Power Supply Reliability Assessment of Distribution Network Considering by Operation, Maintenance and Repair

Lin Xu*, Yufei Teng, Gang Chen, Chang Liu and Hua Yang
Electric Power Research Institute, State Grid Sichuan Electric Power Company, Sichuan, China

*Corresponding author e-mail: 191861187@qq.com

Abstract. In order to realize automation and intelligence of power system, it is essential to improve the power supply reliability assessment of distribution network. A comprehensive evaluation system for the reliability was proposed in the paper. An overall index system was integrated to introduce the criteria of the operation, maintenance and repair, which are important for the reliability. Entropy weight method and fuzzy TOPSIS method were combined to propose the evaluation model. Empirical analysis was implemented to verify the practicality of the evaluation system.

1. Introduction

Distribution network automation is an important foundation for the construction of smart and strong power grid. It is important to optimize the operation mode of distribution network, reduce the power loss of the line and energy consumption [1]. The development of automation and intelligence is inseparable from the application of automation control equipment and control procedures, such as switching equipment, transformer equipment, communication equipment and transmission line, etc [2]. Due to the influence of external factors, operation failure may happen during the operation of these equipment, which can impact on the power supply reliability assessment of distribution network. Thus, operation and maintenance work is very important to improve the reliability of power supply.

Reliability assessment of distribution network is an important measure to improve the modernization level of power industry on the premise of guaranteeing the quality of power supply [3]. Through the reliability evaluation, the management level of the reliability distribution for the whole distribution system can be improved, the weak links and the key can be found out of distribution network [4]. Thus, some concrete improvement measures can be put forward according to the existing problems. There are a large number of literatures to research the power supply reliability. Most of them focus on the measurement of system reliability by means of load flow calculation. There are few literatures to evaluate the reliability of distribution system comprehensively [5,6]. The operation and maintenance situation are not included in the reliability evaluation system in most of the literatures. Thus, a comprehensive evaluation system will be designed in the paper.

First, an evaluation index system should be designed to reflect the power supply reliability of distribution network. Then, suitable approaches were integrated into a comprehensive evaluation model. The entropy weight method was applied to determine the weights of all criteria. Fuzzy TOPSIS was introduced to evaluate the performance of all alternatives. Followingly, an empirical analysis was performed.
2. An Evaluation Index System for the power supply reliability assessment of distribution network

An evaluation index system is particularly essential to assess the power supply reliability for distribution network. A series of appropriate criteria should be adopted into the evaluation index system to reflect the inherent characteristics of DSM. Due to the importance of the operation, maintenance and repair to power supply reliability, related criteria should be selected into the index system. Therefore, the evaluation index could be constructed from the three perspectives of continuous power outage, power quality and level of operation and maintenance. The selected criteria can be arranged at different levels, called target level, attribute level and criteria level, as shown in Figure 1.

![Figure 1. The evaluation index system for the power supply reliability assessment of distribution network](image)

(1) Continuous power outage (A1)
Three sub-criteria affiliated with the continuous power outage criteria were summarized into the index system.

Average number of power outages per customer (ANC) can be used to reflected the outages frequency per customers in a certain period of time. It is:

\[
ANC = \frac{\sum_{i} OC_{i}}{CT},
\]

where \(OC_{i}\) is the number of customers affected in the \(i^{th}\) outage, \(CT\) is the total number of customers and \(N\) is the total number of all outages [7].

Average outage time per customers (ATO) can be applied to represent the outages time per customers in a certain period of time. It is:

\[
ATO = \frac{\sum_{i} OT_{i} \times OC_{i}}{CT},
\]

where \(OT_{i}\) is the duration of each power outage.

Average number of customers in each power outage (ANO) can be represented as the number of users affected by per power outage in a certain period of time, and is calculated as:
(2) Power quality (A2)

Three sub-criteria affiliated with the continuous power outage criteria were summarized into the index system.

