State Evaluation of Circuit Breakers Based on Improved Fuzzy Comprehensive Evaluation Method

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Abstract. In order to quickly and effectively distinguish the operating state of the circuit breaker and improve the accuracy of the state evaluation, an improved fuzzy comprehensive evaluation model is proposed. The evaluation index is weighted based on the combined weighting method, which avoids the dependence of the traditional analytic hierarchy process on the subjective scoring of the weights. The gray correlation theory is introduced to modify the evaluation results, which effectively overcomes the inherent shortcomings of the principle of maximum membership. The improved fuzzy comprehensive evaluation method is applied to the state evaluation of circuit breakers, and the evaluation indexes are established through time parameters, speed parameters, circuit parameters and electrical characteristic parameters, and then a multi-layer fuzzy comprehensive evaluation model is established. Finally, the evaluation model is used to analyze the laboratory circuit breaker, which verifies the feasibility and effectiveness of the model.

1. Introduction

The state assessment of circuit breaker mainly includes fuzzy theory, grey theory, association rules and other methods[1-2]. Literature [3] uses the intuitionistic hierarchy fuzzy analysis method to determine the subjective weights of the evaluation parameters, obtains the objective weights based on the cross-entropy method of analyzing the difference in the amount of information, uses the relative entropy to obtain the optimal combination weights, and uses the cloud model to improve the gray whitening weight function. Not all factors were considered in the result evaluation. Literature [4] proposes an ideal interval method based on the idea of combined weighting to evaluate the state of the circuit breaker. Literature [5] uses gray fuzzy comprehensive evaluation method in the circuit breaker maintenance sequencing method, which comprehensively considers the fuzziness and grayness, However, the analytic hierarchy process is used to determine the weight to get the constant weight, which is highly subjective. Through the above analysis, this paper proposes an improved fuzzy comprehensive evaluation method of circuit breaker status. In determining the weights of related indicators, the interval analytic hierarchy process is used to obtain the subjective weights, the excess weighting method is used to determine the objective weights, and the combined weighting idea is introduced to determine the final weights. Aiming at the inherent shortcomings of the maximum degree of membership determination of the evaluation results, the grey relational theory is introduced to revise the evaluation results. Through the improved fuzzy comprehensive evaluation method, the operating state of the circuit breaker is evaluated and verified by experiments.

2. Materials and Methods

The fuzzy comprehensive evaluation method is a mathematical method that uses uncertainty
mathematical methods to comprehensively evaluate things or phenomena affected by multiple factors. The essence is through fuzzy transformation principle and maximum membership principle. There is an index set \( U = \{U_1, U_2, \cdots, U_n\} \) composed of \( n \) evaluation indicators, and a comment set \( V = \{V_1, V_2, \cdots, V_m\} \) composed of \( m \) reviews, the fuzzy evaluation method can be expressed as

\[
B = A \circ R
\]

Among them, \( A \) is the weight vector corresponding to each evaluation index, \( R \) each index corresponds to the membership matrix of each comment, and \( B \) is the evaluation result vector. According to the principle of maximum membership, the comment corresponding to the maximum membership is selected as the final result.

2.1 Selection of evaluation indicators

According to the fault characteristics of the circuit breaker and the parameters. We can characterize the abnormal operating state, time parameters, speed parameters, current parameters and electrical characteristics parameters are selected as the evaluation indicators of the circuit breaker. Due to too many evaluation indicators, a two-layer fuzzy comprehensive evaluation model is established. A 1-level indicator contains multiple 2-level indicators. As shown in the Figure 1.

![Figure 1 Evaluation index](image)

The time parameter \( (U_1) \) includes different periods of opening \( (U_{11}) \), different periods of closing \( (U_{12}) \), and others \( (U_{13}) \); speed parameters \( (U_2) \) include opening speed \( (U_{21}) \), closing speed \( (U_{22}) \), others \( (U_{23}) \); current parameters \( (U_3) \) include opening current \( (U_{31}) \), closing current \( (U_{32}) \), and others \( (U_{33}) \); electrical characteristic parameters \( (U_4) \) include Stroke \( (U_{41}) \), conductive loop resistance \( (U_{42}) \), distance \( (U_{43}) \), and number of breaks \( (U_{44}) \).

