Reliability Evaluation Method of Distribution Network Based on Consumers’ Sensitivity Classification

Guanghui Sun, Tao Zhang, Qinghui Zeng*, Wanjing Tu, Yunfei Wang and Sihan Zhang
Fenjiang South Road, Chancheng District, Foshan City, Guangdong Province
*Corresponding author’s e-mail: 13927739976@139.com

Abstract. In order to improve the accuracy of power supply reliability evaluation, this paper proposes a reliability evaluation method of distribution network based on consumers’ voltage quality sensitivity. Firstly, 6 indexes of power supply reliability are extracted and divided into general and other indexes to measure consumers-side experience and failure repair capability respectively. Secondly, according to the consumers’ voltage quality sensitivity, they are classified into sensitive consumers, general consumers and insensitive consumers. Based on the data of regional electricity consumers, consumers’ voltage sensitivity classification is obtained. After combining the voltage sensitivity classification of consumers with distribution network reliability index data, a reliability evaluation model of distribution network is established. Finally, an instance analysis shows that consumers’ sensitivity and the proportion of different consumers have significant influence on the evaluation results.

1. Introduction
Power supply reliability refers to the continuous power supply capability of power system and is an important index to measure power quality [1]. In recent years, with the gradual opening of the power market in China, the electricity demand and satisfaction of consumers have become the focus of power enterprises. Improving the reliability of power supply and the consumers’ satisfaction has also become the primary task of power enterprises [2].

The reliability of power supply for consumers is determined by power generation, transmission and distribution network [3]. At present, the research on distribution network reliability mainly focuses on power supply reliability index, evaluation model and improvement measures. In the study of distribution network reliability, literature [4] established an evaluation model based on principal component analysis to determine the power supply reliability indexes and their respective weights. By summarizing the electricity reliability indexes into consumers-side indexes and comparison indexes, another evaluation model is established in literature [5]. Paper [6] explores the risk indexes such as the expected power shortage, and realizes the transformation from risk index to reliability index by defining average capacity. From the different perspectives, the above papers screen and summarize the power supply reliability indexes, and obtain reliability evaluation models with different emphasis. However, the evaluation results of distribution network reliability not only depend on the distribution network itself [7,8], but also depend on the consumers’ evaluation [9]. The above reliability evaluation models all consider the distribution network, but ignore the power consumers' evaluation of power supply reliability.

Aiming at the above problem, this paper combines the consumers’ evaluation with the power supply reliability indexes, and proposes a reliability evaluation method of distribution network based...
on consumers’ voltage sensitivity. First, from the enlightenment of British and American reliability evaluation system\cite{10}, the reliability indexes of power supply are extracted from \cite{11}, \cite{12}, and divided into general index and other index. According to the consumers’ data of the power supply station, the consumers are divided into sensitive consumers, general consumers and insensitive consumers. Second, through the investigation & statistical methods, the weights of various consumers’ distribution networks reliability indexes are obtained, and the reliability evaluation model of distribution network based on consumers’ sensitivity classification is established. Finally, an instance analysis is carried out to verify the rationality of this distribution network reliability index system and the evaluation method.

2. Power supply reliability indexes

According to the reliability indexes defined in the national standard, this paper selects 6 indexes: reliability on service in total, average interruption hours of consumer, average interruption times of consumer, mean interruption duration by failure, mean interruption consumer by failure and average number of consumers on one line, as shown in the table 1.

| First class index | Second class index | Symbol | Description |
|-------------------|--------------------|-------|-------------|
| General index     | Reliability on service in total | $R_{RS-1}$ | The reliability of power grid. |
|                   | Average interruption hours of consumer | $t_{AIHC-1}$ | The hours of customer interruption. |
|                   | Average interruption times of consumer | $n_{AICT-1}$ | The frequency of customer interruption. |
| Other index       | Mean interruption duration by failure | $t_{MID-F}$ | Average interruption hours per failure. |
|                   | Mean interruption consumer by failure | $n_{MIC-F}$ | Average number of customer without power per failure. |
|                   | Average number of consumers in one line | $N$ | Average line capacity |

The three indexes: $R_{RS-1}$, $t_{AIHC-1}$ and $n_{AICT-1}$ reflect the consumers’ experience. Other indexes show the self-recovery ability of power grid.

2.1 General index

2.1.1 Reliability on service in total. Reliability on service in total reflects the level of power supply reliability, that is, the proportion of normal power supply during statistical time, which is denoted as $R_{RS-1}$.

$$R_{RS-1} = (1 - \frac{\sum t_i}{nT}) \times 100\%$$ \hspace{1cm} (1)

Where, $t_i$ represents the total interruption time of the $i$-th consumer in the statistical period. And $n$ represents the total number of consumers. $T$ stands for statistical time.

