Operation status evaluation of low voltage distribution network based on PCA-entropy combined weight method

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Abstract. With the rapid development of smart grid and distribution network intelligence, how to accurately grasp the operating status of the distribution network is an urgent task. Therefore, this paper proposes a method for evaluating the operating status of low-voltage distribution networks based on the PCA-entropy combined weight method. Firstly, the improved principal component analysis (PCA) is used to extract the distribution network evaluation indexes and establish an evaluation index system, which from the four aspects of safety, reliability, quality, and economics. Then model the indexes of each level and calculate the subjective and objective comprehensive weights of the indexes of each level by using the entropy combination weight method. Finally, the feasibility and practicability of the method are verified by comprehensive evaluation of the actual distribution network.

1. Introduction
In recent years, as an important part of the smart grid, the intelligent distribution network has become a new trend in the development of the smart grid, and the low-voltage distribution network is a key link in which the power system is directly connected to users [1-3]. Therefore, it is imperative to build a scientific, effective and accurate low-voltage distribution network operation status evaluation system.

At present, there have been many studies on distribution network evaluation. In [4-6] establish a multi-level evaluation indexes system from different methods, but rely on the experience of experts, ignore the impact of evaluation indexes, and do not consider that there are differences in the importance of different indexes. In [7-9] used AHP-Delphi method to evaluate the operation status of distribution network, or further revised the weight of each level indexes, but AHP-Delphi method was subjective, it is impossible to objectively evaluate the status of the distribution network.

Therefore, this paper proposes a method for evaluating the operating status of low-voltage distribution networks based on PCA-entropy combined weights. Firstly, an improved principal component analysis method is used to extract features to extract the indexes that best reflect the state of the distribution network and construct an evaluation index system. Then use the entropy combination weight method to calculate the comprehensive weights of the indexes of each layer. Finally, by calculating the single index value and the evaluation score, the middle layer score and the total evaluation score are calculated layer by layer to find out the weak link of the distribution network. The evaluation system and method can provide effective technical support and reference opinions for low-voltage distribution network operation state control and management.
2. Feature extraction based on improved principal component analysis

In the evaluation of the operating status of the low-voltage distribution network, the influencing factors of the distribution network state lead to a large number of evaluation indexes, and there is currently no unified and reasonable method to screen the evaluation indexes. In most studies, the evaluation indexes system for distribution network is established through survey analysis and expert opinion. These methods are relatively one-sided, highly subjective, and cannot be used to filter out information attributes with overlapping information attributes at a certain level. Therefore, this paper uses feature extraction based on improved principal component analysis to screen evaluation indexes and extract the indexes that best reflect the state of the distribution network.

(1) Select several parameters of the distribution network evaluation index, quantify each evaluation index, construct a quantification matrix for the evaluation indexes, and eliminate the dimension:

\[ x_j = \frac{x_j - \overline{x_j}}{s_j} \]  

where \( s_j = \frac{1}{n-1} \sum_{i=1}^{n} (x_{ij} - \overline{x_j})^2 \), \( \overline{x_j} = \frac{1}{n} \sum_{i=1}^{n} x_{ij}, j=1,2,3...n, i=1,2,3...p \)

(2) Solve the correlation coefficient matrix, find the eigenvalues and eigenvectors of the coefficient matrix, sort the size of the eigenvalues, and then calculate the cumulative variance contribution rate:

\[ \sum_{i=1}^{k} \lambda_i / \sum_{i=1}^{p} \lambda_i \]  

(3) Feature extraction of indexes: calculate the principal component load matrix:

\[ A = (\sqrt{\lambda_1}a_1, \sqrt{\lambda_2}a_2, \sqrt{\lambda_3}a_3, ..., \sqrt{\lambda_m}a_m) \]  

where \( \lambda_1, \lambda_2, \lambda_3...\lambda_m \) is the eigenvalue of the matrix, \( a_1, a_2, a_3...a_m \) is the eigenvector.

