Fuzzy comprehensive evaluation method of variable weight for power distribution equipment group

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Abstract. The evaluation of equipment group status has some reference value for maintenance strategy optimization and distribution network reliability evaluation. In this paper, the fuzzy evaluation method of variable weight is applied to evaluate the equipment group of power distribution network hierarchically. The importance degree of individual equipment in the evaluation of equipment group is determined by the load size and the importance degree of load borne by the equipment, the network equivalent method is applied to calculate the weight of individual equipment, and the conjoint analysis optimization algorithm is applied to realize dynamic weight variation. A set of transformer winding and casing and a partial 10kV line are taken as examples to verify the effectiveness of the proposed method.

1. Introduction
Distribution equipment is the basis of power distribution network, and its operation reliability directly affects the power supply reliability. State maintenance is an important means to ensure the reliability of operation [1-2]. As the core of state maintenance, the choice of evaluation method affects the final effect of state maintenance.

At present, there have been many achievements in the research of power equipment state evaluation methods at home and abroad, mainly including: fuzzy comprehensive evaluation, rough set theory, evidence theory, neural network, clustering algorithm, Bayesian theory, expert system, mutation theory and the fusion of various algorithms [3-13]. Because of its solid mathematical foundation, simplicity and practicality, fuzzy comprehensive evaluation method has been applied most widely. In the evaluation of equipment of distribution network, the above methods are mainly used to evaluate a single equipment, without evaluating a group of equipment, and almost no weight changes are taken into account.

In this paper, a fuzzy comprehensive evaluation method of variable weight for power distribution network equipment group is proposed, and the power distribution network equipment is evaluated successively by the state quantity of equipment, equipment components, equipment individuals and equipment groups. Variable weight includes two aspects: one is to dynamically change the weight of individual equipment in the group according to the change of load; The other one is to change the weight of the lower index in the upper index evaluation according to the different state of the equipment. The principle of variable weight effectively compensates for the fact that the constant weight evaluation cannot objectively reflect the influence on the importance of equipment of the extreme conditions of key parameters, load changes and network frame changes [14].
2. Establishment of index system
This paper establishes a hierarchical index system as shown in Figure 1.

![Diagram of index system](image)

Figure 1. Grading state index of distribution equipment group.

The evaluation of equipment group is based on the individual evaluation of equipment. In the individual evaluation of equipment state, this paper divides the evaluation indexes into three levels: individual equipment, equipment components and equipment state quantity. The equipment state quantity index is the basis of the whole index system, including: the index directly used for the equipment state evaluation (According to the different ways to obtain the index, which can be divided into three categories: test index, operation index and basic performance index); And the history record index used indirectly to correct the evaluation result of equipment state. Due to the variety of state quantity indexes of various devices, in order to reduce the workload of index weight assignment, the state quantity indexes can be further layered and combined.

3. Design of index weight
The weight design is the basis of fuzzy evaluation, and the index weight reflects its function and position in the evaluation process. On one hand, in the equipment group evaluation, this paper assigns the value according to the weight of load borne by the equipment and the importance degree of load,
and realizes the dynamic variable weight of each device according to the change of load in practical application. On the other hand, in the individual evaluation of equipment, the state quantity indexes of equipment are graded and weighted to distinguish the relative importance of each state quantity index under different state levels.

3.1. Weight of individual equipment index

Weight determination methods can be divided into two categories: subjective weighting method and objective weighting method. Considering that the state maintenance of power distribution network equipment has just started and the accumulation of original data is insufficient, the subjective weighting method should be adopted to evaluate the weight of equipment state at present. The conjoint analysis method [15] is applied to weight the equipment state quantity index. The specific steps are as follows:

1) Attribute and attribute level determined. Attribute refers to the indexes included in the distribution equipment index system, and attribute level refers to the state level of the corresponding indexes.

2) Test designed and performed. In order to shorten the test period, orthogonal test scheme is adopted for multi-attribute tests with three or more attributes.

3) Utility value estimated. Get the estimated utility value of each attribute corresponding to the attribute level through data collection and fitting. The conjoint analysis usually adopts the addition model:

\[ Y = \sum_{i=1}^{m} \sum_{j=1}^{k} u_{ij} x_{ij} \]  

(1)

Where: \( Y \) is the preference score obtained for each experiment; \( u_{ij} \) is the estimated utility value of the attribute level \( j \) of attribute \( i \); \( x_{ij} \) is the dummy variable. When the attribute level \( j \) of attribute \( i \) exists, \( x_{ij} = 1 \); otherwise, \( x_{ij} = 0 \).

