Line Differentiation Planning of Distribution Network Considering Weaknesses Assessment of Resilience

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Abstract: Differentiation planning reasonably has instruction function for strengthening the construction of the distribution network structure with pertinence, as well as improving the ability of withstanding natural disasters. A method of differentiation planning of distribution network structure was proposed, based on its weaknesses. Aimed at the situations of natural disasters and important consumers, network reconfiguration with the objective to minimize the load shedding was used to search for the post-disaster structure. After that, the assessment of economy and resilience index were applied with planning, the optimal planning was determined with the operation method of technique for order preference by similarity to an ideal solution (TOPSIS). By the analysis of example, the resilience assessment of structure weakness plays a conductive role of differentiation planning on distribution network.

Key Words: Weakness, Distribution Network, Resilience Assessment, Differentiation Planning

1 INTRODUCTION

Severe weather events have been occurring more frequently in China in recent years, each of which had a serious impact on stable operation of distribution network. The resulting great amount of economic loss and large-scale failure have raised widespread concerns to the ability of disaster response. Distribution network, as the “capillary” of power system, is closely related to consumers, which is responsible for power distribution. Therefore, in some degree, to strengthen the capability of disaster response can reduce the power outages, as well as economic losses.

Compared with transmission network, distribution network has more lines, more complicated architecture. With these reasons, to reinforce distribution network is of great impendency. To assess the ability of response to natural disasters, some scientific researchers put forward resilience to describe it recently, which is a newly concept in distribution network.

Distribution network planning is known as a non-linear, multi-objective optimization problem, the objective function and intelligent algorithms are more and more comprehensive and complex under the further research, a cost-based objective function to be minimized is employed in most of the planning models, like reference [1-3]. In addition, reliability is taken into consideration as another prevailing objective, as reference [4] and [5] represented. Owing to higher-frequency occurrence of disasters recently, more attentions are paid to the anti-disaster ability of power system. An anti-disaster planning model of transmission network was introduced in [6]. The segment strengthening schemes of lines across different meteorological conditions were determined in [7]. Under recent researches, resilience of power system is proposed in [8-10], and it is worthy of deeply researching. Therefore, this article intends to recognize the weaknesses of distribution network, and undertake the line differentiation planning with the basic of assessment of both economy and resilience under the influence of natural disasters.

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2 WEAKNESSES RECOGNITION

Considering more and more natural disasters occurred, it is necessary to analyze the weaknesses of architecture in distribution network, which is very conductive to do differentiation planning among all the distribution lines. The weaknesses of the network should be regarded as the key consideration of planning, to ensure the reliable operation of weaknesses under the influence of natural disaster, which is helpful to guarantee the power supply of load. The identification of lines weaknesses needs to be considered not only from the view of the network topology, but also from the lines electrical characteristics. In this article, therefore, the calculation and analysis propose mainly through the following aspects to determine the value of the weakness index can be expressed as

$$T_l = \beta_l \left(\alpha_l G_l + B_l + L_l \right) \quad (1)$$

where G_l is the power of branch, B_l is line betweenness, L_l is load grade of distribution line, α_l is the ratio of the active power and apparent power, and β_l is the percentage of the key loads contained in lines of the total loads. Specific calculation of various indexes are given as follows. According to the value and ranking of these indexes, the higher value represents the greater role they played in the recovery process of distribution network.

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When one failure of distribution line results in power outage, load recovery is the most basic goal. When the fault occurs, P_{total} is assumed to express the total load power to be recovered

$$P_{\text{total}} = \sum_{i \in M_{\text{total}}} P_{Li} \tag{2}$$

where i is the number of node in the distribution network, M_{total} is the set of all connected nodes after the failure line putting into operation, and P_{Li} is the maximum active power of node i.

When the branch l is disconnected from the network topology, the load power $P_{\text{total-}l}$ is given by

$$P_{\text{total-}l} = \sum_{i \in M_{\text{total-}l}} P_{Li} \tag{3}$$

where $M_{\text{total-}l}$ is a set of nodes which are connected in the topology except for line l.

