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Comprehensive Evaluation on the Distribution Network Reliability Based on Matter-Element Extension Model

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Abstract

The reliability of power supply in the distribution network, associated to the normality and effectiveness of electric power supply, plays a significant role in all walks of life, such as urban, rural life and public facilities. Considering about this, it is necessary to evaluate the reliability of electric power supply in the distribution network. A comprehensive evaluation index system for the reliability of distribution network is set up in this paper. Meanwhile, a reliability comprehensive evaluation method is proposed based on matter-element extension model, which can realize the reliability evaluation from the perspective of the system operation. The effectiveness and practicality of the model is verified through the case study of a distribution network.

Keywords: *Reliability; Element extension model; Distribution network*

1. Introduction

As we all know, power system should supply electricity to power users uninterruptedly, with a quality standard which can be accepted [1]. The power supply reliability is an indicator measuring the supply capacity of a power system. The reliability level of power supply not only determines the normality and effectiveness of electric power supply for urban, rural and public facilities, but also is a crucial indicator which power regulars focus on [2]. Taking all above into consideration, it is necessary to establish a reasonable index system and an effective method to evaluate the power supply reliability in the distribution network.

Currently, some comprehensive evaluation methods have been used to evaluate the reliability of electricity power supply, such as the analytic hierarchy process(AHP), Monte Carlo analysis method, artificial intelligence method, statistical method and so on [3,4]. Considering the influence of relay protection device and action accuracy, Literature [5] calculated the power supply reliability of a substation based on the simplified Markov model. Literature [6] applied fault tree method to establish the reliability model of micro grid under off net mode and calculated the failure rate during fixed time based on the Monte Carlo simulation method. In order to evaluate the power supply reliability of low-voltage users, Literature [7] extracted some interruption information and calculated the reliability of an area based on probability and statistics theory. Literature [8] used the variable fuzzy evaluation model to evaluate the reliability of distribution network. However, although these traditional methods on the reliability evaluation for power supply are matured and precise, the evaluation object is only focusing on equipment in the system. Unfortunately, the researches on the comprehensive evaluations of power supply reliability from the perspective of the whole system are few.

In an effort to fulfill this research gap on power supply reliability, a comprehensive evaluation model based on matter-element extension model is proposed to realize the evaluation of the reliability for power distribution network, from the perspective of the whole system.

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As an evaluation method to solve the fuzzy, diversity and incompatible of evaluation object, matter-element extension theory can establish performance evaluation model from multiple indicators and standards. The grade of a matter-element can be judged by calculating the correlation degree between evaluation results and evaluation rates. Additionally, the proposed model not only can reflect the performance of an object, but also it has no requirements on the number of samples.

In order to evaluate the power supply reliability of a distribution network, a comprehensive evaluation index system is constructed in this paper, and a new formula method is used to determine the index weights, so as to avoid subjective factors influencing the results. Meanwhile, an evaluation model based on matter-element extension is proposed to evaluate the power supply reliability from a perspective of system. What's more, when some indicators exceed their controlled field, the correlation function cannot be calculated. As a result, to overcome the limitation, the classical domain and matter-element should be normalized. Finally, taking a distribution network as an example, an empirical analysis on the power supply reliability has been performed, which verified the effectiveness and practicality of the model.

2. The Evaluation Index System of Power Supply Reliability in Distribution Network

In order to realize the comprehensive evaluation for the reliability of power supply in distribution network, it is essential to establish a rational evaluation index system. In addition, the quantitative indicators may lay a foundation and basis for the comprehensive evaluation.

According to the 'User Power Supply Reliability Evaluation Code of Power Supply System', the evaluation indicators of power supply reliability should be related to power customers closely. Therefore, the frequency of power outage, time and range of power outage are the basic elements to reflect reliability. The evaluation index system of power supply reliability in this paper is as follows:

(1) Reliability on Service in Total

Reliability on Service in Total refers to the ratio of total hours of effective power supply and total hours of statistical period. It is an indicator reflecting the reliability of a system providing electricity to users. The calculation formula is as follows:

$$\mathrm{Re}\mathit{liability\ on\ Service\ in\ Total} = (1 - \frac{\mathit{Average\ Interruption\ Hours\ of\ Customer}}{\mathit{Statistical\ Period}}) \times 100\% \quad (1)$$

(2) Average Interruption Hours of Customer

Average Interruption Hours of Customer refers to the average interruption hours of power customers in a statistical period, which is an indicator reflecting the time duration of power outage. The calculation formula is as follows:

$$\mathit{Average\ Interruption\ Hours\ of\ Customer} = \frac{\sum(\mathit{Outage\ Time} \times \mathit{Outage\ Number})}{\mathit{Total\ Number}} \quad (2)$$