Average annual power shortage time (APS) is the total power consumption shortfall due to power outages for all users during a year, as is:

\[ APS = \frac{\sum_{i=1}^{c} OR_{i} \times L_{i}}{T} \]  

where \( L_{i} \) is the average loss load per time for \( j \) customer, \( OR_{i} \) is the outage time for \( j \) customer.

Average outage time per unit load for the power system (ATL) can be defined as:

\[ ATL = \frac{\sum_{i=1}^{c} OR_{i} \times L_{i}}{T \times \sum_{j=1}^{n} P_{j}} \]  

where \( P_{j} \) is the average load for \( j \) customer.

Voltage pass rate (VU) is the ratio of the qualified duration of customer side voltage to the certain period of time, as is:

\[ VU = \frac{\sum_{j=1}^{n} u_{j}}{CT \times T} \times 100\% \]  

Where \( u_{j} \) is the duration of unqualified voltage for \( j \) customer.

(3) Level of operation and maintenance (A3)

Ability to deal with power supply failure can be applied to reflect the power supply reliability of distribution network, which can be measured from the aspect of accuracy and timeliness of power supply accident treatment. It includes the following sub-criteria:

Accuracy of power supply fault alarm measures the accuracy of fault alarm mechanism in distribution network system, including the running state of fault alarm devices and the rationality of fault alarm management.

Actual occurrence rate of power supply failure reflects the normal operation level of power distribution equipment. The lower the actual power failure rate is, the better the power distribution system will be.

Mean time to power fault response can reflect the timeliness of power fault handling. And mean time to power failure recovery can reflect the technical level of operation and maintenance personnel in dealing with power failure.

3. An assessment model for the power supply reliability assessment of distribution network

3.1. Entropy weight method

Entropy weight method is based on the inherent information of indictors to calculate the weight. The method can avoid the artificial interference to reveal the intrinsic characteristics of the data. The smaller the entropy value, the more information it contains, the lower the disorder[7]. In order to reflect the information contained into the evaluation data, the entropy weight method was employed to determine the weight of the power supply reliability assessment for distribution network, which is as follows.

Step 1: standardize indicators based on the extreme value method to eliminate the impact of criterion dimension on incommensurability. Supposing there are \( m \) criteria and \( n \) alternatives.

For benefit-type criteria, the standardization process is:

\[ \hat{r}_{ij} = \frac{r_{ij} - \min r_{ij}}{\max r_{ij} - \min r_{ij}} \]  

For cost-type criteria, the standardization process is:
\[ r_{ij} = \frac{\max r_{ij} - r_{ij}}{\max r_{ij} - \min r_{ij}} \]  

where \( r_{ij} \) is the value of criterion \( i \) for the alternative \( j \).

Step 2: calculate the entropy value \( h_i \) for all criteria, as is

\[ f_{ij} = \hat{r}_{ij} \sum_{j=1}^{n} \hat{r}_{ij} \]

\[ h_i = -\sum_{j=1}^{n} f_{ij} \ln f_{ij} \]

Step 3: determine the weights \( w_i \) based on the entropy values, as is:

\[ w_i = \frac{1 - h_i}{m - \sum_{i=1}^{m} h_i} \]

### 3.2. Fuzzy TOPSIS Method

Due to the uncertainty of judgment information, the preference of all criteria for alternatives were determined based on linguistic ratings, as listed in Table 3. The fuzzy TOPSIS approach comprises:

| Table 1. Linguistic variables for evaluating the ratings of subjective criteria |
|----------------------------------|------------------|
| **Linguistic Terms**            | **Triangular Fuzzy Numbers (TFNs)** |
| Very Poor (VP)                  | (0,0,0.2)        |
| Poor (P)                        | (0,0.2,0.4)      |
| Good (G)                        | (0.3,0.5,0.7)    |
| Very Good (VG)                  | (0.6,0.8,1)      |
| Excellent (E)                   | (0.8,1,1)        |

Step 1: Congregate the linguistic ratings of alternatives to get general fuzzy ratings. Suppose there are \( m \) criteria performance to be determined. Let \( \bar{x}_{ik} = (x_{i1}^l, x_{i1}^m, x_{i1}^u) \) be the fuzzy rating for criterion \( i \) of alternative \( k \) according to Table 1, \( x_{i1}^l, x_{i1}^m, x_{i1}^u \) refer to the smallest value, the middle value and the largest value, \( i = 1, \ldots, m \), \( k = 1, \ldots, n \) and \( k = 1, \ldots, n \).

