid failures have had a great impact on social development. I have been working in a solar power plant for two years and have a certain understanding of the reliability of the power grid. Taking our unit as an example, power generation reliability is an important indicator for evaluating the level of power stations. The scale of China's smart grid is expanding, the operation mode of the power grid will become more complicated, and the control will become more and more difficult. How to accurately, quickly and comprehensively assess the safety level of smart grids, and use this as a basis to develop a reasonable early warning program has become the key to avoid large-scale blackouts.

Reference [1] shows that when determining the weak link of the system bus, the equivalent potential and impedance value obtained by the system in real time are determined by simple calculation. The voltage stability index uses the minimum value corresponding to all load buses in the system, then these minimum values the corresponding busbar is the weak link of the system. In [2], the typical scenarios of the operating state and trend anomaly of the power system are analyzed. By constructing a state feature and trend indicator system and evaluation process that can reflect the abnormal operation of the power system, the power system will be developed for a period of time in the future. Correlation between trends, causes of deterioration, and status quo of real-time operations.

Based on this, this paper synthesizes internal factors such as real-time transmission line conditions, overload and external factors such as environment, improper human operation, etc., using AHP to calculate the weight of relevant evaluation indicators, and conduct consistency test, and finally combine fuzzy The theory conducts risk warnings to better provide a basis for power dispatching.
2. Selection of Smart Grid Evaluation Indicators

In this paper, based on the reference [12], based on the opinions of the on-site operation and maintenance personnel, the use of a large number of information resources to establish a smart grid risk warning evaluation indicators as shown in Figure 1.

![Smart Grid Risk Early Warning Assessment Indicator Structure Chart](image)

Figure 1. Smart grid risk early warning assessment indicator structure chart.
3. Determination of the weight of each indicator

3.1. Weighting method
The methods commonly used to determine the weight of each indicator are: AHP, ANP and entropy method. According to the specific example, this paper chooses AHP to determine the index weight.

3.2. Determination of AHP weight

3.2.1. Flow chart. Flow chart shown in Figure 2.

Figure 2. AHP determines the weight flow chart.

3.2.2. Structural judgment matrix. The degree of importance of two factors is usually used to indicate the relative importance of the two factors, which is a significant feature of the analytic hierarchy
process. The judgment matrix is a matrix composed of the results of the two-two comparison. The assignment of the nine importance levels given by Saaty is listed in Table 1.

| Factor i ratio factor j          | Scaling |
|----------------------------------|---------|
| Equally                         | 1       |
| Slightly important              | 3       |
| Stronger                        | 5       |
| Strongly important              | 7       |
| Extremely important             | 9       |
| Intermediate value of two adjacent judgments | 2,4,6,8 |

3.2.3. Hierarchical single sort. The problem of calculating the weight of the relative importance of an index element in the upper layer according to the judgment matrix is called hierarchical single ordering. The maximum eigenvalue of the approximation and its corresponding eigenvector can be found on the computer by iterative method. The calculation steps of the maximum eigenvalue of the calculation matrix and its corresponding eigenvector square root method are given as follows:

1) Calculate the product of each row of the judgment matrix \( M_i \):

\[
M_i = \prod_{j=1}^{n} a_{ij}
\]  

2) Calculate \( \overline{W}_i \):

\[
\overline{W}_i = \sqrt[n]{M_i}
\]  

3) Normalize and normalize the vector \( \overline{W} = [\overline{W}_1, \overline{W}_2, \ldots, \overline{W}_n]^T \):

\[
W_i = \frac{\overline{W}_i}{\sum_{j=1}^{n} \overline{W}_j}
\]  

\( \overline{W} = [\overline{W}_1, \overline{W}_2, \ldots, \overline{W}_n]^T \) is the eigenvector sought.