When performing fuzzy comprehensive evaluation, the calculation starts with the second-level indicators. And the membership matrix of the first-level indicators is composed of the calculation results of the second-level indicators. Then then the final evaluation results are obtained.

2.2 Determination of weight

2.2.1 Obtaining subjective weight

Subjective weight is obtained by improved analytic hierarchy process\(^6\). Aiming at the shortcoming of relying too much on subjective scoring caused by the use of a single value in the traditional analytic hierarchy process, the analytic hierarchy process is improved by replacing a single value with a numerical interval. This method can dilute the uncertainty caused by subjective scoring. To make the model more accurate, the main steps are:

(1) When establishing the judgment matrix \( A \), replace a with the interval number \([a^-, a^+]\) to express the result of the pairwise comparison. The improved judgment matrix is as follows:

\[
A = \begin{bmatrix}
[a_{11}^-, a_{11}^+] & [a_{12}^-, a_{12}^+] & \cdots & [a_{1n}^-, a_{1n}^+]

[a_{21}^-, a_{21}^+] & [a_{22}^-, a_{22}^+] & \cdots & [a_{2n}^-, a_{2n}^+]

\vdots & \vdots & \ddots & \vdots

[a_{n1}^-, a_{n1}^+] & [a_{n2}^-, a_{n2}^+] & \cdots & [a_{nn}^-, a_{nn}^+]
\end{bmatrix}
\]

(2) The judgment matrix of the above for-mula is divided into \( A^- \) and \( A^+ \) according to the lower
limit of the interval and the upper limit of the interval, and the maximum eigenvalues of the two matrices and the corresponding normalized eigenvectors \( \lambda_+ \) and \( \lambda_- \) are calculated respectively, and then the weight vector is obtained:

\[
a_+ = \alpha \lambda_+, \quad a_- = \beta \lambda_-
\]

Among them \( \alpha = \sqrt{\frac{\sum_{j=1}^{n} \left( \sum_{i=1}^{n} a_{ij}^+ \right)^{-1}}{\sum_{j=1}^{n} \left( \sum_{i=1}^{n} a_{ij}^- \right)^{-1}}} \)

(3) Take the average of the two weights and finally get the subjective weight \( a_p \)

\[
a_p = (a_+ + a_-) / 2
\]

(4) Finally, the consistency of the results is tested according to the consistency test method of the traditional analytic hierarchy process.

2.2.2 Obtaining objective weight
The objective weight is obtained by the excess weighting method \cite{7}. The solution formula of this method is simple, easy to calculate, and considers the statistical average of a single indicator in multiple criteria. In the engineering background of this article, it is convenient to obtain the average value of each evaluation index and its subordinate indexes in the operating state of the circuit breaker, so this method is closer to reality than the entropy method. The calculation steps of the excess weighting method are shown in the formula

\[
ex_n = x_n / a_n
\]

(4) \( x_n \) is the actual measured value of the nth discriminant index, and \( a_n \) is the statistical average of the index in each standard. After normalization, the objective weight of each index \( a_q \) can be obtained.

\[
a_q = \frac{x_n / a_n}{\sum (x_n / a_n)}
\]

(5)

2.2.3 Combination weighting
Based on the combination weighting idea, the combination weight \( a \) is obtained by the above two weighting methods. Considering that the subjective and objective weights have different effects on the evaluation results, in order to achieve the goal of subjective and objective unification as much as possible, the combination is introduced as shown in the formula. Combination weighting factor \( \gamma \), this paper takes \( \gamma = 0.5 \):

\[
a = \gamma a_p + (1 - \gamma) a_q
\]

(6)

Then can get the final weight vector \( A = [a_1, a_2, \ldots, a_n] \)

2.3 Determination of membership function
Four levels are selected as the final comment set \( V = \{ \text{excellent}(V_1), \text{good}(V_2), \text{moderate}(V_3), \text{poor}(V_4) \} \), and the membership function of "triangular and semi-trapezoidal combination" is adopted. For each evaluation index, the membership degree of the factor to each comment is determined according to the value \( x \), as shown in Table 1 show, and the membership function is represented by the coordinate diagram in Figure 2.

