

Research Article

Research on Distribution Network Security Analysis Based on $K(N - 1 + k)$ Criterion and Rank Preference Optimal Ordering

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The objective of security analysis is to find the weak link of distribution network. The $K(N - 1 + k)$ criterion based on the characteristics of distribution network was proposed for distribution network security analysis. According to the $K(N - 1 + k)$ criterion, the electrical devices in the contingency set can be classified into two kinds. The first kind meets the requirement of the $K(N - 1 + k)$ criterion. The rank preference optimal ordering (RPOO) was proposed to evaluate the damage degree of power system. The second kind does not meet the requirement of the $K(N - 1 + k)$ criterion, and it is the weak link of distribution network. A numerical experiment shows that the method is efficient and feasible, and the proposed method can provide assistant decision-making for safety precautions.

1. Introduction

With the rapid development of distribution management system (DMS), distribution network security analysis (DNSA) is a vital part of DMS and has attracted wide attention [1].

Compared to the study of transmission network security analysis (TNSA), the study of DNSA is still relatively less. Distribution network is designed in closed loop and operated in open loop [2, 3]. Transmission network has no limit on operation in open loop [4, 5]. The TNSA is based on the $N - 1$ criterion [6–8]. The essence of the $N - 1$ criterion is uninterrupted power supply, when one of electrical devices is fault. There are lots of switches in distribution network for the failure isolation and restoration. When permanent fault occurs in the distribution network, the short-term power off is inevitable in the nonfault and out-of-service areas. In this perspective, the DNSA cannot simply copy the $N - 1$ criterion of TNSA.

Traditional DNSA [9, 10] only focused on finding out the electrical devices which dissatisfy the requirement of the security analysis criterion. And it is not to evaluate the damage degree caused by the fault of these electrical devices. Once an electrical device is fault, it will bring a harmful effect on power system. DNSA should be to evaluate the damage

degree after a fault occurs and to further find out the potential weakness in power grid.

This paper presented the $K(N - 1 + k)$ criterion for DNSA. According to the $K(N - 1 + k)$ criterion, the rank preference optimal ordering method (RPOO) was introduced to evaluate damage degree, and it can identify the potential weakness in distribution network.

2. $K(N - 1 + k)$ Criterion

Considering the characteristics of the distribution network, study [11] presented the $N - 1 + 1$ criterion for DNSA. The N is the number of electrical equipment in power system. The -1 means that one of electrical devices is fault and isolation. The $+1$ means that one time of switching operation is needed for supply restoration. However many studies [12–14] illustrate that numbers of switching operation are required for supply restoration. Thus, the $N - 1 + 1$ criterion for DNSA is not fit to the practical engineering.

The analysis of DNSA is based on the given operation mode. It is supposed that the electrical devices are fault one by one. Under the condition of the system operation constraint, the DNSA is to evaluate the safety of distribution network and

to find out the weaknesses in the system by judging whether power supply can be resumed completely.

The $N - 1 + k$ criterion is improved based on the $N - 1 + 1$ criterion. When one of the electrical devices is fault and it has been detected and isolated, in order to restore power in the nonfault and out-of-service areas, k times of switching operation are need.

Because of the variable structure characteristic of distribution network, the restoration scheme is not always single but K . In the perspective of the security, greater value of K is desired.

Based on the $N-1+k$ criterion, the $K(N-1+k)$ criterion is proposed further. The K is the number of feasible restoration schemes which meet the requirement of the $N-1+k$ criterion.

3. Evaluation Indexes of DNSA

The main purpose of DNSA is to discover the potential weakness. According to the $K(N - 1 + k)$ criterion, the electrical devices in the contingency set can be classified into two kinds. The first kind meets the requirement of the $K(N - 1 + k)$ criterion. It will cause negative effects on the power system when this kind of the electrical devices is fault. The evaluation of negative effects can find the weakness in the system. The second kind does not meet the requirement of the $K(N - 1 + k)$ criterion, and it is the weak link in power system. For this kind of the electrical devices, the customers that cannot be served need more attention.

3.1. The Evaluation Indexes for the First Kind. For the devices that meet the requirement of the $K(N - 1 + k)$ criterion, the evaluation indexes of DNSA are as follows.

The f_1 is the amount of restorable loads in nonfault and out-of-service areas, and it is proportional to the short-term power failure:

$$f_1 = \sum_{i \in A} P_i, \quad (1)$$

where A is the collection of restorable nodes and P_i is the active power of the i th node.

The f_2 is the time of switching operation for service restoration and it represents the cost of restoration process:

$$f_2 = k, \quad (2)$$

where k is the time of switching operation.

The f_3 is the load rate and it describes the maximum load rate of the electrical device in distribution network:

$$f_3 = \max_{i \in B} \left(\frac{I_i}{I_{Ni}} \right), \quad (3)$$

where I_i is the current at the i th feeder; I_{Ni} is the rated current of the i th feeder; B is the collection of feeders.