4) Weight calculated. Calculate the weight of each attribute according to the estimated utility value of all attribute levels of each attribute:

\[ I_i = \{\max(u_{ij}) - \min(u_{ij})\} \]  

(2)

\[ W_i = \frac{I_i}{\sum_{j=1}^{m} I_j} \]  

(3)

Where: \( \max(u_{ij}) \) is the estimated utility value of the optimal state level of each attribute; \( \min(u_{ij}) \) is the estimated utility value of the worst state level of each attribute;

5) Variable weight is applied to different attribute levels of the same attribute. The variable weight principle of factor space is introduced to define the state variable weight vector of m dimension [16]:

\[ S(X) = (S_1(X), S_2(X), ..., S_m(X))^T \]  

(4)

The constant weight vector corresponding to the state variable weight vector is:

\[ W_0(X) = (w_{01}, w_{20}, ..., w_{m0})^T \]  

(5)

Then the state variable weight vector can be expressed as:

\[ W(X) = \left(\frac{w_{01}S_1(X), w_{20}S_2(X), ..., w_{m0}S_m(X)}{\sum_{j=1}^{m} w_{j0}S_j(X)}\right) \]  

(6)

Considering that the conjoint analysis method has implied variable weight in the process expert investigation, and the process of conjoint analysis is also the process of index evaluation, the evaluation results of conjoint analysis can be taken as the basis of index variable weight.
The state variable weight function of each index $S_i(X)$ is discretized into the variable weight coefficient of $n$ kinds of attribute level: $S_{i1} \sim S_{in}$. For each attribute at the attribute level $i$, let its membership degree vector be 1 in the $i$ element and 0 in the rest. For a certain component index, several different combinations of its state quantity indexes were selected, and the evaluation results were obtained by conjoint analysis evaluation and fuzzy evaluation respectively, and the value of $S_{i2} \sim S_{in}$ was determined.

The objective function to determine the variable weight coefficient is as follows:

$$Obj = \min \sum C \left| ST_{\text{evi}} - ST_{\text{con}} \right|$$

Where: $C$ is the combination of state indexes. The selection principle can be that all state levels are selected successively for a certain state index, and the orthogonal test scheme is adopted for other indexes. $ST_{\text{evi}}$, $ST_{\text{con}}$ are the evaluation results of the two evaluations, valued as 1, 2, ..., $n$. In practical application, different components need different state-variable weight function models, and the following constraint conditions are added to the objective function according to the required model [17]:

- $S_{i1} < S_{i2} < S_{i3} < \ldots < S_{in}$ (punishment type);
- $S_{i1} > S_{i2} > S_{i3} > \ldots > S_{in}$ (incentive type);
- $S_{i1} > S_{i2} > \ldots > S_{ij} < \ldots < S_{in}$ (partial punishment - incentive type 1);
- $S_{i1} < S_{i2} < \ldots < S_{ij} > \ldots > S_{in}$ (partial punishment - incentive type 2).

By using the optimization algorithm (such as genetic algorithm), the objective function is solved to obtain the optimal variable weight coefficient, improving the weight obtained by the conjoint analysis method by using Formula (6).

![Figure 2. The first equivalent of a complex network.](image)

3.2. Weight of equipment group index
The structure of distribution network is complicated and changeable, and there are many kinds of equipment combinations, so it is difficult to grade and stratify them. It is not realistic to use the subjective weighting method to weight each equipment. Combined with the essential function of power distribution network, based on network analysis method, the weight of individual equipment in the equipment group is determined according to the load borne by the equipment and its importance in this paper. The specific steps are as follows:

1) most distribution networks work in a radial manner, and the network equivalent method is adopted to calculate the load of each branch [18]. First, each branch is regarded as a component. The
load of each branch is calculated step by step. The processed branches can be combined into a component, and the sum of the load of all branches is taken as the load value of the component, which is gradually simplified until the various load of each branch are obtained. Figure 2 and Figure 3 show the simplified process of a complex network.

![Image](image1.png)

**Figure 3.** The second and third equivalent of a complex network.

2) determining the cardinal number of importance of various loads and calculate the weight of each branch. The specific formula is as follows:

$$\omega_i = \frac{\sum_{j=1}^{m} \alpha_j P_i^j}{\sum_{i=1}^{n} \sum_{j=1}^{m} \alpha_j P_i^j}$$

(8)

Where: $\alpha_j$ is the cardinal number of the importance of various loads, which shall be determined by experts or operators; $n$ is the number of initial equivalent network nodes, that is, the number of branches.

3) calculate the weight of each equipment in the equipment group:

$$\omega_i' = \frac{\omega_i}{k_i}$$

(9)

Where: $k_i$ is the total number of equipment participating in the state evaluation of each branch.

