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EVALUATION INDEX AND METHOD FOR NETWORKS STRENGTH AND RESILIENCE RESOURCE ALLOCATION TO AGAINST EXTREME DISASTERS

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ABSTRACT

The network strength and resilience resource allocation are the most important guarantees for the safe operation of distribution network, which also reflects the capability to resist disasters. To fully evaluate the network strength and resilience resource allocation, the evaluation indexes are proposed from perspectives of the grid robustness, emergency power supporting ability and failure repair capability. Meanwhile, an evaluation method is built to calculate the index weight by analytic hierarchy process-entropy method-grey relational analysis (AHP-EM- GRA), so as to overcome the impact caused by different physical significance and types of indexes. The result of case study indicates the validity and rationality of the proposed indexes and methods.

Keywords: network strength, resilience resource allocation, evaluation index, grey relational analysis, emergency power

1. INTRODUCTION

Since the increasing extreme disasters brought incalculable losses to distribution network, the network strength and resilience resource allocation have become important influence factors for distribution network to resist extreme disasters.

At present, the ability of distribution network to against disasters is mainly measured from the angle of vulnerability and resilience [1]. In order to identify the weak points of the power grid rapidly, reference [2] puts up an assessing model for power grid vulnerability, comprehensively considering the influence of system voltage stability and other factors. Reference [3] pays attention to the impact of protection devices on vulnerability of power grid while constructing the evaluation model to achieve a greater identification effectiveness and accuracy of vulnerability. In view of the resilience of power grid under extreme disasters, reference [4] puts forward an *N-1* safe, financial, scheduling optimized model that takes resilience space of transmission operation into account, and evaluates its economic benefits by applying to the actual interconnection system. Reference [5] comes up with a framework to evaluate the resilience of power grid under extreme conditions, and utilizes micro-grids to improve its resilience. The existing researches mainly put forward evaluation indexes from the perspective of operation rather than comprehensively evaluate the impact of network structure, resilience resource capacity and types on the anti-disaster ability of distribution network.

In this paper, evaluation indexes are proposed from aspects of network structure, resilience resource allocation capacity and types. To elaborate the advantages of combining method in data processing, three methods of analytic hierarchy process, entropy method and gray relational analysis are combined to calculate the index weight. Finally, an example of actual distribution network is studied to demonstrate the rationality and accuracy of the proposed indexes and methods.

2. EVALUATION INDEXES OF NETWORK STRENGTH AND RESILIENCE RESOURCE ALLOCATION

First grade indexes are proposed to reflect the level of the network strength and resilience resource allocation of the whole grid by analyzing their characteristics. Then second grade indexes are built by analyzing the characteristics of each first grade index, as shown in Fig 1.

2.1 Grid robustness (A_1)

Grid robustness is defined as the ability of the grid to maintain load operation through the grid structure. Compared with the existing researches, A_1 not only studies the connection between nodes and lines, but also analyzes the impact of grid supply capacity and failure probability of lines.

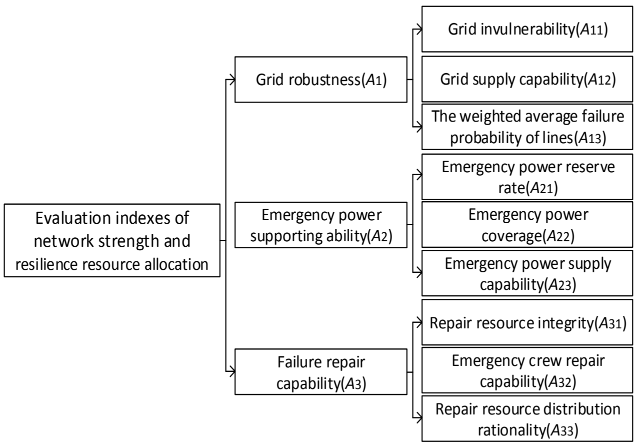

Fig 1 Evaluation indexes of distribution network

2.1.1 Grid invulnerability (A_{11})

The more the connection paths between any two nodes in the grid exist, the stronger the power supply capability between each other will be. Reference [6] uses natural connectivity to represent network invulnerability but ignores the importance of nodes. Therefore, grid invulnerability is defined from both natural connectivity and the degree of node importance. In addition, the nodes are subdivided into three levels according to their importance, and the weights are set to w_1, w_2 and w_3 respectively.

$$A_{11} = \ln(\frac{1}{N}\sum_{i=1}^{N} w_j e^{\xi_i}) \tag{1}$$

where N is the number of grid nodes. w_j(j=1,2,3) is the weight of node i. ξ_i represents the i-th eigenvalue of the adjacent matrix generated by the graph in order of node number.

2.1.2 Grid supply capability (A_{12})

In network graph G, path L of the graph is constituted by a series of edges which starting from one node and moving along the edge to another, whose path length l is the number of edges that the path passes through. The greater number of power supply paths from all power points (including the switchable standby power) to node i indicate the stronger power supply capability.

$$A_{12} = \frac{\sum_{i=1}^{N_1} w_1 L_i P_i}{\sum_{i=1}^{N} w_j L_i P_i} \tag{2}$$

where N_1 is the load number of first grade nodes. w_1 refers to the load weight of first grade nodes. L_i represents the number of supply paths from node i to the power. P_i is the node load power.