(3) Average Failure Interruption Times of Customer

Average Failure Interruption Times of Customer refers to the mean outage frequencies of customers in the statistical period, which is an indicator reflecting the power-cut frequency of a power supply system. The calculation formula is as follows:

$$\mathit{Average\ Failure\ Interruption\ Times\ of\ Customer} = \frac{\sum \mathit{Outage\ Number}}{\mathit{Total\ Number}} \quad (3)$$

(4) Mean Interruption Customer

Mean Interruption Customer refers to the average number of customers who are affected by power-failure in the statistical period. It is an indicator used to reflect the sphere of influence of power interruption of power supply system. The calculation formula is as follows:

$$Mean\ Interruption\ Customer = \frac{\sum (Outage\ Number)}{Failure\ \ Interruption\ \ Times} \tag{4}$$

(5) Average Repeat Failure Interruption Times of Customer

Average Repeat Failure Interruption Times of Customer refers to the ratio of repeated outages occur to the users. The calculation formula is as follows:

$$Average\ Repeat\ Failure\ Interruption\ Times\ of\ \ Customer = \frac{\sum Repeat\ Outage\ Number}{Total\ Number} \tag{5}$$

(6) Energy not supplied due to Interruption

Energy not Supplied due to Interruption refers to the electricity short for users during a power outage. The calculation formula is as follows:

$$W = K \times S_1 \times T \tag{6}$$

Where W denotes “Energy not supplied due to Interruption; K represents the ratio of loading capacity coefficient, which is updated at the beginning of each year on the basis of the specific circumstances of last year; S_1 refers to the outage capacity, namely the total loading capacity of the outage users; T represents interruption duration.

3. Construction of the Model

3.1 Basic Theory of Matter-Element Model

Matter-element extension model is established based on the theoretical framework of matter-element theory and extension set theory. Through establishing classical field, controlled field, evaluation level and correlation function, the level of an object can be determined by the association degree between the matter-element to be evaluated and evaluation grade [9-10].

The basic idea of matter-element evaluation method is as follows: first of all, the object is divided into j levels which are determined by database or experts; secondly, determine the weight of each index; finally, calculate the correlation degree between index value and each evaluation grade. Moreover, the larger correlation degree is, the better matter-element is compliance with this level.

3.2 Proposed Model

Matter element is the logic unit of matter-element extension model, which describes objects through an ordered triple $R=(P，C，V)$. Where, P, C, V represents the name, characters and value of things respectively. The basic steps of the improved matter-element extension model are as follows:

(1) Determine the classical domain, controlled field and matter-element of the object to be evaluated.

Suppose $\boldsymbol{R}_j = (\boldsymbol{P}_j, \mathrm{c}_i, \mathrm{v}_{ij})$ as the classical domain matter-element:

$$\boldsymbol{R}_j = (\boldsymbol{P}_j, \mathrm{c}_i, \mathrm{v}_{ij}) = \begin{bmatrix} P_j & c_1 & v_{1j} \\ & c_2 & v_{2j} \\ & \vdots & \vdots \\ & c_n & v_{nj} \end{bmatrix} = \begin{bmatrix} P_j & c_1 & \langle a_{1j}, b_{1j} \rangle \\ & c_2 & \langle a_{2j}, b_{2j} \rangle \\ & \vdots & \vdots \\ & c_n & \langle a_{nj}, b_{nj} \rangle \end{bmatrix} \tag{7}$$

Where P_j represents the evaluation grade of j th, $c_1,c_2,\ldots,c_n$ represent the characteristics of P_j, and $v_{j1},v_{j2},\ldots$, v_{jn} denote the value ranges of $c_1,c_2,\ldots,c_n$ for P_j respectively, which are called the classical fields.

Suppose the controlled field matter-element as $R_p=(R,C_i,V_{pi})$:

$$\boldsymbol{R}_p=(\boldsymbol{P},\boldsymbol{C}_i,\boldsymbol{V}_{pi})=\begin{bmatrix} P & c_1 & v_{p1} \\ & c_2 & v_{p2} \\ & \cdots & \cdots \\ & c_n & v_{pn} \end{bmatrix}=\begin{bmatrix} P & c_1 & \langle a_{p1},b_{p1}\rangle \\ & c_2 & \langle a_{p2},b_{p2}\rangle \\ & \cdots & \cdots \\ & c_n & \langle a_{pn},b_{pn}\rangle \end{bmatrix} \tag{8}$$

Where P denotes all grades of the object, the value ranges of P about $c_1,c_2,\ldots$, c_n are represent by $v_{p1},v_{p2},\ldots,v_{pn}$, namely the controlled field of P.

