Reliability Index Evaluation System of Distribution Network Based on Maximum Deviation and Application

Shigong Jiang¹, Weihong Yang¹, Jiaming Deng²*, Yaru Zhao², Junjie Li², Peng Li² and Zixuan Wang²

¹ State Grid Economic and Technological Research Institute Co., Ltd., Beijing, 102209, China
² School of Electrical and Electronic Engineering, North China Electric Power University, Baoding, Hebei, 071003, China
*Corresponding author’s e-mail: 2192213058@ncepu.edu.cn

Abstract. With the in-depth reform of the power industry, the reliability index evaluation system of the distribution network has become an important direction for the research of my country's distribution network. Firstly, the load points are classified based on the power supply information of the distribution network, and the power supply reliability indicators of the system and consumers are established. Secondly, a comprehensive evaluation system of distribution network indicators is established based on the entropy weight-analytic hierarchy process with maximum deviation. Finally, the comprehensive evaluation index results are used to establish a distribution network reliability incremental cost calculation model, and the distribution network reliability electricity price that takes into account the differentiated reliability requirements is obtained. The analysis of calculation examples shows that the proposed evaluation system can obtain comprehensive reliability evaluation indicators with subjective and objective evaluation. And the results can be applied to reliability electricity price calculation to obtain reliability electricity prices that take into account both reliability and economy.

1. Introduction

As users have more and more stringent requirements on the reliability of power supply, reliability evaluation has received increasing attention [1]. Therefore, how to conduct a more accurate reliability assessment of the complex distribution network and take into account the impact of end-user differentiation has become a problem facing the current power industry [2].

In order to better evaluate the power supply reliability of the distribution network and establish a scientific and reasonable distribution network operation reliability index system [5], a distribution network reliability index evaluation method that considers the differentiation of end users should be proposed. The analytic hierarchy process is used to assign weights to different reliability indicators in [7], but it cannot fully reflect the objective difference between reliability indicators. Grey relational analysis is introduced into the comprehensive evaluation system, and an evaluation method based on improved grey relational degree is proposed [9]. And the defects of expert empowerment are overcome, and the evaluation accuracy is effectively improved. In the actual operating distribution network, the coordinated control of the grid needs to be considered [2]. And the index selection source is complicated, so the reliability evaluation of the distribution network should consider many factors [11]. The above
documents establish the reliability evaluation system of the distribution network from different perspectives, but the differentiated reliability requirements of different types of end users have not yet been taken into account.

In this paper, a combination of entropy weight and the analytic hierarchy process weighting evaluation method based on maximum deviation is proposed. This method combines the flexibility of expert weighting and the objectivity of entropy weighting. The defect of similar index weights corresponding to different influencing factors is overcome. At the same time, according to the differentiated reliability needs of users, the optimal comprehensive index weights with both subjective and objective evaluation are obtained. This evaluation method is applied to the reliability cost calculation to obtain a more accurate cost estimate and electricity price setting mechanism.

2. Distribution network reliability index system

2.1. System side reliability index

In this paper, the power supply reliability index of the distribution network is selected from the three dimensions of time, power and frequency and from the system side and the user side.

System average interruption frequency $\lambda_s : \lambda_i$ represents the average number of power outages in a certain system, and the time is one year.

$$\lambda_s = \frac{\sum_{i=1}^{n} \lambda_i N_i}{\sum_{i=1}^{n} N_i}$$  \hspace{1cm} (1)

Where $\lambda_i$ is the failure rate from the load point to the power supply.

System average interruption time $U_s : U_c$ represents the cumulative sum of the power outage time of all load points of a system in one year.

$$U_s = \frac{\sum_{i=1}^{n} R_i N_i}{\sum_{i=1}^{n} N_i}$$  \hspace{1cm} (2)

Where $R_i$ is the time from load point to power failure.

Average service availability index: $ASAI$ refers to the ratio of the number of hours of power available to users to the number of hours of power supply required by users in a year.

$$ASAI = \frac{\sum_{i=1}^{n} 8760 N_i - R_i N_i}{\sum_{i=1}^{n} 8760 N_i}$$  \hspace{1cm} (3)

2.2. User-side reliability indicators

This article gives the power supply reliability indicators on the user side as shown below.