Step 2: Construct the initial fuzzy decision matrix \( D \) for alternatives according to fuzzy rating results, as is:

\[ D = \begin{bmatrix} \bar{x}_{11} & \bar{x}_{12} & \cdots & \bar{x}_{1n} \\ \bar{x}_{21} & \bar{x}_{22} & \cdots & \bar{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \bar{x}_{m1} & \bar{x}_{m2} & \cdots & \bar{x}_{mn} \end{bmatrix} = \begin{bmatrix} (x_{11}^l, x_{11}^m, x_{11}^u) & (x_{12}^l, x_{12}^m, x_{12}^u) & \cdots & (x_{1m}^l, x_{1m}^m, x_{1m}^u) \\ (x_{l1}^l, x_{l1}^m, x_{l1}^u) & (x_{l2}^l, x_{l2}^m, x_{l2}^u) & \cdots & (x_{lm}^l, x_{lm}^m, x_{lm}^u) \\ \vdots & \vdots & \ddots & \vdots \\ (x_{m1}^l, x_{m1}^m, x_{m1}^u) & (x_{m2}^l, x_{m2}^m, x_{m2}^u) & \cdots & (x_{mn}^l, x_{mn}^m, x_{mn}^u) \end{bmatrix} \]

Step 3: Normalize the \( D \) by using the linear scaling transformation. Let \( \bar{y}_{ik} = (y_{ik}^l, y_{ik}^u, y_{ik}^M) \) be the normalized TFN.

For a benefit-type indicator, \( \bar{y}_{ik} = \left( \frac{x_{ik}^l}{u_i^l}, \frac{x_{ik}^M}{u_i^l}, \frac{x_{ik}^u}{u_i^l} \right) \) and \( u_i^l = \max \{ x_{ik}^l \} \).

For a cost-type indicator, \( \bar{y}_{ik} = \left( \frac{u_i}{x_{ik}^l}, \frac{u_i}{x_{ik}^M}, \frac{u_i}{x_{ik}^u} \right) \) and \( u_i^l = \min \{ x_{ik}^l \} \).
Step 4: Establish a weighted normalized fuzzy decision matrix $G$ to contain the importance of the criteria. It can be calculated by multiplying the weight $w_i$ by $\hat{y}_{ik}$:

$$G = \begin{bmatrix}
(w_1y_{11}^M, w_1y_{11}^L, w_1y_{11}^R) & (w_2y_{21}^M, w_2y_{21}^L, w_2y_{21}^R) & \cdots & (w_ny_{n1}^M, w_ny_{n1}^L, w_ny_{n1}^R) \\
(w_1y_{12}^M, w_1y_{12}^L, w_1y_{12}^R) & (w_2y_{22}^M, w_2y_{22}^L, w_2y_{22}^R) & \cdots & (w_ny_{n2}^M, w_ny_{n2}^L, w_ny_{n2}^R) \\
\vdots & \vdots & & \vdots \\
(w_1y_{1m}^M, w_1y_{1m}^L, w_1y_{1m}^R) & (w_2y_{2m}^M, w_2y_{2m}^L, w_2y_{2m}^R) & \cdots & (w_ny_{nm}^M, w_ny_{nm}^L, w_ny_{nm}^R)
\end{bmatrix}$$

(15)

Step 5: Determine the fuzzy positive ideal solution $Z^+$ and the fuzzy negative ideal solution $Z^-$. $G_1$ refers to a benefit-type indicator set, $G_2$ refers to a cost-type indicator set. $\tilde{z}_i^+ = (z_i^L, z_i^M, z_i^R)$ and $\tilde{z}_i^- = (z_i^{-L}, z_i^{-M}, z_i^{-R})$ represent the fuzzy positive ideal solution and the fuzzy negative ideal solution for criterion $i$.