Suppose the matter-element to be evaluated as $\boldsymbol{R}_0=(\boldsymbol{P}_0,\boldsymbol{C}_i,\boldsymbol{V}_i)$:

$$\boldsymbol{R}_0=(\boldsymbol{P}_0,\boldsymbol{C}_i,\boldsymbol{V}_i)=\begin{bmatrix} P_0 & c_1 & v_1 \\ & c_2 & v_2 \\ & \cdots & \cdots \\ & c_n & v_n \end{bmatrix} \tag{9}$$

Where P_0 represents all grades of the object to be evaluated, and $v_{p1},v_{p2},\ldots,v_{pn}$ are actual data of P_0 about $c_1,c_2,\ldots$, c_n.

(2) Normalization

The classical domain and matter-element evaluation should be normalized when an index value exceeds its controlled field. The correlation function cannot be calculated since the denominator is zero. Against the limitation, matter-element and extension model should be improved. Therefore, the classical domain R_j and matter-element evaluation R_0 should be normalized [11], which are shown as follows:

$$\boldsymbol{R}'_j=(\boldsymbol{P}_j,\boldsymbol{C}_i,\boldsymbol{V}'_{ij})=\begin{bmatrix} P_j & c_1 & \left\langle \dfrac{a_{1j}}{b_{p1}},\dfrac{b_{1j}}{b_{p1}}\right\rangle \\ & c_2 & \left\langle \dfrac{a_{2j}}{b_{p2}},\dfrac{b_{2j}}{b_{p2}}\right\rangle \\ & \cdots & \cdots \\ & c_n & \left\langle \dfrac{a_{nj}}{b_{pn}},\dfrac{b_{nj}}{b_{pn}}\right\rangle \end{bmatrix} \tag{10}$$

$$\boldsymbol{R}'_0=\begin{bmatrix} P_0 & c_1 & v_1/b_{p1} \\ & c_2 & v_2/b_{p2} \\ & \cdots & \cdots \\ & c_n & v_n/b_{pn} \end{bmatrix} \tag{11}$$

(3) Determined index weights

The index weights are very important to the evaluation result of power distribution reliability, since the index weights directly affect the quality and feasibility of the comprehensive evaluation. There are various weighting methods, such as Delphi method, interval estimation method, Analytic Network Process and so on. However, all these methods are easily influenced by subjective factors. Therefore, the index weights of power distribution reliability are determined by a new formula method, which is shown as follows:

$$W_i'=\begin{cases}\frac{1}{2}+\frac{\sqrt{-2\ln(\frac{2(i-1)}{n})}}{6} & (1<i\le\frac{n+1}{2})\\ \frac{1}{2}-\frac{\sqrt{-2\ln(2-\frac{2(i-1)}{n})}}{6} & (\frac{n+1}{2}<i\le n)\end{cases} \tag{12}$$

Where, W_i' and i $i=1,2,\ldots,$ $m(m\le n)$ denotes the importance of index and index orders respectively. The index orders are determined according to the importance of indexes. The more important indicator is, the smaller the value of i is.

And then, the index weight W_i can be obtained through the normalization of W_i'.

(4) Calculate the correlation degree

The correlation degree function is shown as follows:

$$N_j(p_0)=1-\sum_{i=1}^{n}D_j(v_i')w_i(X) \tag{13}$$

And $D_j(v_i')$ refers to the distance between the evaluated object and its corresponding normalized classical field, namely,

$$D_j(v_i')=\left|v_i'-\frac{a_{ij}'+b_{ij}'}{2}\right|-\frac{1}{2}(b_{ij}'-a_{ij}') \tag{14}$$

Where N represents the value of correlation degree; denotes the distance of matter-element $w_i(X)$ is the index weight.

(5) Rating

Suppose $N_{j'}(p_0)=\max\left\{N_j(p_0)\right\}$, the matter-element to be evaluated P_0 belongs to the j th level.

4. Case Study

In this section, a power distribution network is used to exemplify the applicability of the proposed model. The specific analysis processes of the evaluation of power distribution reliability are shown as below:

(1) Determine the classical domain, controlled field and matter-element of the power distribution reliability.