2.1.2 Average interruption hours of consumer. Average interruption hours of consumer reflects the length of consumers’ interruption time, that is, all consumers’ average interruption hours within the statistical time, which is denoted as $t_{AIHC-1}$.

$$t_{AIHC-1} = \frac{\sum t_{nj}}{n}$$ \hspace{1cm} (2)

Where, $t_{nj}$ represents the interruption time of the $n$-th consumer in the $j$-th continuous interruption.
2.1.3 Average interruption times of consumers. The average interruption times of consumers reflects the frequency of consumers’ interruption, that is, average number of all consumers’ interruption. Record it as $n_{AITC-1}$.

$$n_{AITC-1} = \frac{1}{n} \sum_{j} n_j$$

(3)

Where, $n_j$ is the number of consumers affected in the $j$-th interruption. And $n$ is the total number of all consumers.

2.2 Other indexes

2.2.1 Mean interruption duration by failure. The mean interruption duration by failure reflects the ability to recover from failure, that is, average time per failure. Record it as $t_{MID-F}$.

$$t_{MID-F} = \frac{1}{m} \sum_{i} t_i$$

(4)

Where, $t_i$ represents the interruption time of the $i$-th failure, and $m$ represents the total number of failures in the statistical period.

2.2.2 Mean interruption consumer by failure. It reflects the scope of failure, namely the number of consumers for each interruption by failure. And the formula is.

$$n_{MIC-F} = \frac{1}{m} \sum_{i} n_i$$

(5)

Where, $n_i$ represents the number of consumers without power supply in the $i$-th failure. And $m$ is the total number of failures in the statistical time.

2.2.3 Average number of consumers in one line. It reflects the load capacity of each line, that is, the number of consumers on each line, and the formula is.

$$N = \frac{1}{n} \sum_{i} l_i$$

(6)

Where, $l_i$ is the length of the $i$-th line. And $n$ represents the total number of consumers in the statistical scope.

3. The evaluation of power supply reliability based on consumers’ sensitivity classification

3.1 The classification of consumers

First, we obtain the information of consumers from the power supply station. And according to the level of the consumers’ electronic informatization and the characteristics of their electrical equipment, they are divided into the following classification, as shown in the table 2.

| The consumers’ classification | Symbol | Industry |
|------------------------------|--------|---------|
| Sensitive consumers          | $s$    | High-tech industries, such as precision instruments, computer manufacturing, communications, medicine, electronics, electrical appliances, transportation, machinery, plastic, glass, hardware manufacturing, chemical industry, ceramics, etc. |

Table 2. The consumers’ classification based on voltage quality sensitivity.
General consumers  
Conventional industries, such as general food, clothing, shoes, leather goods, toys, printing, furniture, paper, textiles, agricultural products processing, etc.

Insensitive consumers  
Industries with characteristics of residential electricity, such as residents, logistics, real estate, services, trade, exhibitions, agriculture, etc.

Sensitive consumers have the highest level of electronic informatization, whose power equipment mainly includes programmable controllers, inverters, computers, etc. Computer manufacturing enterprises, communication enterprises and electronic enterprises are typical sensitive consumers. Sensitive consumers have high voltage quality requirements. And a slight voltage fluctuation will cause them to suspend production and bring huge economic losses.

Compared with sensitive consumers, the general consumers’ electronic informatization level is lower. Most of them are conventional industries with a high level of automation, whose requirements for voltage quality are not high. Their product quality and production will only be affected if the voltage quality drops seriously.

Insensitive consumers have the lowest level of electronic informatization. And their electrical equipment mainly is lighting equipment and living appliances. Insensitive consumers have the characteristics of residential electricity consumption, such as residents, real estate, services, agriculture and so on. They have the lowest requirements for voltage quality, so when voltage quality problems occur, their economic losses are relatively low.

3.2 The weight of each index.
Next, we use the investigation & statistical method to determine the weight of each power supply reliability index for sensitive consumers, general consumers, and insensitive consumers.

According to the survey, we obtain the importance of various power supply reliability indexes to different consumers. The table used for the survey is as follows.

| The degree of importance | $R_{RS-1}$ | $t_{AHC-1}$ | $n_{AITC-1}$ | $t_{MID-F}$ | $n_{MIC-F}$ | $N$ |
|--------------------------|------------|-------------|--------------|--------------|--------------|-----|
| 0                        | 0.2        | √           | √            |              |              |     |
|                           | 0.4        | √           | √            | √            |              |     |
|                           | 0.6        | √           | √            | √            | √            |     |
|                           | 0.8        | √           |              |              |              |     |
|                           | 1.0        |              |              |              |              |     |