Then calculate the importance of each evaluation index. The calculation formula is as follows:

\[ H = \sqrt{\lambda_1}a_1 + \sqrt{\lambda_2}a_2 + \sqrt{\lambda_3}a_3 + ... + \sqrt{\lambda_m}a_m \]  

Then, the importance degree \( H \) of the obtained state evaluation index parameters is normalized. The greater the importance degree \( H \), the stronger the correlation, that is, the state evaluation index is more representative among the many evaluation indexes and finally get the key indexes of the evaluation.

3. Entropy combination weight method to determine comprehensive weight

This paper mainly evaluates the operating status of the low-voltage distribution network. After constructing the status evaluation index system, the weights of various indexes need to be determined. At present, there are many methods for determining the weight, such as the analytic hierarchy process, Delphi method, etc. However, the above method cannot objectively reflect the importance of indexes.

In view of the above problems, this paper uses an entropy combination weight method to determine the weight of the evaluation index. Firstly, use the AHP-Delphi method to judge the importance of each evaluation index, and calculate the subjective weight of the them. Then use the entropy weight method to obtain the objective weight of the evaluation index [10]. Finally calculate the comprehensive weight and use the Lagrange multiplier method for optimization.

3.1 AHP-Delphi method to determine subjective weights

The calculation process of AHP-Delphi method to determine the weight of evaluation index is as follows:

Construct a judgment matrix: \( u_i, u_j \ (i,j=1,2,...,n) \) represent factors, while \( u_{ij} \) represents the importance of \( u_i \) relative to \( u_j \), and judgment matrix \( P \) is formed through \( u_{ij} \) as follows:
(2) Calculate the largest eigenvalue $\lambda_{\text{max}}$ in $P$ and the corresponding eigenvector $\omega$ as follows:

$$P\omega = \lambda_{\text{max}}\omega$$  \hfill (6)

(3) Consistency check: in order to verify whether the weight distribution of income is reasonable, the consistency check of the judgment matrix needs to be as follows:

$$CR = CI / RI$$  \hfill (7)

Where $CI=(\lambda_{\text{max}}-n)/(n-1)$, $RI$ are shown in Table 1, when $CR<0.1$, $CI=0$, fulfill the requirements.

Table 1. Mean random consistency index.

| n  | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  |
|----|----|----|----|----|----|----|----|----|----|
| R1 | 0  | 0  | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.46 |

### 3.2 Entropy weight method to determine objective weights

If there are $m$ units to be evaluated and $n$ evaluation indexes, the original data matrix is as follows:

$$X = (x_{ij})_{mn}$$  \hfill (8)

For one of the evaluation indexes, the information entropy is:

$$E_j = -\sum_{i=1}^{m} p_i \ln p_i / \ln m$$ \hfill (9)

The difference of the evaluation indexes is defined as $D_j = 1 - E_j$, then the entropy weight as follow:

$$w_j = D_j / \sum_{j=1}^{n} D_j$$ \hfill (10)

### 3.3 Determine comprehensive weights and optimization

Based on the AHP-Delphi method and the entropy weight method, each has its own disadvantages when it is used to determine the weight of the evaluation index. This paper uses the entropy combination weight method to determine the weight of the low-voltage distribution network evaluation index.

1. Forward and non-dimension the selected state evaluation indexes, if $X_j$ is the positive index:

$$X_j^* = \frac{X_j - \min(X_j)}{\max(X_j) - \min(X_j)}$$  \hfill (11)

If is the reverse index:

$$X_j^* = \frac{\max(X_j) - X_j}{\max(X_j) - \min(X_j)}$$  \hfill (12)

If $X_j$ is the interval index:

$$X_j^* = \begin{cases} \frac{X_j - \min(X_j)}{a - \min(X_j)}, & \text{min}(X_j) \leq X_j < a \\ 1, & a \leq X_j \leq b \\ \frac{\max(X_j) - X_j}{\max(X_j) - b}, & b < X_j \leq \max(X_j) \end{cases}$$ \hfill (13)