The resulting membership degree vector \( r_i = [r_{i1}, r_{i2}, r_{i3}, r_{i4}] \) represents the membership degree of the i-th evaluation index for the four reviews.

Determine the membership degree of each evaluation index one by one, and finally get the membership matrix \( R = [r_{11}, r_{12}, \ldots, r_{n1}] \).
Table 1 Fuzzy distribution membership function

| Comments | Membership function | Comments | Membership function |
|----------|---------------------|----------|---------------------|
| Excellent (V₁) | \[ 1 \quad x_i \leq a_1 \]
\[ \frac{a_1 - x_i}{a_1 - a_1} \quad a_1 \leq x_i \leq a_2 \]
\[ 0 \quad x_i \geq a_2 \] | Moderate (V₃) | \[ \frac{x_i - a_6}{a_6 - a_6} \quad a_6 \leq x_i \leq a_7 \]
\[ \frac{a_7 - x_i}{a_7 - a_7} \quad a_7 \leq x_i \leq a_8 \]
\[ 0 \quad x_i \leq a_8 \text{ or } x_i \geq a_9 \] |
| Good (V₂) | \[ \frac{x_i - a_3}{a_3 - a_3} \quad a_3 \leq x_i \leq a_4 \]
\[ \frac{a_4 - x_i}{a_4 - a_4} \quad a_4 \leq x_i \leq a_5 \]
\[ 0 \quad x_i \leq a_5 \text{ or } x_i \geq a_6 \] | Poor (V₄) | \[ \frac{x_i - a_9}{a_9 - a_9} \quad a_9 \leq x_i \leq a_{10} \]
\[ 1 \quad x_i \geq a_{10} \] |

Figure 2 Fuzzy distribution membership function diagram

2.4 Fuzzy operator selection and evaluation results are determined

Fuzzy operator is essentially a composite operation of weight vector and membership degree matrix. This paper selects the weighted average operator \( M(+,+) \), which takes into account both main factors and non-main factors, and use index information as much as possible.

After fuzzy calculation, the judgment result \( B = A \circ R = [b_1, b_2, b_3, b_4] \) can be obtained.

The traditional fuzzy comprehensive evaluation method uses the principle of maximum membership degree to determine the final evaluation result, that is, the comment corresponding to the largest value in \( B \) is selected as the final evaluation result. The disadvantage of this method is that only the most important factors are considered and too much information is lost. Therefore, this paper introduces the grey relational theory to improve the method of determining the evaluation result. After the evaluation result of the formula is obtained by the fuzzy operation, the reference vector \( B' \) is established, and the final evaluation result is determined through the correlation between \( B \) and the reference vector.

The basic idea of relevance is to judge the degree of relevance according to the similarity in the curve. It is a kind of quantitative analysis. Set the reference vector as \( x_0 \) and the compared vector as \( x_i \), which is recorded as

\[ x_0 = [x_{01}, x_{02}, \ldots, x_{0m}] \quad , \quad x_i = [x_{i1}, x_{i2}, \ldots, x_{im}] \]

The absolute difference of the two vectors at the \( k \)-th point is

\[ \Delta_i(k) = |X'_0(k) - X'_i(k)| \]
The minimum difference \( M_{\text{min}} \) and the maximum difference \( M_{\text{max}} \) between the two levels is:

\[
M_{\text{min}} = \min_i \min_k \Delta_i(k), \quad M_{\text{max}} = \max_i \max_k \Delta_i(k)
\]  