The consumer can tick one or two marks in the table. One tick mark indicates that the degree of importance is equal to the value ticked, and the two tick marks indicate that the degree of importance is an interval, the size of which is determined by the value ticked. The score of the $j$-th power supply reliability index in the $i$-th sample of consumer $u$ is recorded as $[a_{ij}, b_{ij}]$. The mean value is expressed as

$$ w_{ij}^u = \frac{a_{ij}^u + b_{ij}^u}{2} $$

Where, $u = \{s, g, l\}$, $j = 1, 2, ..., 6$. Comparing the mean of all samples of the $j$-th index of consumer $u$, we can get $\max\{w_{ij}^u\}$ and $\min\{w_{ij}^u\}$. Then, we calculate the value of $\max\{w_{ij}^u\} - \min\{w_{ij}^u\}$,
and compare it with a set $\lambda$. If $\max\{w_u^v\} - \min\{w_u^v\} < \lambda$, the weight range of the $j$-th index of consumer $u$ is

$$w_j^u = \frac{1}{n} \left( \sum a_u^v \lambda + \sum b_u^v \lambda \right)$$  \hspace{1cm} (8)$$

To simplify the process, we extract the mean of the weight range as the weight. Therefore, the weight of the $j$-th index of consumer $u$ is

$$w_j^u = \frac{1}{2n} \left( \sum a_u^v + \sum b_u^v \right)$$  \hspace{1cm} (9)$$

Finally, we adjust the weight value so that the weight sum of all indexes is 1, and get the weight of the $j$-th index of consumer $u$.

$$w_j^u = \frac{w_j^u}{\sum w_j^u}$$  \hspace{1cm} (10)$$

If $\max\{w_u^v\} - \min\{w_u^v\} \geq \lambda$, we need to remove $\max\{w_u^v\}$ and $\min\{w_u^v\}$, and select $\max\{w_u^v\}$ and $\min\{w_u^v\}$ again from the remaining samples until they meet the requirements.

3.3 Power supply reliability evaluation steps

The steps of the power supply reliability evaluation algorithm proposed in this paper as follows,

- First, we get consumers’ data.
- According to their voltage sensitivity, we divide consumers into sensitive consumers, general consumers and insensitive consumers.
  - And the proportion of various consumers are calculated.
- Then, we determine the power supply reliability evaluation indexes and obtain the value of each index.
  - Through investigation & statistical methods, we determine the weight of power supply reliability indexes for each type of consumers.
  - Next, we calculate the power supply reliability evaluation value of each type of consumer. The power supply reliability formula is

$$y^u = w_u^v x^u \times 100 + \sum w_j^u (1 - \frac{x_j^u}{2x_j^u})$$  \hspace{1cm} (11)$$

Where, $y^u$ is the evaluation value of consumer $u$ in a certain region. $w_j^u$ is the weight of the $j$-th index of consumer $u$. For example, $w_j^v$ is the weight of sensitive consumers’ reliability on service in total. $x^u$ is the value of the $j$-th power supply reliability index of consumer $u$ in a certain region. $\bar{x}_j^u$ is the average value of the $j$-th power supply reliability index of consumers $u$ in all regions.

- In final, we calculate the final evaluation result based on the proportion of different consumers. The power supply reliability evaluation function based on consumers’ sensitivity classification is

$$y = u_s y_s + u_g y_g + u_i y_i$$  \hspace{1cm} (12)$$

The flow chart of power supply reliability evaluation is shown in figure 1.

4. Instance analysis

In this paper, six power supply stations in a district of Foshan city are selected as the research objects. Using the evaluation model, we evaluate the power supply reliability of these six samples.
Start

Get consumers’ data

Divide consumes into s, g, i.

Calculate the proportion of consumers

Determine the power supply reliability evaluation indexes

Determine the weight of power supply reliability indexes

Calculate the weight

Calculate the power supply reliability evaluation value of each type of consumer

Calculate the final evaluation result based on the proportion of different consumers.

Over

Figure 1. The flow chart of power supply reliability evaluation.

4.1 Data acquisition and analysis

For convenience of description, these six samples are represented by A1, A2, A3, A4, A5, and A6 in sequence. The indexes data of the six samples is shown in the table 4.

| Distribution network number | $R_{RS-1}$ | $t_{AHC-1}$ | $n_{AITC-1}$ | $t_{MID-F}$ | $n_{MIC-F}$ | $N$ |
|-----------------------------|-------------|-------------|--------------|-------------|-------------|-----|
| A1                          | 99.975      | 2.2215      | 0.7348       | 6.85        | 7           | 11.2348 |
| A2                          | 99.902      | 8.614       | 1.0978       | 2.6456      | 19.8947     | 14.6488 |
| A3                          | 99.932      | 5.963       | 1.0782       | 3.1065      | 11.1296     | 13.1182 |
| A4                          | 99.952      | 4.2405      | 0.8842       | 2.4714      | 19.4643     | 16.6047 |
| A5                          | 99.927      | 6.395       | 1.0411       | 3.3653      | 12.1944     | 14.6167 |
| A6                          | 99.892      | 9.4537      | 1.4117       | 2.6792      | 9.75        | 15.3924 |

By comparison, we find that the reliability on service in total of A1 is the highest. In addition, its average interruption hours of consumer, and mean interruption consumer by failure are the best among the six samples. However, the mean interruption duration by failure of A1 is the longest.