Customer average interruption time $U_c : U_c$ refers to the total duration of power outages for each load node user in one year.

$$U_c = \sum_{i=1}^{n} \lambda_i r_i$$  \hspace{1cm} (4)

Where $r_i$ is the average duration of power outage from the load point to the power source.

Customer average interruption frequency $\lambda_c : \lambda_i$ refers to Number of power outages for users of each load node in a year.

$$\lambda_c = \sum_{i=1}^{n} \lambda_i$$  \hspace{1cm} (5)
Expected loss of energy $EENS_\text{s}$: $EENS_\text{s}$ refers to the average power loss of users due to power outages in a year.

$$EENS_\text{s} = L_\text{s} \times U_\text{s}$$  \hspace{1cm} (6)

2.3. Establishment of reliability index systems

The reliability indicators mentioned above can be divided into two categories from a macro perspective: reliability contribution category and reliability loss category. Among them, the definition of reliability contribution index is an index type that increases reliability. Defining reliability loss indicators is a type of indicators that reduce the reliability of distribution networks. The flowchart is shown in Figure 1.

![Reliability Evaluation Index System of Distribution Network](image)

3. Distribution network reliability index evaluation system based on maximum deviation

3.1. Index evaluation model based on entropy method

Entropy weight method is an objective evaluation method that determines the weight of indicators based on information entropy, in which the degree of variation has a negative correlation with information entropy. The main steps are as follows:

Step 1: Assuming that a system contains $n$ indicators and $m$ objects, the evaluation matrix $X_{ij}$ can be obtained.

Step 2: Since the indicators have positive indicators and negative indicators, namely reliability contribution indicators and loss indicators, the evaluation matrix should be normalized. The standardization method is $R_{ij}$. The entropy of each indicator is

$$H_j = -\ln n \sum_{i=1}^{n} R_{ij} \ln R_{ij}$$  \hspace{1cm} (7)

Step 3: The weight of each indicator is

$$\omega_j = \frac{1 - H_j}{m - \sum_{j=1}^{m} H_j} \hspace{1cm} \text{and} \hspace{1cm} \sum_{j=1}^{n} \omega_j = 1$$  \hspace{1cm} (8)

This method has simple steps and makes full use of basic indicator data to obtain objective results of indicator weights. The greater the weight value, the greater the overall impact.

3.2. Index evaluation model based on analytic hierarchy process

The analytic hierarchy process is a subjective weighting method. It is a weighting method that solves multi-objective decision-making problems by layering and derives layer by layer to obtain the final evaluation. The detailed steps are as follows.

Step 1: The reliability index of the distribution network is divided into three levels. The highest level is the target level. The middle level represents the direction of the index's effect on reliability. And the lowest level is the basic index such as time and frequency.
Step 2: The experts compare the basic indicators pairwise based on experience, and then assign the discriminant matrix values according to the difference in importance.

Step 3: The consistency index $CI$ is calculated, and the smaller the value $CI$, the greater the consistency. The consistency index is defined as

$$CI = \frac{\lambda - n}{n - 1}$$  \hspace{1cm} (9)

Step 4: Comprehensive weight ranking. Assuming that the weight of the secondary indicator relative to the target is $W_0$, the weight of the secondary indicator relative to the overall target is $W_0 = W_1W_2$  \hspace{1cm} (10)

In the formula, $W_1$ represents the weight of the intermediate layer relative to the overall goal, and $W_2$ represents the weight of the lowest layer relative to the intermediate layer.

The analytic hierarchy process overcomes the flaws of the principle of equal weight. The importance of core indicators is highlighted, and the interference of edge indicators is reduced.

3.3. Distribution network reliability index evaluation system based on maximum deviation

In order to improve the accuracy of the evaluation system, this paper adopts the entropy weight-analytic hierarchy process based on the principle of maximizing deviation. The shortcomings of direct multiplication and the accuracy of the weighting results are improved.