$$Z^+ = \left\{ \tilde{z}_i^+ \mid i \in G_1 \right\} = \left\{ \max z_{i\nu} \mid i \in G_1 \right\}$$

(16)

$$Z^- = \left\{ \tilde{z}_i^- \mid i \in G_2 \right\} = \left\{ \min z_{i\nu} \mid i \in G_2 \right\}$$

(17)

Step 6: Compute the distances $d_r^+$ and $d_r^-$ of each alternative from $Z^+$ and $Z^-$ respectively.

In order to obtain exact information, the $L2$-metric distance approach is employed for easy implementation [8]. The distance $d(\tilde{z}_i, \tilde{z}_j)$ between $\tilde{z}_i$ and $\tilde{z}_j$ is:

$$d(\tilde{z}_i, \tilde{z}_j) = \left\{ \left( z_i^L - z_j^L \right)^2 + 4 \times \left( z_i^M - z_j^M \right)^2 + \left( z_i^R - z_j^R \right)^2 \right\}^{1/2} / 6$$

(18)

Suppose $\tilde{d}(\cdot, \cdot)$ is the distance between two TFNs, $d_r^+$ and $d_r^-$ are:

$$d_r^+ = \sum_{i=1}^{n} \left\{ \left( z_i^L - z_i^L \right)^2 + 4 \times \left( z_i^M - z_i^M \right)^2 + \left( z_i^R - z_i^R \right)^2 \right\}^{1/2} / 6$$

(19)

$$d_r^- = \sum_{i=1}^{n} \left\{ \left( z_i^{-L} - z_i^{-L} \right)^2 + 4 \times \left( z_i^{-M} - z_i^{-M} \right)^2 + \left( z_i^{-R} - z_i^{-R} \right)^2 \right\}^{1/2} / 6$$

(20)

Step 7: Determine the closeness coefficient value (CCVR) of each alternative:

$$CCVR_r = \frac{d_r^+}{d_r^+ + d_r^-}$$

(21)

According to Chen [9], the performance of the best alternative $r$ is farther from $Z^-$ and closer to $Z^+$ than others.

4. Example Study and Discussion

Three representative urban distribution networks in a province were selected as evaluation objects to verify the effectiveness of the evaluation model. City 1 is a small city with numerous private enterprises and rapid commercial development. The city has a high income from electricity sales, and the main distribution network equipment runs for 8 years. City 2 is a medium-sized city with well-developed medical, education and tourism industries. It is the primary target of power supply. The main distribution equipment has been running for 11 years. City 3 is a medium-sized city with large GDP, good economic development and low cost of living. The main distribution network equipment has been running for 9 years. According to the evaluation model constructed in this paper, combined with the distribution network data, the reliability of three city distribution networks was comprehensively evaluated in a certain time in February 2019.

First, the fuzzy ratings can be obtained by aggregating the criteria data in February 2019. According to the definition of TFNs, the smallest data is the first number, the largest data is the third number and the average of all data is the second number in TFNs. Then, the exact numbers of all criteria were
calculated based on the L2-metric distance approach to obtain the criteria weights. The results of criteria weights were shown in Table 2.

| Criteria | C1   | C2   | C3   | C4   | C5   | C6   | C7   | C8   | C9   | C10  |
|----------|------|------|------|------|------|------|------|------|------|------|
| Entropy Value | 0.764 | 0.78  | 0.685 | 0.713 | 0.814 | 0.793 | 0.775 | 0.716 | 0.724 | 0.767 |
| Weight   | 0.096 | 0.089 | 0.128 | 0.116 | 0.075 | 0.084 | 0.091 | 0.115 | 0.112 | 0.094 |

Third, the power supply reliability assessment was implemented based on the fuzzy TOPSIS. The evaluation processes and calculate results were shown in the Table 3.