2. Calculate the subjective weight of each index according to AHP-Delphi method.
3. Calculate the objective weight of each index according to the entropy weight method.
4. Calculating the comprehensive weight from the subjective and objective weights obtained above:
Then the Lagrange multiplier method is used to obtain the above comprehensive weights:

$$
\omega = \left\{ \frac{W_i w_i}{\sum_{j=1}^{n} W_j w_j}, \ldots \right\} = (\omega_1, \omega_2, \ldots, \omega_n)
$$

(14)

Then the Lagrange multiplier method is used to obtain the above comprehensive weights:

$$
\omega_j = \frac{(W_j w_j)^{1/2}}{\sum_{j=1}^{n} (W_j w_j)^{1/2}}
$$

(15)

4. Modelling of Distribution Network Evaluation Indexes

See the example analysis for the distribution network operation evaluation index system constructed by the improved principal component analysis method. Here, models the evaluation index system.

(1) Security index

Three phase unbalances: refers to the ratio of the difference between the maximum load and the average load of the transformer to the average load. Calculated as follows:

$$
X_1 = \frac{3 \max \{P_A, P_B, P_C\} - (P_A + P_B + P_C)}{P_A + P_B + P_C}
$$

(16)

Where $P_A, P_B, P_C$ respectively represents the load of three-phase A, B, C at the transformer.

Transformer load rate: refers to the ratio of the output power of the transformer. Calculated as follows:

$$
X_2 = \frac{W_t}{S}
$$

(17)

Where $W_t$ refers to the power supply load within $t$ time, and $S$ is the transformer capacity.

(2) Reliability index

Operational failure probability: refers to the number of power outages per 100km of the distribution network within a year. Calculated as follows:

$$
X_3 = \lambda \cdot \frac{8760h}{t}
$$

(18)

Where, $\lambda$ is the rate of failure in the statistical time, and $t$ is the number of hours in the statistical time.

Reliability of power supply: refers to the ability of the distribution network to continuously deliver higher-than-qualified power to users. Calculated as follows:

$$
X_4 = (1 - \frac{t}{t_0}) \times 100\%
$$

(19)

Where $t_0$ is the average power consumption time of all users.

(3) Quality index: voltage eligibility rate refers to the ratio of the time of the monitoring point voltage within the qualified range to the total time. Calculated as follows:

$$
X_5 = (1 - \frac{t_0}{t}) \times 100\%
$$

(20)

Where $t_0$ is the voltage over-limit time, $t$ is the statistical time.

(4) Economic index: line loss rate refers to the ratio of line loss to the power. Calculated as follows:

$$
X_6 = \frac{P_1 - P_2}{P_1} \times 100\%
$$

(21)

Where $P_1$ is power supply, $P_2$ is power sold.
5. Example analysis

5.1 Construction of a status evaluation index system

In the evaluation of low-voltage distribution networks, too many numbers of evaluation indexes will affect the efficiency and accuracy of the evaluation. Therefore, the use of improved principal component analysis for index extraction and removal of redundant indexes can improve evaluation efficiency.

Firstly, several evaluation indexes of the distribution network are pre-selected as shown in Table 2:

| Index number | Evaluation index                | Index number | Evaluation index                |
|--------------|---------------------------------|--------------|---------------------------------|
| 1            | Linking-up road rate            | 8            | Line overload rate              |
| 2            | Three phase unbalances          | 9            | Voltage eligibility rate        |
| 3            | Risk of loss of load            | 10           | Transformer failure rate        |
| 4            | Line loss rate                  | 11           | Voltage deviation               |
| 5            | Frame power factor              | 12           | Reliability of power supply     |
| 6            | Operation failure rate          | 13           | Harmonics distortion            |
| 7            | Transformer load rate           | 14           | Non-transferable rate           |

Then extract the pre-selected indexes based on improved PCA, construct a quantization matrix, calculate the eigenvalues and variance contribution ratios, obtain the principal component load and calculate the importance degree of each evaluation index. The results are shown in Figure 1:

![Figure 1. Importance degree of single evaluation indexes.](image)

The importance degree of each single evaluation index is normalized to [0, 1]. This paper selects the single evaluation index whose importance degree is higher than 0.5, and selects 6 single evaluation indexes for the operation status of the low-voltage distribution network, and establish a hierarchy analysis index system as shown in Figure 2:

![Figure 2. Evaluation index system of distribution network.](image)

5.2 Evaluation of actual distribution network operation status

(1) Determine the weight of evaluation indexes: Calculate the subjective weights of six evaluation indexes according to the AHP-Delphi method. Then calculate the objective weights of each evaluation
index according to the entropy weight method. Then calculate the comprehensive weight of indexes, and the subjective and objective weights of the obtained indexes are shown in Table 3 below:

| Index | Subjective weight | Objective weight | Comprehensive weights |
|-------|-------------------|------------------|-----------------------|
| $X_1$ | 0.2107            | 0.0923           | 0.1493                |
| $X_2$ | 0.1328            | 0.3751           | 0.2383                |
| $X_3$ | 0.1247            | 0.2051           | 0.1701                |
| $X_4$ | 0.1531            | 0.0831           | 0.1207                |
| $X_5$ | 0.2428            | 0.1171           | 0.1803                |
| $X_6$ | 0.1351            | 0.1295           | 0.1414                |

After obtaining the weight of each individual index, calculate the indexes weight of the middle layer of the indexes system to the upper layer, and then arrange the weight factors of the evaluation indexes system for the operating status of the low-voltage distribution network as shown in Table 4:

| Intermediate index | Weight | Single index          | Weight |
|--------------------|--------|-----------------------|--------|
| Security           | 0.3876 | Three phase unbalances| 0.3845 |
|                    |        | Transformer load rate | 0.6155 |
| Reliability        | 0.2908 | Operation failure rate| 0.5861 |
|                    |        | Reliability of power supply| 0.4139 |
| Quality            | 0.1803 | Voltage eligibility rate| 1      |
| Economic           | 0.1414 | Line loss rate        | 1      |

(2) Calculate the evaluation score and compare: select the AHP-Delphi method and the PCA-entropy combined weight method in this paper to evaluate and compare the operating status of the distribution network, and combine the single index model and the weight factor to calculate. Finally, the comparison of the evaluation scores of the low-voltage distribution network in the region is shown in Table 5:

| Data source                    | Security | Reliability | Quality | Economic | Total score |
|--------------------------------|----------|-------------|---------|----------|-------------|
| AHP-Delphi method              | 69.08    | 87.81       | 78.33   | 70.91    | 76.46       |
| PCA-entropy combined weight method| 66.32    | 83.23       | 61.27   | 75.22    | 71.59       |

From the above Table 5, it can be concluded that the overall score of the operating status of the distribution network in the region is 76.24, and the score is relatively healthy. Among them, the evaluation score by the AHP-Delphi method is higher than the evaluation score of the PCA-entropy combination method in this paper, and the score is much higher than the method in this paper in terms of quality. After investigation and analysis, the voltage eligibility rate in this area is average. In particular, the low-voltage phenomenon is more common and cannot reach a very healthy level, which proves that there is a large deviation when only using the AHP-Delphi method for evaluation. It is further proved that the method for evaluating the operating status of low-voltage distribution networks based on the PCA-entropy combined weight method can truly reflect the actual status of the distribution network.

6. Conclusion
This paper proposes a method for evaluating the operating status of low-voltage distribution networks based on PCA-entropy combined weights. An improved principal component analysis method is used to construct a condition evaluation index system. In addition, the entropy combination weight method is used to calculate the comprehensive weights of evaluation index, and evaluation of the distribution network is performed from the aspects of safety, reliability, quality and economy. Formed a set of scientific and effective low-voltage distribution network operation status evaluation system.
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