The power loss due to the fault of line l is defined as the branch power G_l

$$G_l = P_{\text{total}} - P_{\text{total-}l} \tag{4}$$

As we seen from the formula (3), the greater G_l indicates this line of more importance, and also of more effectivity in fault recovery process.

Line betweenness represents the important extent of line l in the distribution network topology, defined as

$$B_l = \frac{\sum_{i \neq j \in V} N_{ij}(l)}{\sum_{i \neq j \in V} N_{ij}} \tag{5}$$

where $\sum_{i \neq j \in V} N_{ij}(l)$ is the number of the coincidences between the shortest path of any two points and line l in the topology, $\sum_{i \neq j \in V} N_{ij}$ is the total number of the shortest paths between any two points in whole network. The importance of line in the network topology can be seen from this index, which indirectly reflects significance of each line in the topology during the fault recovery.

The load grade of line reflects the important level in the current operating state, and is defined as

$$L_l = \left| \frac{P_l}{P_{l\max}} \right| \tag{6}$$

where P_l is the current transmission power of line l, $P_{l\max}$ is the maximum power. If the line does not exceed the limit, then $0 \le L_l \le 1$.

Recognized weaknesses of the distribution network lay the foundation for the analysis of line differentiation planning and assessment.

3 PLANNING METHOD

Fig 1 shows the flowchart of differentiation planning of distribution network lines.

With the ranking of lines according to the weakness index, differentiation planning schemes can be achieved as the Table 1 proposed.

3.1 Economic Assessment

The cost of investment needed is different from the different planning schemes. With the in-depth analysis of planning schemes, it is possible to achieve greater benefits with smaller investment costs. The income increment cost increment evaluation method (abbreviation as iB/C) is used to determine the economic optimal planning scheme.

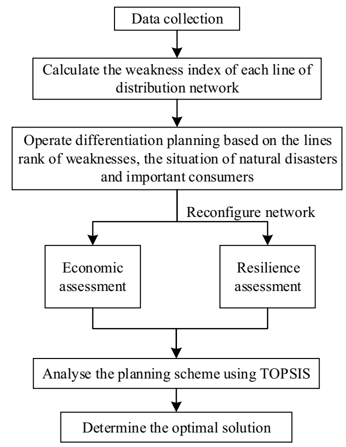

Fig 1. Flowchart of the differentiation planning

Table1. Differential upgrade planning scheme

Planning Scheme	Line including	Number
Plan 1	first ranking line	1
Plan 2	ranking first two line	2
···		···
Plan *n*	all the ranking line	*n*

The investment cost C is defined as comprehensive cost of planning measures, including direct benefits B_1 and indirect benefits B_2. Direct benefits include important load security gains, general load security gains, line loss reduction and emergency investment, denoted as B_{11}, B_{12}, B_{13}, B_{14} respectively. Indirect benefits include social salvage charges, important consumers compensation and other social benefits.

$$B = B_1 + B_2 = B_{11} + B_{12} + B_{13} + B_{14} + B_2 \tag{7}$$

$$B_{11} = (\varepsilon_2 - \varepsilon_1) L_1 t_1 + (\varepsilon_2 - \varepsilon_0) L_1 t_1 \tag{8}$$

$$B_{12} = (\varepsilon_2 - \varepsilon_1) L_2 t_2 + (\varepsilon_2 - \varepsilon_0) L_2 t_2 \tag{9}$$

where ε_0, ε_1, ε_2 is generating cost, generation sale price, electricity market price respectively, L_1 and L_2 are the number of important loads and general loads, respectively, t_1 and t_2 are the reduction of outage time of loads mentioned above under disasters, respectively. In addition, the default of B_{14} is considered to be equal to the investment without differentiation planning.

Define the income increment cost increment index Q_{iBC} as the ratio of the income and cost increment of differentiation planning. The original network scheme and differentiation planning schemes are listed, and the income and cost of each scheme can be calculated. The larger value represents the better economy of differentiation planning scheme.