| Criteria | C1   | C2   | C3   | C4   | C5   | C6   | C7   | C8   | C9   | C10  |
|----------|------|------|------|------|------|------|------|------|------|------|
| Z⁺       | (0.67,0.82,1) | (0.57,0.8,1) | (0.62,0.81,1) | (0.63,0.84,1) | (0.75,0.9,1) |
| Z⁻       | (0.03,0.21) | (0.14,0.34,0.57) | (0.21,0.42,0.63) | (0.08,0.21,0.42) | (0.25,0.45,0.65) |
| Criteria | C6   | C7   | C8   | C9   | C10  |
| Z⁺       | (0.66,0.89,1) | (0.82,0.91,1) | (0.1,0.25,1) | (0.55,0.79,1) |
| Z⁻       | (0.14,0.34,0.62) | (0.05,0.25,0.45) | (0.03,0.03,0.05) | (0.16,0.28,0.44) |

The distances of alternatives from the Z⁺ and Z⁻ were calculated

\[ d_1^+ = 0.641, \quad d_2^+ = 0.574, \quad d_3^+ = 0.447 \]
\[ d_1^- = 0.317, \quad d_2^- = 0.283, \quad d_3^- = 0.235. \]

The closeness coefficient for the urban distribution networks was calculated. The results are:

\[ CCV_1 = 0.5354, \quad CCV_2 = 0.4568, \quad CCV_3 = 0.6445. \]

The larger the closeness coefficient value, the higher the corresponding grade. The closeness coefficient values were ranked in decreasing order:

\[ CCV_3 > CCV_1 > CCV_2. \]

Therefore, the distribution networks for City 3 is the best alternative. And the evaluation model proposed by the paper can be applied to assess the power reliability of distribution network. Importantly, the impact of maintenance and repair on power reliability is taken into account as an important factor effectively in the model.

5. Conclusion

Power supply reliability assessment of distribution network is important to the development of the automation and intelligence of the power system. Due to the importance of the operation, maintenance and repair for the reliability, the essential criteria were introduced into the evaluation of the power supply reliability for distribution network. Then, considering the subjectivity of criteria judgment, a comprehensive evaluation model was employed based on the entropy weight method and the fuzzy TOPSIS method. Empirical analysis was implemented to verify the practicality of the evaluation model.

Acknowledgements

This study is supported by the science and technology project of State Grid Sichuan Electric Power Company of China (Research on urban power supply system reliability and power quality evaluation and assistant decision system development, 521997180022)
References

[1] Z. Ling, Y. Shan-shui, C. Lin., et al, Reliability analysis of DC power distribution network based on minimal cut sets, Proceedings of the 2011 14th European Conference on Power Electronics and Applications. (2011) 1-7.

[2] A. Saifdarian., M. Z Degefa., M.Lehtonen, et al, Distribution network reliability improvements in presence of demand response, IET Generation, Transmission & Distribution. 8(2014) 2027-2035.

[3] C. Liu, Y. Zhang, Distribution network reliability considering distribution generation. Automation of Electric power systems, 31(2007) 46-49.

[4] P. Zhang, S.Wang, A novel interval method for reliability evaluation of large scale distribution system. Proceedings of the CSEE, 3(2004).

[5] L. Cheng, Y. Wan, L. Tian, et al, Evaluating energy supply service reliability for commercial air conditioning loads from the distribution network aspect, Applied Energy, 253(2019) 113547.

[6] Ye Lin Hao, Research of Evaluation Theory and Optimization Improvement of Key Operation Characteristics for Active Distribution Network, South China University of Technology, 2018.

[7] Qi Wanga, Chong Wu, Yang Sun, Evaluating corporate social responsibility of airlines using entropy weight and grey relation analysis. Journal of Air Transport Management, 42(2015) 55-62.

[8] Li, D.F. Compromise ratio method for fuzzy multi-attribute group decision making. Application Software Compute, 7(2007) 807–817.

[9] Chen, C.T., Extensions of the TOPSIS for group decision-making under fuzzy environment. Fuzzy Set System, 114(2000) 1–9.