Then the correlation coefficient of the two vectors at point \( k \) is:

\[
\xi(k) = \frac{M_{\text{min}} + 0.5M_{\text{max}}}{\Delta_i(k) + 0.5M_{\text{max}}}
\]  

Finally, the correlation degree of the two vectors can be obtained. According to the degree of relevance, the final judgment result can be determined:

\[
r = \frac{1}{m} \sum_{k=1}^{m} \xi(k)
\]  

3. Results & Discussion

In order to verify the evaluation method of this article, the model ZN63 (VS1) -12 circuit breaker was used for experiments. Its operating characteristics and technical parameters are shown in Table 2:

| Project               | Value         | Project               | Value         |
|-----------------------|---------------|-----------------------|---------------|
| Opening time          | 15-50ms       | Closing time          | 35-70ms       |
| Different period      | \( \leq 2\text{ms} \) | First opening speed   | 0.9-1.2m/s    |
| Open distance         | 11\( \pm 1\)mm | First closing speed   | 0.5-0.8m/s    |
| Overtravel            | 3.5\( \pm 0.5\)mm | Loop resistance      | \( \leq 60\mu\Omega \) |

Select an experiment data as shown in the Table 3:

| Project               | Value         | Project               | Value         |
|-----------------------|---------------|-----------------------|---------------|
| Different period of opening | 1.2ms      | Stroke                | 14.5mm        |
| Opening speed         | 1.64m/s       | Closing speed         | 1.04m/s       |
| Opening current       | 1.78A         | Maximum opening speed | 1.65m/s       |
|                       |               | Maximum closing speed | 1.40m/s       |

Calculate the weight of each indicator according to the method described in section 2.2:

The time parameter weight \( A_1 \) is \( A_1 = [0.5160, 0.3938, 0.0902] \).

The speed parameter weight \( A_2 \) is \( A_2 = [0.5278, 0.3325, 0.1397] \).

The current parameter weight \( A_3 \) is \( A_3 = [0.4545, 0.4545, 0.0910] \).

The electrical characteristic parameter weight \( A_4 \) is \( A_4 = [0.1891, 0.3509, 0.3509, 0.1091] \).

Carry out consistency test, the result shows that the weight distribution is more reasonable.

Then determine the degree of membership. Here we take the different periods of opening and closing as an example to establish the membership function. According to the technical parameters of the circuit breaker, the different periods of opening and closing of the three items should be less than or equal to 2ms, so multiple experiments have been performed to determine the appropriate \( a_1 \) to \( a_{10} \). The membership functions of different periods of opening and closing are established as shown in Table 4 and The membership function diagram is shown in Figure 3:
Table 4 Different membership functions

| Comments   | The membership functions | Comments   | The membership functions |
|------------|--------------------------|------------|--------------------------|
| Excellent  | \( V_1 = \begin{cases} 1 & x_i \leq 0.5 \\ 2 - 2x & 0.5 \leq x_i \leq 1 \\ 0 & x_i \geq 1 \end{cases} \) | Moderate  | \( V_2 = \begin{cases} 2x - 1.5 & 0.75 \leq x_i \leq 1.25 \\ 3.5 - 2x & 1.25 \leq x_i \leq 1.75 \\ 0 & x_i \leq 0.75 \text{ or } x_i \geq 1.75 \end{cases} \) |
| Good       | \( V_2 = \begin{cases} 2x - 0.5 & 0.25 \leq x_i \leq 0.75 \\ 2.5 - 2x & 0.75 \leq x_i \leq 1.25 \\ 0 & x_i \leq 0.5 \text{ or } x_i \geq 1.25 \end{cases} \) | Poor      | \( V_4 = \begin{cases} 0 & x_i \leq 1.5 \\ 2x - 3 & 1.5 \leq x_i \leq 2 \\ 1 & x_i \geq 2 \end{cases} \) |