2.1.3 The weighted average failure probability of lines (A_{13})

Higher strength of the line decreases its failure probability in distribution network. Since important lines play a crucial role in the whole grid, the edge betweenness is introduced. The edge betweenness is the proportion of the number of lines passing through a certain side in the total number of shortest paths in the grid, reflecting the importance of corresponding lines.

$$A_{13} = \frac{k}{X}\sum_{x\in X}\frac{2\alpha_x}{N(N-1)}\lambda_x \tag{3}$$

where X is the total number of lines in distribution network. k is a constant term. λ_x refers to the failure probability of line x. α_x represents the number of edges passing through line x in the shortest path between any two nodes in the grid.

2.2 Emergency power supporting ability (A_2)

The feasible disposition of the emergency power is helpful to maintain the stable operation of distribution network.

2.2.1 Emergency power reserve rate (A_{21})

Emergency power reserve rate is the rate of all emergency power capacity to the total capacity of distribution network.

$$A_{21} = \frac{C_{SUM,ES}}{C_{SUM,DN}} \tag{4}$$

where $C_{SUM,ES}$ is the total capacity of emergency power. $C_{SUM,DN}$ is the total capacity of distribution network.

2.2.2 Emergency power coverage (A_{22})

Emergency power supply radius refers to the line length between the emergency power point and the farthest load it supplies. The large supply radius can strengthen the emergency power coverage.

$$A_{22} = \frac{\sum_{a\in f}\sum_{i=1}^{N_a} w_j P_i}{\sum_{i=1}^{N} w_j P_i} \tag{5}$$

where f represents the total number of emergency powers. N_a is the number of loads that can be provided within the supply radius of emergency power *a*.

2.2.3 Emergency power supply capability (A_{23})

Emergency power is primarily used to keep the power supply to critical loads, so the shorter the path length *l* between critical load nodes and emergency powers, the stronger the supporting capability to the distribution network.

$$A_{23} = \frac{1}{\frac{1}{N_1}\sum_{j=1}^{f}\sum_{i=1}^{N_1} l_{ij}} \tag{6}$$

where l_{ij} is the length of the path.

2.3 Failure repair capability (A_3)

After disaster, the roads, communication facilities and distribution lines will suffer different degrees of losses, so it becomes the primary task to promptly repair these components to ensure the security of the distribution network.

2.3.1 Repair resource integrity (A_{31})

Multiple equipment is required to repair the distribution network, therefore, the greater integrity of the repair resources means the stronger ability of distribution network to deal with disasters.

$$A_{31} = \frac{1}{Q}\sum_{q=1}^{Q}\frac{1}{u_q}\sum_{d=1}^{u_q}\frac{z_d}{b_d} \tag{7}$$

where *Q* is the number of types of repair resources. U_q refers to the type of equipment to be configured as required for type *q*. b_d is the quantity of equipment d to be configured as required. z_d ($z_d \le b_d$) represents the actual number of equipment *d* in the distribution network.

2.3.2 Emergency crew repair capability (A_{32})

In order to evaluate the ability of the emergency crew, the mean ability a_{dq} ($0 \le a_{dq} \le 1$) of them to operate equipment *d* in type *q* resources will be expressed.

$$A_{32} = \frac{1}{Q}\sum_{q=1}^{Q}\frac{1}{u_q}\sum_{d=1}^{u_q} a_{dq} \tag{8}$$

2.3.3 Repair resource distribution rationality (A_{33})

According to the repair demand of the distribution network, it will be beneficial to increase the repair efficiency by reasonable arrangement of the repair resources. The distribution rationality of the locations where the repair resources are stored in the distribution network is described by

$$A_{33} = \frac{1}{\sum_{x\in X}\lambda_x R_{x,\min}} \tag{9}$$

where $R_{x,min}$ is the shortest distance between line *x* and the nearby repair resources.

3. EVALUATION MODEL BASED ON AHP-EM-GRA

The first grade indexes are qualitative, so AHP is applied to compute their weights λ_i. The second grade indexes are quantitative , accordingly EM is applied to calculate their weights δ_{ij}. Furthermore, the reference number series *Y* is constituted by selecting optimal values of indexes before using GRA. The cost type index A_{13} is uniformly processed by subtraction, and the average method is used in dimensionless processing on the index data. Then, correlation degree r_{ij} of all indexes is calculated. AHP and EM results are calculated on the basis of formula (10) to obtain the entire second grade indexes weight φ_{ij}. Finally, the index weight γ_{ij} is calculated on the basis of formula (11) in combination with φ_{ij} and r_{ij}.

$$\varphi_{ij} = \sum_{i\in m}\sum_{j\in n}\lambda_i \delta_{ij} \tag{10}$$

$$\gamma_{ij} = \sigma_1\varphi_{ij} + \sigma_2 r_{ij} \tag{11}$$

where *m* is the number of first grade indexes. *n* represents the number of second grade indexes.