In practical application, the selected load can be the maximum or minimum load in distribution network planning, or the load of each node can be adjusted regularly according to the operating conditions, so as to achieve dynamic weight change for equipment of each branch.

4. Fuzzy comprehensive evaluation method of variable weight

The state information of distribution equipment has complex sources and diverse forms. The state information should be uniformly quantified before the state evaluation, this paper uses the method proposed in Literature [3] to divide the underlying state quantity indexes into qualitative and quantitative indexes, and adopts different quantitative methods to achieve unified quantification. The qualitative index adopts the fuzzy statistical test method and obtains the membership degree according to the expert survey. By introducing the relative deterioration degree, the quantitative index constructs the deterioration interval, and designs the membership function based on the deterioration interval.

The evaluation method adopts variable Fuzzy Comprehensive Evaluation Method of Variable Weight, and the fuzzy evaluation matrix is as follows:

$$B = [b_1, b_2, \ldots, b_n] = W^T \bullet R = [w_1, w_2, \ldots, w_n] \bullet \begin{bmatrix} r_{11} & \cdots & r_{1m} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nm} \end{bmatrix}$$

(10)

Where: $B$ is the evaluation result; $W$ is the weight set, which can be obtained by conjoint analysis. $R$ is the membership set of each state level corresponding to each state index; $\bullet$ is the fuzzy operator, and here takes the multiplication.
Variable weights for each state level are introduced in the evaluation of equipment component level indexes. Component index evaluation adopts the following formula:

\[ B = W^T \cdot (S \oplus R) \]  

(11)

Where: \( S \) is the variable weight coefficient matrix obtained by the variable weight method. \( \oplus \) Take the multiplication of the corresponding elements of two matrices. According to the variable weight principle proposed in Section 3.1, the results of \( B \) need to be normalized.

In practical application, when the membership degree of a certain index to a certain state level is much larger than other state levels, the maximum membership degree principle can be directly used to determine the state of the index. That is to take the state corresponding to the maximum membership degree as the final evaluation result.

5. **Case analysis**

5.1. **Single equipment**

Take the winding and casing state evaluation of dry type transformer as an example, the index system is shown in Figure 4. The attributes include 8 state quantity indexes, such as insulation resistance, DC resistance, load rate, three-phase unbalance rate, temperature of joint, temperature of transformer, pollution status, and integrity. The attribute levels are selected as 4 state levels, such as normal, attention, abnormal and serious in the case analysis.

![Figure 4. Index system of transformer winding and casing.](image)

The conjoint analysis method is adopted to calculate the estimated utility value of each index’s state level based on the expert score. More than thirty experienced experts were invited to score the state indexes of the transformer winding and casing. Therefore the weights of the state indexes were obtained from the empirical data. and the weight of each state quantity index is obtained by using Equations (2) and (3), as shown in Table 1.

| Table 1. Transformer winding and casing index weight. |
|-----------------------------------------------|
| Insulation resistance | DC resistance | Load rate | Three-phase unbalance rate |
|-----------------------|---------------|-----------|----------------------------|
| 0.209                 | 0.234         | 0.010     | 0.114                      |
| Temperature of joint  | Temperature of transformer | Pollution status | Integrity |
| 0.093                 | 0.104         | 0.059     | 0.088                      |
The variable weight method proposed in Section 3.1 is adopted to obtain the evaluation results of winding and casing state for the four state levels of each state index by using the conjoint analysis method and the fuzzy evaluation method. The genetic algorithm is used to solve Equation (7) to obtain the variable weight coefficients of each index, as shown in Table 2.

**Table 2. Variable weight coefficients of each index attribute level.**

|                        | Normal | Attention | Abnormal | Serious |
|------------------------|--------|-----------|----------|---------|
| Insulation resistance  | 1.000  | 0.463     | 1.417    | 4.792   |
| DC resistance          | 1.000  | 0.231     | 1.208    | 3.833   |
| Load rate              | 1.000  | 0.758     | 2.750    | 4.250   |
| Three-phase unbalance  | 1.000  | 0.641     | 1.875    | 2.875   |
| Temperature of joint   | 1.000  | 1.583     | 2.542    | 3.917   |
| Temperature of transformer | 1.000  | 0.250     | 2.125    | 3.375   |
| Pollution status       | 1.000  | 0.672     | 0.953    | 3.000   |
| Integrity              | 1.000  | 0.250     | 2.333    | 3.625   |

For a 400kVA Dyn11 connected dry type transformer, the phase-to-phase difference of winding DC resistance is 2% of the average three-phase value, the measured value of winding and casing insulation resistance is 85% of the initial value, the load rate is 85%, the three-phase unbalance rate is 30%, the temperature of joint is 85 degrees, the temperature of transformer is 15% above the manufacturer's allowable value, slight pollution, integrity. The membership function model combining half trapezoid and triangle is used to calculate the membership vector of each index, as shown in Table 3.