Figure 3 Different membership function diagram

According to the experimental data and the membership function, the time parameter membership matrix \( R_1 \) is obtained as:
\[
R_1 = \begin{bmatrix} 0.6667 & 0.3333 & 0 & 0 \\ 0.8 & 0.2 & 0 & 0 \\ 0.7 & 0.3 & 0 & 0 \end{bmatrix}.
\]

Then follow this step to successively establish the membership functions of other judgement factors and determine the membership degree of each factor to obtain the speed parameter membership matrix \( R_2 \), current parameter membership matrix \( R_3 \), electrical characteristic parameter membership matrix \( R_4 \): 
\[
R_2 = \begin{bmatrix} 0.75 & 0.15 & 0.1 & 0 \\ 0.7 & 0.15 & 0.15 & 0 \end{bmatrix}, R_3 = \begin{bmatrix} 0.9 & 0.1 & 0 & 0 \\ 0.95 & 0.15 & 0 & 0 \end{bmatrix}, R_4 = \begin{bmatrix} 0.65 & 0.2 & 0.15 & 0 \\ 0.5 & 0.2 & 0.2 & 0.1 \\ 0.6 & 0.3 & 0.1 & 0 \\ 0.25 & 0.25 & 0.3 & 0.2 \end{bmatrix}.
\]

Perform fuzzy calculation to get the second-level evaluation result:

The evaluation result of the time parameter \( U_1 \) is: \( B_1 = A_1 \circ R_1 = (0.7222, 0.2778, 0, 0) \).

The evaluation result of the speed parameter \( U_2 \) is: \( B_2 = A_2 \circ R_2 = (0.7543, 0.1430, 0.1027, 0) \).

The evaluation result of the current parameter parameter \( U_3 \) is: \( B_3 = A_3 \circ R_3 = (0.8864, 0.1136, 0, 0) \).

The evaluation result of the electrical characteristic parameter \( U_4 \) is: \( B_4 = A_4 \circ R_4 = (0.5284, 0.2309, 0.1748, 0.0578) \).

The membership matrix \( R \) of the first level index composed of four two-level evaluation result vectors is:
Then calculate the final judgment result $B$:

$$B = A \circ R = (0.7699, 0.1687, 0.0551, 0.0063)$$

It can be seen from this that the degree of membership corresponding to the comment "excellent" is 0.7699, which is an absolute advantage in the vector, so the current comment can be used as the final evaluation of the circuit breaker's operating status.

But take another set of data to conduct experiments and find that the final judgment result $B$ is:

$$(0.0502, 0.4598, 0.4672, 0.0228)$$

Since the difference between 0.4598 and 0.4672 is not large, it is obviously unreasonable to blindly identify the evaluation result as "medium". At this time, using the method introduced in section 2.4, the reference vector $B_2 = (0, 1, 0, 0)$ and $B_3 = (0, 0, 1, 0)$ is introduced to calculate the gray correlation degree to get $r^2 = 0.725$ and $r^3 = 0.609$. From this result, we have reason to believe that the reorganization data is evaluated as "good", and the actual state of the circuit breaker is 458 times of breaking times, which is far less than the prescribed times of 2000 times. The results obtained by using the gray correlation theory are more realistic.

### 4. Conclusions

This paper constructs an improved fuzzy comprehensive evaluation method to evaluate the operating status of the circuit breaker. Introduce the idea of combination weighting, and fully consider subjective weight and objective weight to combine weighting of evaluation indicators. Among them, the subjective weight is obtained by the interval analytic hierarchy process, and the objective weight is obtained by the excess weighting method. In order to overcome the inherent shortcomings caused by the determination of the maximum degree of membership, the gray correlation theory is introduced to modify the evaluation results. The experimental verification shows that the model has strong practicability. Compared with the traditional fuzzy comprehensive evaluation method, it can determine the operating state of the circuit breaker more accurately, and can provide a reference for the maintenance of the circuit breaker.

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