4) Calculate the largest eigenvalue of the judgment matrix:

\[
\lambda_{\text{max}} = \sum_{i=1}^{n} \frac{(AW)_i}{nW_i}
\]  

The maximum eigenvalue \( \lambda_{\text{max}} \) of the judgment matrix can be obtained by combining formulas (1), (2), (3) and (4). And the eigenvector corresponding to \( \lambda_{\text{max}} \), after the eigenvector is normalized and normalized, it is recorded as \( \overline{W} \).

3.2.4. Consistency check of hierarchical single ordering. The consistency test refers to determining the allowable range of inconsistency in the judgment matrix, and whether the calculated feature vector is hierarchical single order, and consistency check is required. If the unique non-zero eigenvalue of the \( n \)-order uniform array is \( n \), \( \lambda \) is the largest eigenvalue of the judgment matrix, the following
relationship exists: $\hat{\lambda} \geq n$. The consistency index is expressed by $CI$. The smaller $CI$ is, the larger the consistency is, and the more satisfactory the judgment matrix $A$ is. Define the consistency indicator as:

$$CI = \frac{\hat{\lambda} - n}{n - 1}$$  (5)

This paper introduces the random consistency index $RI$ to measure the size of $CI$. The random consistency index $RI$ is related to the order of the judgment matrix. In general, the probability of the random deviation of the matrix is increasing with the order of the matrix. As shown in Table 2, the relationship between the standard values of the random consistency index and the corresponding matrix order is shown.

| Matrix order | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|--------------|----|----|----|----|----|----|----|----|----|----|
| $RI$         | 0  | 0  | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

This paper gives the test coefficient $CR$:

$$CR = \frac{CI}{RI}$$  (6)

Generally if $CR < 0.1$, then, the judgment matrix is considered to pass the consistency test, otherwise the judgment matrix needs to be reconstructed.

3.2.5. Hierarchical total ordering and its consistency test. The process of calculating the relative importance weights of all factors at a certain level to the target layer is called the hierarchical total ordering. This process is generally carried out in order from the highest level to the lowest level. After the calculation is completed, it is still necessary to perform consistency check on the total order of the levels.

4. Establishment of a comprehensive evaluation model

4.1. Determination of the membership value of quantitative indicators
In this paper, the benefit index and the cost index are divided into two membership functions.

1) For the benefit index, firstly, according to the actual situation of power system planning and stable operation, the optimal and worst critical values $\alpha$ and $\beta$ of the index are determined. $(\alpha, \beta)$ then inserts three equidistant points $c_1$, $c_2$, and $c_3$ to obtain an evaluation. Indicator $x_{ij}$ is subject to the degree of membership of each risk level.

$$x_{ij}^{(1)} = \begin{cases} 
1, & \lambda \geq \beta \\
(\lambda - c_3) / r, & c_3 \leq \lambda < \beta \\
0, & \lambda < c_3
\end{cases}$$  (7)

$$x_{ij}^{(m)} = \begin{cases} 
0, & c_{5-m+1} \leq \lambda \\
(c_{5-m+1} - \lambda) / r, & c_{5-m} \leq \lambda < c_{5-m+1} \\
(\lambda - c_{5-m+1}) / r, & c_{5-m+1} \leq \lambda < c_{5-m} \\
0, & \lambda < c_{5-m+1}
\end{cases}$$  (8)
The cost type indicator, the method of determining the membership function is similar to the benefit type indicator. The degree of membership of the evaluation indicator $x_{ij}$ belonging to each risk level is as follows:

$$x_{ij}^{(5)} = \begin{cases} 1, & \lambda < \alpha \\ \frac{c_i - \lambda}{r}, & \alpha \leq \lambda < c_1 \\ 0, & \lambda \geq c_1 \end{cases}$$

(9)

$$x_{ij}^{(1)} = \begin{cases} 1, & \lambda < \alpha \\ \frac{(c_i - \lambda)}{r}, & \alpha \leq \lambda < c_1 \\ 0, & \lambda \geq c_1 \end{cases}$$