The f_4 is the power loss of the power grid:

$$f_4 = \sum_{i \in B} P_{i\text{loss}}, \quad (4)$$

where $P_{i\text{loss}}$ is the i th feeder power loss.

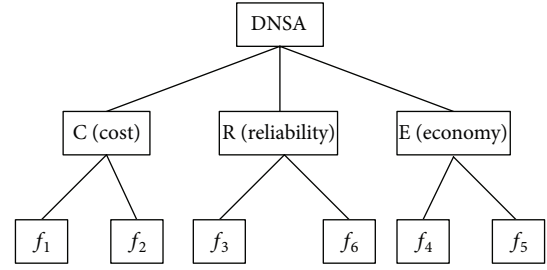


FIGURE 1: The hierarchy model of the first kind.

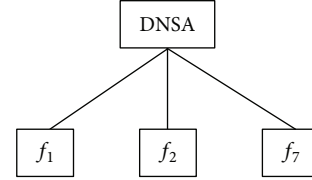


FIGURE 2: The hierarchy model of the second kind.

The f_5 is the lowest bus voltage in the distribution network after service restoration. For the quality of power supply, the f_5 should be as high as possible:

$$f_5 = \min_{i \in \Omega} (V_i), \quad (5)$$

where V_i is the voltage of the i th bus and Ω is the collection of the buses.

The f_6 is the number of the feasible restoration schemes:

$$f_6 = K, \quad (6)$$

where K is the number of the feasible restoration schemes.

According to the indexes above, the f_1 and f_2 are cost type index, and the $f_3, f_4, f_5,$ and f_6 are benefit type index. The smaller index value of cost type is better, and the larger index value of cost type is better.

The analytic hierarchy process (AHP) [15] is applied to determine the weight of each index. The f_1 and f_2 are cost index. The f_3 and f_6 are reliability index. The f_4 and f_5 are economy index. The hierarchy model is shown as Figure 1.

3.2. The Evaluation Indexes for the Second Kind. For these devices that do not meet the requirement of the $K(N - 1 + k)$ criterion, the situation of power supply is the main concern. The $f_1, f_2,$ and f_7 are used to evaluate the security of distribution network, and they are cost type index.

The f_7 is the amount of unrecovered loads in nonfault and out-of-service areas:

$$f_7 = \sum_{i \in A'} P_i, \quad (7)$$

where A' is the collection of unrecovered buses.

The hierarchy model is shown as Figure 2.

4. The Evaluation Method for DNSA

The rank preference optimal ordering method (RPOO) [16] was introduced for DNSA. On the multiobjective decision-making method, the RPOO is simple and practical, and it can get the obvious differences among alternatives.

4.1. *The Rank Preference Optimal Ordering Method.* The m schemes are needed to be evaluated, and each scheme has n evaluation indexes.

The evaluation matrix $R(m \times n)$ is as follows:

$$R = [f_{ij}]_{m \times n}, \tag{8}$$

where f_{ij} is the actual value of the j th index related to the i th evaluation scheme.

The index can be divided into two categories, the benefit type and the cost type. The higher the index value of the benefit type is, the better it is. And the cost type is just opposite. The h intervals are formed from the maximum index value to the minimum index value. The h is larger, and the different index value is easier to fall into the different intervals.

The h intervals of the benefit type are divided as follows:

$$\begin{matrix} 1 & \left[\min_j \{f_{ij}\}, \min_j \{f_{ij}\} + \frac{1}{h}d_j \right) \\ \vdots & \vdots \\ k & \left[\min_j \{f_{ij}\} + \frac{k-1}{h}d_j, \min_j \{f_{ij}\} + \frac{k}{h}d_j \right) \\ \vdots & \vdots \\ n & \left[\min_j \{f_{ij}\} + \frac{h-1}{h}d_j, \max_j \{f_{ij}\} \right]. \end{matrix} \tag{9}$$

The h intervals of the cost type are divided as follows:

$$\begin{matrix} 1 & \left[\min_j \{f_{ij}\} + \frac{h-1}{h}d_j, \max_j \{f_{ij}\} \right) \\ \vdots & \vdots \\ k & \left[\min_j \{f_{ij}\} + \frac{k-1}{h}d_j, \min_j \{f_{ij}\} + \frac{k}{h}d_j \right) \\ \vdots & \vdots \\ n & \left[\min_j \{f_{ij}\}, \min_j \{f_{ij}\} + \frac{1}{h}d_j \right). \end{matrix} \tag{10}$$

The d_j is defined as follows:

$$d_j = \max_j \{f_{ij}\} - \min_j \{f_{ij}\}, \tag{11}$$

where the $\max_j \{f_{ij}\}$ and $\min_j \{f_{ij}\}$ denote the maximum and minimum value of the j th index related to all schemes. The d_j is the difference between the maximum and minimum value of the j th index.