4. CASE STUDY

In this paper, the network structure and resilience resource allocation are analyzed based on two 10kV

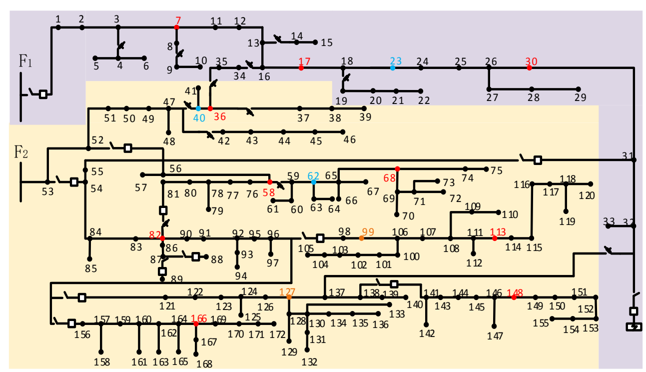

Fig 2 Network structure of F1 and F2

feeders (F_1 and F_2) as shown in Fig 2, where F_1 represents the upper part and F_2 represents the lower part.

The total capacity of F_1 is 2124kVA. The emergency power points are located at nodes 7, 17, 30, and each capacity is 4800kVA. The repair resource is located at node 23. The total capacity of F_2 is 11567 kVA. The emergency power points are located at nodes 36, 58, 68, 82, 99, 113, 127, 148, 166, and each capacity is 10000 kVA. The repair resources are located at nodes 40, 62, 99, and 127. The types of repair resources include on-the-spot detection equipment, emergency communication equipment, emergency transportation equipment, energy power security equipment, transportation and geotechnical repair equipment, etc. In addition, the constant term k is 100.

Firstly, calculate the index values through the index calculation method. Afterwards, the judgment matrix B= [1, 3, 2; 1/3, 1, 1/2; 1/2, 2, 1] is constructed by AHP to obtain the weights of first grade indexes. Secondly, calculate the weights of second grade indexes through EM in Table 1. Finally, calculate the correlation degree of all indexes through GRA, and calculate the combination weights as shown in Fig 3. According to Table 1 and Fig 3, scores of indexes and feeders are calculated as shown in Table 2.

Table 1. Indexes data and weights

Type	A_1			A_2			A_3		
	A_{11}	A_{12}	A_{13}	A_{21}	A_{22}	A_{23}	A_{31}	A_{32}	A_{33}
F_1	4.84	0.91	0.38	6.78	1.29	0.48	0.90	0.94	1.45
F_2	5.54	0.92	0.15	7.78	1.22	0.37	0.90	0.94	1.59
AHP		0.54			0.16			0.30	
EM	0.23	0.28	0.49	0.20	0.34	0.46	0.16	0.33	0.51

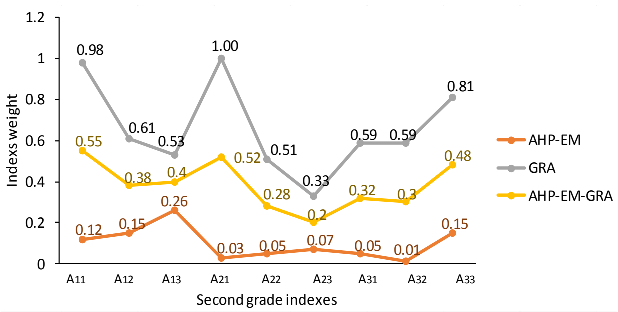

Fig 3 Second grade indexes weight

Table 2. First grade indexes and feeders scores

First grade indexes	Second grade indexes	Indexes scores		Total scores	
		F_1	F_2	F_1	F_2
A_1	A_{11}, A_{12}, A_{13}	2.86	3.34	8.10	9.13
A_2	A_{21}, A_{22}, A_{23}	3.99	4.46		
A_3	A_{31}, A_{32}, A_{33}	1.27	1.33		

The results in Fig 3 show that GRA and AHP-EM have disadvantages such as GRA ignores the subjective and objective influences, and AHP-EM neglects internal connection of data, while the combined AHP-EM-GRA can avoid the index volatility and make the result more reasonable. In addition, the results in Table 2 show that the ability of F_2 to handle disasters is stronger than that of F_1, because F_2 is better in terms of grid robustness, emergency power supporting ability and failure repair capability. Among them, grid robustness, emergency power reserve rate, and repair resource distribution rationality of F_2 play a key role in resisting disasters, and the line weighted average failure probability is lower than that of F_1.

5. CONCLUSIONS

In this paper, the evaluation indexes based on the network strength and resilience resource allocation are presented. The combined method of AHP-EM-GRA is used to evaluate two feeders. We draw the following conclusions: 1) The grid invulnerability, emergency power reserve rate and the repair resource distribution rationality are the most critical factors that can affect the ability of distribution network to withstand extreme disasters. 2) The combination of AHP-EM-GRA can reflect the volatility and internal connection of data. 3) Higher network strength and rational allocation of resilience resources are helpful to improve the anti-disaster capability of distribution network.

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