(10)

$$x_{ij}^{(m)} = \begin{cases} 0, & \lambda < c_{m-2} \\ \frac{(\lambda - c_{m-2})}{r}, & c_{m-2} < \lambda < c_{m-1} \\ \frac{(c_m - \lambda)}{r}, & c_{m-1} \leq \lambda < c_m \\ 0, & \lambda \geq c_m \end{cases}$$

(11)

$$x_{ij}^{(5)} = \begin{cases} 0, & \lambda < c_3 \\ \frac{(\lambda - c_3)}{r}, & c_3 \leq \lambda < c_4 \\ 1, & \lambda \geq \beta \end{cases}$$

(12)

among them $m = 2, 3, 4$ ; $r = (\beta - \alpha) / 4$ ; $c_0 = \alpha$ ; $c_4 = \beta$ ; $\lambda$ is the actual value of $x_{ij}$.

4.2. Establish an evaluation model

For each indicator to evaluate the single indicator, this paper uses the membership function to substitute each index value into the corresponding membership function to establish a single indicator evaluation matrix:

$$R = (r_{ij})_{n \times s}$$

(13)

The comprehensive weight vector sought in the hierarchical total ordering is:

$$W = (w_{ij})_{s \times n}$$

(14)

among them $n$ is the number of indicators, $s$ is the number of levels.

The evaluation result obtained by applying the fuzzy synthesis operation is:

$$B = W \circ R$$

(15)

among them $\circ$ is Fuzzy synthesis operator.

5. Determination of the comment set

People often use different colors to distinguish the level of things, and different colors to represent different levels of risk. This article reviews the reference to the meteorological disaster warning system, combined with the literature [12] to indicate five risk levels in five colors: green (1), blue (2),...
yellow (3), red (4), and black (5). (Class I, II, III, IV, V) are normal, mild, slightly heavier, severe, and super serious. This article can also use the number corresponding to the warning level as a quantitative description of the risk range, the green level range is [0, 1], the blue level range is (1, 2], the yellow level range is (2, 3], the red level range is (3, 4] and the black level range is (4, 5].

6. Case analysis
According to the actual operation of a power grid in northwest China, combined with the above examples, the power system risk warning level is analyzed and explained. The condition of the study is: On April 12, 2018, 11:30 to 12:00 for power system risk early warning analysis, the total active power load forecast is 12,600 MW, the weather forecast temperature is 24, and the relative humidity is 20%. The wind is a northwesterly wind of 1 level, and the light intensity is weak. Through the data monitored by the dispatch center, the values of each index are calculated as shown in Table 3.

| Judging index | C1   | C2   | C3   | C4   | C5   | C6   | C7   | C8   | C9   | C10  | C11  | C12  | C13  |
|---------------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Index value   | 0.785| 0.486| 8.564| 8.325| 11.743| 3.587| 556  | 0.165| 128.3| 0.782| 0    | 0    | 387.543|

| Judging index | C14  | C15  | C16  | C17  | C18  | C19  | C20  | C21  | C22  | C23  | C24  | C25  | C26  |
|---------------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Index value   | 5.200| 0    | 0.213| 32   | 10   | 49   | 32.245| 1    | 0    | 0    | 1    | 1    | 11.567|

6.1. Weight determination
From the power system risk early warning assessment indicators in Figure 1, they are compared in pairs to form the judgment matrix as $A, B_1, B_2, B_3$, and calculate the hierarchical order and its consistency test.

Construct the judgment matrix as follows:

$$A = \begin{bmatrix} 1 & 3 & 5 & 7 \\ 1/3 & 1 & 3 & 4 \\ 1/5 & 1/3 & 1 & 3 \\ 1/7 & 1/5 & 1/3 & 1 \end{bmatrix}$$

Combine the formulas (1), (2), (3) and (4) and use Matlab to obtain the maximum eigenvalue $\lambda_{\text{max},A}$ of the judgment matrix, the feature vector corresponding to $\lambda_{\text{max},A}$, and the feature vector is normalized and normalized, and then recorded as $W_A$.