The G is the index rank matrix and is defined as follows:

$$G = [g_{ij}]_{m \times n}, \tag{12}$$

where the g_{ij} is the rank value of the j th index related to the i th evaluation scheme.

The index optimal number, a_{ilj} , describes the dominant degree which is the comparison of the j th index related to the i th scheme and the j th index related to the l th scheme, and it is defined as follows:

$$a_{ilj} = \begin{cases} 1 & g_{ij} - g_{lj} = h - 1 \\ \vdots & \vdots \\ \frac{h-1}{2(h-1)-k} & g_{ij} - g_{lj} = k \\ \vdots & \vdots \\ \frac{h-1}{2(h-1)-1} & g_{ij} - g_{lj} = 1 \\ 0.5 & g_{ij} = g_{lj} \\ 0 & \text{other.} \end{cases} \tag{13}$$

To solve the practical multiobjective decision-making problem, the relative importance of each index needs to be taken into account. The weight of index is as follows:

$$\sum_{j=1}^n w_j = 1, \tag{14}$$

where the w_j is the weight of the j th index and $w_j \in [0, 1]$.

The optimal number, a_{il} , describes the dominant degree which is the comparison of the i th scheme and the l th scheme, and it is defined as follows:

$$a_{il} = \begin{cases} \sum_{j=1}^n w_j a_{ilj} & i \neq l, \\ 0 & i = l. \end{cases} \tag{15}$$

The total optimal number (TON) describes the dominant degree which is the comparison of the i th scheme and the other schemes. Larger TON is better. The TON is defined as follows:

$$T_i = \sum_{l=1}^m a_{il}, \tag{16}$$

where T_i is the TON of the i th scheme.

4.2. *The Steps of the RPOO.* The steps of the RPOO method are shown as follows.

Step 1. Calculate the index values of each scheme, and obtain the evaluation matrix.

Step 2. Determine the weights and the h , and get the index rank matrix.

Step 3. According to the index rank matrix, get the index optimal number.

Step 4. According to the index optimal number and the weight, get the optimal number.

Step 5. Calculate the TON of each scheme according to the optimal number.

4.3. *The Steps of the DNSA.* The steps of the DNSA are shown as follows.

Step 1. Establish the contingency set, and obtain the weights of the evaluation index based on the AHP.

Step 2. Assume that the electrical devices in the contingency set are fault one by one, and get, respectively, the feasible restoration scheme and the best restoration scheme by the service restoration algorithm [17].

The paper [17] used the nondominated sorting genetic algorithm-II to solve the service restoration. The feasible restoration scheme is the Pareto optimal solution, and the best restoration scheme is got by the preference knowledge described in the paper [17].

Step 3. Calculate the index values of DNSA based on the best restoration scheme and the feasible restoration scheme.

Step 4. According to the $K(N - 1 + k)$ criterion, the electrical devices in the contingency set are classified into two kinds. The first kind meets the requirement of the $K(N - 1 + k)$ criterion. The second kind does not meet the requirement of the $K(N - 1 + k)$ criterion.

Step 5. Evaluate the two kinds of electrical equipment, respectively, by using the RPOO.

5. Case Studying

In order to verify the performance of the proposed method, a model [18] as Figure 3 is used. The solid line represents the on state of the switch, and the dashed line represents the off state of the switch. The system holds 16 feeders, and each feeder has switch. Its rated voltage is 23 kV. It is assumed that the rated current of each feeder is 700 A. The sum of the loads is $28.7 + j17.3$ MVA. With the operation condition shown in Figure 3, the network loss is 511.44 kW. And the current of feeders is showed as follows: 1-4 (394.13 A), 2-8 (691.61 A), and 3-13 (223.53 A).

It is assumed that the contingency set comprises all 16 feeders. And the h is 100.

The weight of each index is obtained by the method of AHP. The judgment matrix and the weights of the second kind are shown in Table 1.

The judgment matrixes and the weights of the first kind are shown in Tables 2, 3, 4, 5, and 6.

It is assumed that the electrical devices in the contingency set are fault one by one, and the restoration algorithm [17] is used to get the corresponding solutions. According to the $K(N - 1 + k)$ criterion, the electrical devices in the contingency set were classified into two kinds. And the RPOO was introduced to evaluate the damage effect of the two kinds.