The classical domain R_j of each indicator is determined according to relative standards and requirements. The classical domains of all grades P_1、P_2、P_3 represent high reliability, medium reliability, and low reliability respectively.

$$R_j=\begin{bmatrix} P_j & P_1 & P_2 & P_3\\ C_1 & (99.9\%,100\%) & (99.85\%,99.9\%) & (99.8\%,99.5\%)\\ C_2 & (3,4) & (4,4.8) & (4.8,5.5)\\ C_3 & (0,1) & (1,2) & (2,4)\\ C_4 & (0,15) & (15,20) & (20,23)\\ C_5 & (0,150) & (150,250) & (250,400)\\ C_6 & (0,2) & (2,5) & (5,10)\end{bmatrix} \tag{15}$$

The controlled field of each index which is equal to the sum of all classical field values is R_p.

$$\boldsymbol{R}_p = \begin{bmatrix} \mathrm{P} & c_1 & (99.5\%,100\%) \\ & c_2 & (3,5.5) \\ & c_3 & (0,4) \\ & c_4 & (0,23) \\ & c_5 & (0,400) \\ & c_6 & (0,10) \end{bmatrix} \tag{16}$$

The matter-element to be evaluated is R_0, which is shown as follows:

$$\boldsymbol{R_0} = \begin{bmatrix} \mathrm{P}_0 & c_1 & 99.92\% \\ & c_2 & 4.3 \\ & c_3 & 4.2 \\ & c_4 & 13 \\ & c_5 & 165 \\ & c_6 & 3 \end{bmatrix} \tag{17}$$

(2) Normalization

Since some index values exceed the controlled fields, the classical domain R_j and matter-element evaluation R_p, should be normalized, which are shown as follows:

$$\mathrm{R}_j' = \begin{bmatrix} \mathrm{P}_j & \mathrm{P}_1' & \mathrm{P}_2' & \mathrm{P}_3' \\ \mathrm{C}_1 & (99.9\%,100\%) & (99.85\%,99.9\%) & (99.85\%,99.5\%) \\ \mathrm{C}_2 & (0.545,0.727) & (0.727,0.873) & (0.873,1) \\ \mathrm{C}_3 & (0,0.25) & (0.25,0.5) & (0.5,1) \\ \mathrm{C}_4 & (0,0.652) & (0.652,0.87) & (0.87,1) \\ \mathrm{C}_5 & (0,0.375) & (0.375,0.625) & (0.625,1) \\ \mathrm{C}_6 & (0,0.2) & (0.2,0.5) & (0.5,1) \end{bmatrix}, \boldsymbol{R_0}' = \begin{bmatrix} \mathrm{P}_0 & c_1 & 99.92\% \\ & c_2 & 0.782 \\ & c_3 & 1.05 \\ & c_4 & 0.565 \\ & c_5 & 0.413 \\ & c_6 & 0.3 \end{bmatrix} \tag{18}$$

(3) Determined index weights

The index weights are calculated by formula method according to the equation (12), and the results are shown in Table 1.

Table 1. Index Weights and the Value of $D_j(v_i')$

Indicator	High $D_1(v_i')$	Medium $D_2(v_i')$	Low $D_3(v_i')$	Index weight
c1	-0.0002	0.0002	0.0042	0.2500
c2	0.055	-0.055	0.091	0.1814
c3	0.8	0.55	0.05	0.2500
c4	-0.087	0.087	0.305	0.1528
c5	0.038	-0.038	0.212	0.0686
c6	0.1	-0.1	0.2	0.0972

(4) Calculate the correlation degree

Firstly, according to the equation (12), the distances $D_j(v_i')$ of the evaluated matter-element related to new classical domain are calculated, which is shown in the table1. And then, calculate the correlation degree between R_0, and all grades, just as shown in bellow:

$$\begin{aligned} N_1(p_0) &= 1-\sum_{i=1}^{6} D_1(v_i{}')w_i(X) = 0.79104 \\ N_2(p_0) &= 1-\sum_{i=1}^{6} D_2(v_i{}')w_i(X) = 0.87146 \\ N_3(p_0) &= 1-\sum_{i=1}^{6} D_3(v_i{}')w_i(X) = 0.88936 \end{aligned} \tag{18}$$

(4) The grade of power distribution reliability

According the correlation degree of R_0, related to each grade, the grade of power distribution reliability can be judged. Owning to $N_3(p_0) = \max\{N_j(p_0)\} = 0.88936$, j=1,2,3, the reliability in this power distribution network belongs to “low” level.

5. Conclusion

(1) A comprehensive evaluation model based on matter-element extension is proposed to evaluate the power supply reliability in power distribution network. In addition, compared with the evaluation method aiming at equipment, this paper evaluates the reliability of power supply from the perspective of power distribution network system.

(2) In the process of the reliability evaluation, some index values exceed the controlled fields. To overcome this limitation, the classical domain and matter-element evaluation are normalized in this paper. Meanwhile, the effectiveness and practicality of the model is verified through the case study of a distribution network.

(3) An empirical analysis of a distribution network is performed in this paper, and the evaluation result shows that the power supply reliability is “low”. Thereafter, the equipment in this network should be frequently overhauled and replaced, so as to reduce the probability of failure.

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