Can calculate $W_A = \begin{bmatrix} 0.5720 \\ 0.2527 \\ 0.1195 \\ 0.0558 \end{bmatrix}$, $\lambda_{\text{max},A} = 4.0641$, $RI_A = 0.9000$, $CI_A = 0.0214$, $CR_A = 0.0237 < 0.1$. Judgment matrix $A$ passes the consistency test; Similarly, for the judgment matrix $B_1, B_2, B_3, B_4$ the feature vector and the eigenvalue can be obtained in turn, and the consistency test is passed. Calculated its comprehensive weight is:

$$W = [0.0281, 0.0149, 0.0578, 0.0611, 0.1219, 0.2882, 0.1186, 0.0174, 0.0343, 0.0657, 0.0084, 0.0084, 0.0674, 0.0316, 0.0066, 0.0141, 0.0079, 0.0021, 0.0149, 0.0079, 0.0009, 0.0013, 0.0043, 0.0128, 0.0027, 0.0009]$$
and perform consistency check on the total order of the hierarchy. Calculate $RI = 1.2133$, $CI = 0.0681, CR = 0.0561 < 0.1$, the total ranking of the levels is checked by consistency.

6.2. System comprehensive evaluation

Establish an evaluation matrix for the above indicators based on the benefit type and cost type membership functions:

$$ R = \begin{bmatrix} 0.1400 & 0.8600 & 0 & 0 & 0 \\ 0 & 0 & 0.9400 & 0.0560 & 0 \\ 0 & 0.8512 & 0.1488 & 0 & 0 \\ 0 & 0.6600 & 0.3400 & 0 & 0 \\ 0 & 0 & 0.3944 & 0.6056 & 0 \\ 0 & 0.8696 & 0.1304 & 0 & 0 \end{bmatrix} $$

Calculate $R_2, R_1, R_4$ in turn, $R = [R_1; R_2; R_3; R_4]$; Using Matlab to programmatically substitute data into fuzzy relation $B = W \cdot R$. Calculate $B = [0.0674, 0.2882, 0.1304, 0.1219, 0.1186]$; Weighted average method:

$$ v_0 = \frac{\sum_{j=1}^{m} b_j v_j}{\sum_{j=1}^{m} b_j} \quad (16) $$

Among them: $v_0$ is the comprehensive evaluation value, $v_j$ is the evaluation level, and $b_j$ level corresponds to the membership degree. Calculate $v_0 = 3.0880$. Combined with the principle of maximum membership, the result of the evaluation is red, indicating that the power supply system has serious problems, the power of the grid is more severely unbalanced and the voltage stability margin is lower, obviously, at 12:00 to the peak of power consumption, the above situation generally occurs, so the prediction of this algorithm is credible, this provides a basis for the reasonable scheduling of the dispatch center to ensure efficient and stable operation of the power system.

7. Conclusion

Establishing a power system risk early warning system plays an important role in ensuring the safe and stable operation of the power system. The indicators in this paper can directly or indirectly affect the factors of the power system from the system line, load, system power supply capacity and environment, and establish an evaluation matrix. Power system risk warnings are more intuitive, sensitive, and widely credible. In the aspect of determining the weight of indicators, AHP is more objectively used to determine the weight of indicators, avoiding the subjective influence of using expert scoring, and the reliability of the evaluation results is higher. Using fuzzy evaluation method, the index is divided into two levels of fuzzy comprehensive evaluation, which can better reflect the special requirements of power system risk warning. However, in the establishment process of the evaluation matrix, the membership function is adopted, and the selection of the index interval depends on the subjective consciousness of the site operation and maintenance personnel. The artificial factors are more. In the future research, further research can be conducted in this aspect to make the early warning. The results are more objective and credible.

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