**Table 3. Membership vector of each attribute result from the example of the evaluation.**

|                        | Normal | Attention | Abnormal | Serious |
|------------------------|--------|-----------|----------|---------|
| Insulation resistance  | 1      | 0         | 0        | 0       |
| DC resistance          | 0.5    | 0.5       | 0        | 0       |
| Load rate              | 0.5    | 0.5       | 0        | 0       |
| Three-phase unbalance  | 0.667  | 0.333     | 0        | 0       |
| Temperature of joint   | 0      | 0.5       | 0.5      | 0       |
| Temperature of transformer | 0      | 0.5       | 0.5      | 0       |
| Pollution status       | 0.875  | 0.125     | 0        | 0       |
| Integrity              | 1      | 0         | 0        | 0       |

Then the fuzzy evaluation result is:

\[
B = \begin{bmatrix}
0.209^T \\ 0.234 \\ 0.010 \\ 0.114 \\ 0.093 \\ 0.104 \\ 0.059 \\ 0.088
\end{bmatrix} = \begin{bmatrix}
1 \\ 0.5 \\ 0.5 \\ 0.667 \\ 0 \\ 0 \\ 0.875 \\ 1
\end{bmatrix}
\]

Normalized treatment:

\[
B = \begin{bmatrix}
0.593 \\ 0.159 \\ 0.248 \\ 0
\end{bmatrix}
\]

According to the evaluation results, the state of winding and casing of the transformer can be judged as 'normal' by using the principle of maximum membership degree. However, due to the
abnormality of the temperature of joint and transformer, the final evaluation result is largely affected. The membership degrees of 'attention' and 'abnormal' are also relatively high, so it is necessary to check the state of the transformer regularly.

5.2. Equipment group

Since the state evaluation of the equipment group is also based on the fuzzy theory, the following case analysis is only about the acquisition of weights. Taking a partial 10kV line as an example, Figure 5 is the equivalent circuit diagram of the equipment group, and Figure 6 is the initial equivalent network diagram.

![Figure 5. Equivalent circuit diagram of a partial 10kV line.](image)

![Figure 6. Equivalent network diagram of a partial 10kV line.](image)

Assuming that the important coefficients of three classes of load are 3, 2 and 1 respectively, the weights of each equipment calculated from Equations (8) and (9) are shown in Table 4.

| Node Serial number | Number of main equipment | First class load (kW) | Second class load (kW) | Third class load (kW) | Weight of each equipment |
|--------------------|--------------------------|-----------------------|------------------------|-----------------------|--------------------------|
| 1                  | 3                        | 40                    | 23                     | 15                    | 0.026                    |
| 2                  | 3                        | 21                    | 50                     | 177                   | 0.048                    |
| 3                  | 2                        | 61                    | 73                     | 192                   | 0.111                    |
| 4                  | 2                        | 104                   | 192                    | 222                   | 0.195                    |
| 5                  | 3                        | 43                    | 119                    | 30                    | 0.056                    |

As can be seen from the table, the more loads flow through, the higher weight an equipment is of in the evaluation of equipment group, which is also consistent with the objective fact.

6. Conclusions

In this paper, the evaluation method of equipment group based on the individual evaluation of equipment, in which the network structure, the size and importance of load is given full consideration, is presented to carry on the overall state assessment on the feeder, station, regional power grid and so on. Supporting the formulation and optimization of state maintenance strategy of distribution network. The method is more in line with the distribution network actual operation and maintenance characteristics, can effectively improve the maintenance efficiency, reduce the maintenance cost.

For the weight determination of a single equipment state index, this paper proposes a dynamic variable weight method based on the conjoint analysis method, which intuitively presents the idea of variable weight implied by the conjoint analysis method, and effectively overcomes the problem that the traditional variable weight coefficient is difficult to determine and the high subjective dependence.

For the weight determination of each individual equipment in the equipment group, this paper proposes a weight calculation method based on the network equivalent method. According to the network structure of each equipment, the load size and importance degree borne by each equipment are calculated, and dynamic weight is assigned to each equipment according to the load change.
In this paper, the winding and casing of a transformer and a partial 10kV line are respectively taken as examples for case analysis, and the calculation results are consistent with the actual situation. However, the accuracy and efficiency of this method have yet to be tested by long-term application in the face of complex and variable state combinations.

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