Assuming that the subjective weight obtained is $W^'$, and the weight obtained by the entropy weight method is $\omega$, the joint weight model is obtained as shown below.

$$\max V(\omega) = \sum_{j} V_j(\omega) = \sum_{i=1}^{m} \sum_{k=1}^{n} [v_{ij} - r_{ij}] \omega_j$$

s.t. \hspace{0.5cm} \sum_{j=1}^{m} \omega_j^2 = 1

(11)

In this method, the shortcomings of the subjective evaluation method and the objective evaluation method are effectively compensated, and the loss of important indicators due to the unity of the evaluation method is avoided.

4. Application of the reliability index evaluation system of distribution network

4.1. Application of reliability index evaluation system in reliability cost

Taking into account the actual situation, the cost required to continue to improve the reliability level is increasing when providing high-reliability service levels. In the reliability index system, there are a large number of reliability loss indicators, which have a greater impact on the cost. Therefore, when calculating the reliability incremental cost of each load point, only the reliability loss indicators are considered. The process is as follows:

The reliability incremental cost corresponding to each indicator $\Delta P_i$ is:

$$|\Delta P_i| = \frac{|\Delta F_i|}{F_0^2} P_0 = \frac{|F_i - F_0|}{F_0^2} P_0$$  \hspace{1cm} (12)

Then the electricity price corresponding to the reliability index is:

$$P_i(U_i) = \begin{cases} P_0 + |\Delta P_i| & F_i < F_0 \\ P_0 & F_i = F_0 \\ P_0 - |\Delta P_i| & F_0 < F_i \leq \epsilon F_0 \\ P_{0\min} & F_i > \epsilon F_0 \end{cases}$$  \hspace{1cm} (13)
Where: $1 < \varepsilon < 2$; $P_i$ is the initial electricity price of the distribution network. When satisfied
$F_i > \varepsilon F_0$, there is the lowest reliable electricity price to protect the basic interests of the power supply
company. According to the reliability index evaluation system of the distribution network proposed in
this paper, the reliability price can be obtained by adding the weighted sum of the reliability electricity
prices corresponding to the three indexes.

5. Example analysis

This paper uses the user power supply reliability data of a demonstration park in Tianjin to analyze the
calculation example. The formulas in 2.1 and 2.2 of this paper are used to calculate the power supply
reliability index of the four virtual load points. The results are shown in Table 1.

| Load point | $\lambda$ (times/year) | $U$ (min/year) | $\lambda$ (kwh/year) |
|------------|------------------------|----------------|---------------------|
| L1         | 0.33                   | 13.52          | 42.254              |
| L2         | 1.70                   | 18.16          | 48.013              |
| L3         | 2.24                   | 27.62          | 78.347              |
| L4         | 2.57                   | 28.14          | 92.836              |

The formulas in 3.1 and 3.2 of this paper are used to calculate the optimal comprehensive
indicators of user power supply reliability obtained by different methods. It is shown in Table 2.

| Load point | $\lambda$ (times/year) | $U$ (min/year) | $\lambda$ (kwh/year) |
|------------|------------------------|----------------|---------------------|
| Entropy method | 0.2539           | 0.3194         | 0.4267              |
| AHP        | 0.2924                | 0.3882         | 0.3194              |
| Combination method | 0.2731          | 0.3538         | 0.3731              |

At the same time, the entropy weight-analytic hierarchy process balances and combines the results
of the entropy weight method and the analytic hierarchy process. The shortcomings of lack of expert
experience or pure objectivity of the data were overcome. The lack of important indicators and the
central shift phenomenon have been improved.

According to the requirements of the four load points of power supply reliability, the reliability cost
and the electricity price of the distribution network corresponding to each reliability index are
calculated, as shown in Table 3.

| Load point | $P_i(\lambda)$/(yuan/kwh) | $P_i(U)$/(yuan/kwh) | $P_i(E)$/(yuan/kwh) | $P_i$/(yuan/kwh) | $P_i$/(yuan/kwh) |
|------------|-----------------------------|----------------------|---------------------|------------------|------------------|
| L1         | 0.8773                      | 0.7716               | 0.8372              | 0.8249           | 1.5773           |
| L2         | 0.3677                      | 0.3864               | 0.6300              | 0.4722           | 1.2246           |
| L3         | 0.2000                      | 0.2000               | 0.2316              | 0.2316           | 0.984            |
| L4         | 0.2000                      | 0.2000               | 0.2846              | 0.2846           | 1.0256           |