Table 7 shows the second kind. This kind does not meet the requirement of the $K(N - 1 + k)$ criterion. When a fault occurs on 9-12, there are no switches connecting with the nonfault and out-of-service areas, node 12, so the load of node 12 cannot be transformed to other feeders. When one of 4-5, 13-14, and 2-8 is fault, there is not enough usable amount of

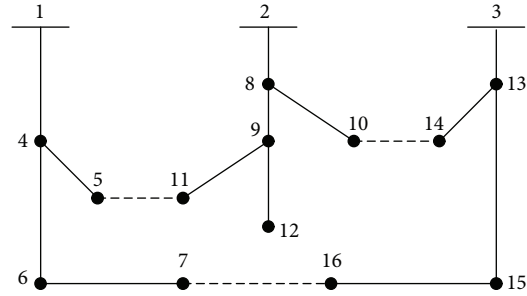


FIGURE 3: IEEE distribution system diagram with 16 feeders.

TABLE 1: Judgment matrix and weight for the security analysis.

Security analysis	f_1	f_2	f_7	Weight
f_1	1	3	1/7	0.1549
f_2	1/3	1	1/9	0.0685
f_7	7	9	1	0.7766

TABLE 2: Judgment matrix for the security analysis.

Security analysis	C	E	R
C	1	3	1/5
E	1/3	1	3
R	5	1/3	1

TABLE 3: Judgment matrix for the cost.

Cost	f_1	f_2
f_1	1	1/3
f_2	3	1

TABLE 4: Judgment matrix for the economy.

Economy	f_4	f_5
f_4	1	5
f_5	1/5	1

TABLE 5: Judgment matrix for the reliability.

Reliability	f_3	f_6
f_3	1	3
f_6	1/3	1

TABLE 6: Weight for the security analysis.

Index	f_1	f_2	f_3	f_4	f_5	f_6
Weight	0.0748	0.2245	0.2762	0.2772	0.0554	0.0921

transmission capacity to transform the load of the nonfault and out-of-service areas. So, malfunction of these electrical devices reduces the reliability of power supply and should be taken seriously.

From Table 7 we can see that the fault of 2-8 causes the most negative impacts on the distribution network than the others. When 2-8 is fault, 9.6 MW loads are power failure

TABLE 7: The electrical devices of the second kind.

Electrical device	The best restoration scheme	f_1 /MW	f_2	f_7 /MW	TON
4-5	4-5	0	0	3	1.3787
	5-11				
	7-16				
	10-14				
2-8	2-8	9.6	4	4	0.3883
	9-12				
	8-9				
	7-16				
9-12	5-11	0	0	4	0.8351
	7-16				
	10-14				
	9-12				
13-14	5-11	0	0	1	2.5825
	7-16				
	10-14				
	13-14				

TABLE 8: The electrical devices of the first kind.

Electrical device	The best restoration scheme	f_1 /MW	f_2	f_3	f_4 /kW	f_5	f_6	TON
1-4	1-4	8.5	1	0.9880	945.24	0.9348	3	2.2305
	5-11							
	10-14							
4-6	4-6	3.5	3	0.9125	551.52	0.9714	4	2.8580
	5-11							
	8-10							
6-7	6-7	1.5	3	0.9125	497.54	0.9714	3	3.8306
	5-11							
	8-10							
8-10	5-11	1	1	0.9125	483.86	0.9714	2	5.3212
	8-10							
	7-16							
8-9	4-6	10.1	3	0.9792	703.46	0.9578	2	1.6052
	8-9							
	10-14							
9-11	9-11	0.6	1	0.9574	493.15	0.9693	2	4.2470
	10-14							
	7-16							
3-13	9-11	5.1	3	0.9574	658.84	0.9662	2	2.1315
	10-14							
	3-13							
13-15	5-11	3.1	3	0.9125	539.82	0.9714	3	3.2484
	8-10							
	13-15							
15-16	5-11	2.1	3	0.9125	508.02	0.9714	3	3.4830
	8-10							
	15-16							

temporarily, and 4 MW loads cannot be restored. And the TON of the 2–8 is the smallest. So, the TON can reflect damage degree caused by the malfunction of the electrical devices, and the TON is in inverse proportion to the damage effect of the distribution network.

Table 8 shows the first kind. This kind meets the requirement of the $K(N - 1 + k)$ criterion.

Form the indexes shown in Table 8, the fault of 8-9 causes the most negative impacts on the distribution network than the others. When 8–10 is fault, the operation condition is better than the others. And the TON reveals the trend.

The TON can get the obvious differences among alternatives, and it can help engineers to find weak points of the distribution network.

6. Conclusion

The $K(N - 1 + k)$ criterion was proposed for distribution network security analysis, and it is suitable for the radial structure of distribution network. The RPOO was introduced to the multi-index decision-making, and it can get the obvious differences among alternatives. The total optimal number can reflect damage degree caused by the fault of electrical device in the contingency set. The validity and effectiveness of the proposed approach are verified with a numerical example. The proposed approach can point out the weakness of the distribution network and provide guidance for the distribution network transformation and the security defense.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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