By analysing the industry and electricity consumption of consumers in each distribution network, the proportion of various consumers is obtained, as shown in the following table 5.

| Distribution network number | Sensitive consumers | General consumers | Insensitive consumers |
|-----------------------------|---------------------|-------------------|----------------------|
| A1                          | 13%                 | 75%               | 12%                  |
There are many conventional industries in A1, so the consumers of A1 are mainly general consumers. A3 is located in the centre areas of the city, and there are many high-tech industries. In A2, A4, A5 and A6, consumers are mainly residents, and there are few factories and enterprises.

4.2 Weight analysis

Through investigation & statistical methods, the weights of various indexes of different consumers are shown in the following table.

| index | Sensitive consumers | General consumers | Insensitive consumers |
|-------|---------------------|-------------------|-----------------------|
|      |                     |                   |                       |
| $R_{RS-1}$ | 0.225              | 0.214             | 0.2                   |
| $i_{AHC-1}$ | 0.2                | 0.190             | 0.166                 |
| $n_{ATC-1}$ | 0.2                | 0.214             | 0.166                 |
| $i_{MID-F}$ | 0.2                | 0.190             | 0.166                 |
| $N$ | 0.075               | 0.047             | 0.133                 |

From the analysis of different indexes and consumers’ sensitivity, we can get the following conclusions.

- Regardless of the type of user, the following inequality is always true. The weight of $R_{RS-1} > \max\{\text{the weight of } i_{AHC-1}, n_{ATC-1}, i_{MID-F} \text{ and } N\}$.
- Sensitive consumers concern on the reliability on service in total, frequency of failures and interruption time. The general consumers focus on the reliability on service in total and frequency of failures. Insensitive consumers pay more attention to the average number of consumers in one line.

4.3 Results of power supply reliability evaluation

Using formula (11), we obtain the evaluation value of different consumers for the distribution network reliability. And according to formula (12), the final evaluation result based on the proportion of different consumers is obtained.

| A1 | A2 | A3 | A4 | A5 | A6 |
|----|----|----|----|----|----|
| Sensitive consumers $s$ | 22.912 | 22.819 | 22.894 | 22.923 | 22.874 | 22.808 |
| General consumers $g$ | 21.827 | 21.714 | 21.800 | 21.818 | 21.781 | 21.719 |
| Insensitive consumers $i$ | 20.446 | 20.318 | 20.413 | 20.402 | 20.389 | 20.339 |
| Final evaluation result | 21.802 | 20.932 | 22.085 | 21.079 | 20.737 | 20.877 |
| Ranking | 2 | 4 | 1 | 3 | 6 | 5 |

From the score sheet, we can get the following information. Sensitive consumers believe that the A4 area has the best distribution network reliability. For general consumers and insensitive consumers, A1 scores the highest. The highest overall score is A3. Therefore, consumers have different voltage quality sensitivity, and their evaluation values for the same index are different. Consumers’ sensitivity has a significant impact on the evaluation value.
Among the six samples, A1 has the optimal $R_{RS-1}$, $t_{AIHC-1}$, $n_{AITC-1}$, $n_{MIF-}$ and $N$. In addition, general consumers and insensitive consumers think that A1 has the best distribution network reliability. But in the final evaluation result, A3 scored higher than A1. It can be seen that the proportion of different consumers has a significant impact on the evaluation value of distribution network reliability.

5. Conclusion

Aiming at the problem that existing reliability evaluation methods ignore consumers, this paper proposes a reliability evaluation method of distribution network based on consumers’ sensitivity classification. First, the reliability indexes of power supply are extracted, and divided into general indexes and other indexes. According to the consumers’ data of the power supply station, the consumers are divided into sensitive consumers, general consumers and insensitive consumers. Second, through the investigation & statistical methods, we obtain the weights of various consumers' distribution networks reliability indexes, and establish the reliability evaluation model of distribution network based on consumers’ sensitivity classification. Finally, we make an example analysis. The results show that the consumer’s sensitivity is different, the evaluation values of the same reliability index are different, and the proportion of different consumer has a significant impact on the evaluation value.

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