It can be seen that the reliability electricity price based on the cost corresponding to each reliability
index is similar to the electricity price set by the actual electricity market. The distribution network
evaluation index system is used to calculate the weights of different indicators. Therefore, the
shortcomings of the average weight of indicators in the calculation of electricity prices are avoided.
The interference of marginal indicators on the reliability evaluation of the distribution network is
reduced, and the resulting electricity price setting method is more scientific and reasonable.
6. Conclusion
This paper proposes a distribution network reliability index evaluation model based on maximum dispersion, and the shortcomings of subjective and objective weighting methods are improved. This method is applied to the reliability cost calculation of the incremental cost caused by the multi-phase planning of the actual distribution network and the user's differentiated reliability requirements, and the results are more scientific and reasonable. A reference direction for the actual distribution network to formulate high-reliability electricity prices is provided.

Acknowledgements
This work was supported by the SGCC Science and Technology Project (5400-202012118A-0-0-00)

References
[1] Li, G., Bie, Z., Xie, H., Lin, Y. (2016) Customer satisfaction based on reliability evaluation of active distribution networks. J. Applied Energy, 162.
[2] Li, P., Guo, T., Han, X., Liu, H., Yang, J., Wang, J., Yang, Y., Wang, Z. (2021) The Optimal Decentralized Coordinated Control Method Based on the H\(\infty\) Performance Index for an AC/DC Hybrid Microgrid. J. International Journal of Electrical Power & Energy Systems, 125:106442.
[3] Li, P., Guo, T., Zhou, F., Yang, J., Liu, Y. (2020) Nonlinear coordinated control of parallel bidirectional power converters in an AC/DC hybrid microgrid. J. International Journal of Electrical Power & Energy Systems, 122:106208.
[4] Li, P., Wang, Z., Yang, W., Liu, H., Yin, Y., Wang, J., Guo, T. (2020) Hierarchically partitioned coordinated operation of distributed integrated energy system based on a master-slave game. J. Energy, 214: 119006.
[5] Huang, Z. (2017) Distribution network planning practice based on power supply reliability. J. Distribution & Utilization, 34(03):42-46.
[6] Feng, X., Sun, Y., Lin, S., Liu, M., Zhang, T. (2013) Comprehensive Evaluation Index System of Distribution Network and Evaluation Method. Guangdong Electric Power, 26(11):20-25+53.
[7] Yuan, A., He, P., Wang, K., Bai, X., Guan, Y. (2019) Research on Comprehensive Evaluation System of Distribution Network Based on Analytic Hierarchy Process. J. Electrical & Energy Management Technology, (24):75-78.
[8] Li, C., Yin, Z., Wang, X., Zhang, G., Lin, Y., Wang, Q. (2019) Assessment on Distribution Network Dispatching Based on Analytic Hierarchy Process and Entropy Weigh Method. J. Proceedings of the CSU-EPSA, 31(07):81-87.
[9] Hu, B., Ren, X., Ye, B., Wang, X., Dai, L. (2018) Evaluation Method of Low Voltage Contribution Degree Based on Improved Grey Relation Analysis in Distribution Network. J. Power Capacitor & Reactive Power Compensation, 39(02):90-94.
[10] Hao, Y., Zhang, L., Liu, Y., Wang, Y., Yang, L., Lu, Q. (2017) GIS quality evaluation based on improved grey relational analysis. J. Electric Power Automation Equipment, 37(07):161-165.
[11] Xia, Y., Xiao, F. (2020) Comprehensive Reliability Evaluation Method for Smart Distribution Network Considering Influence of Secondary System. J/OL. Automation of Electric Power Systems:1-12.
[12] Li, Yilin., Xu, Wu., Tao, J., Huo, Y., Zhang, E. (2020) Reliability evaluation of active distribution network considering outage superposition. J. Modern Electronics Technique, 43(15):140-142+147.