3.2 Modeling

According to the consumers' grade classification based on their categories, network reconfiguration with the objective to minimize the load shedding is employed with the certain load capacity and location of existing substation. Network reconfiguration mathematical model is as follows

$$\begin{cases} \min \Delta L_{\Sigma} = \sum_{j\in V} \zeta_j \Delta L_j \\ s.t. \quad V_{\min} \le V_i \le V_{\max} \\ \qquad S_{ij} \le S_{ij\max} \\ \qquad \phi(x) = 0 \end{cases} \tag{10}$$

where ΔL_j expresses the load shedding of line j; ζ_j is the load weight coefficient; ΔL_{Σ} is load shedding considering the weighted loads; i indicates the selected node, $V_{\max}$ and $V_{\min}$ are the upper and lower limits of node voltage respectively, S_{ij} stands for the flow between two nodes, $S_{ij\max}$ is the maximum of flow allowed.

The value of ζ_j is determined according to the important load grade. The more important load is, the greater value becomes. Besides the value, it is ruled that the minimum load's product of node power and weight coefficient must be greater than the maximum load's product, considering the unreasonable recovery of load unbalancing when selecting the weight coefficient.

3.3 Resilience Assessment

Resilience assessment of distribution system mainly analyzed from the following three aspects:

1) The load recovery completion of distribution network outage recovery process under natural disasters;

2) Emergency repair capacity of Grid Company and emergency response capacity of social infrastructure;

3) The outage loss of consumers.

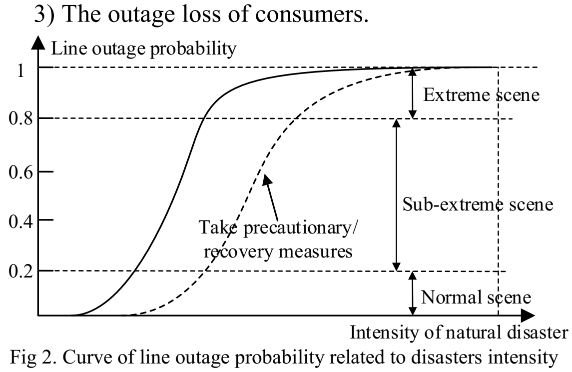

Fig 2. Curve of line outage probability related to disasters intensity

According to the historical data of the studied area, it can be included that the outage probability of lines relates to the frequency and impact of the meteorological conditions to some extent. Divide line outage probability into three levels as [0,0.2], [0.2,0.8] and [0.8,1]. The three levels correspond to the normal scene, sub-extreme scene and extreme scene respectively, as Figure 1 depicted. The occurrence probability of the three scenarios are also different. Taking these factors into consideration, the meteorological disasters influence on distribution lines can be analyzed more objectively. In addition, the analyses of the load grade of important consumers are appropriately useful for the resilience assessment.

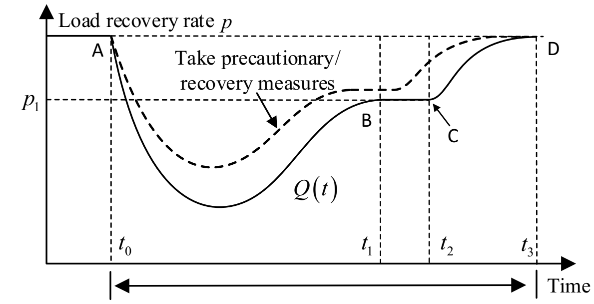

Fig 3. Load recovery curve of distribution network in natural disasters

Resilience of distribution network is based on the view of load protection. So the load recovery probability is selected as the ordinate of responding curve under disasters influence. The curve is shown on Figure 3, where t_0, t_1 is the occurrence time of disasters and recovery time of network itself, t_1~t_2 is the time waiting for social emergency aid, t_3 is the end of recovery, $Q(t)$ is the approximate function of load recovery probability.

With the collecting of node voltage in distribution network at the interval time, we can conclude the relation curve of load recovery probability and time under the influence of natural disasters. Based on this curve, the load recovery index S can be described as

$$S = \frac{1}{t_1 - t_0} \int_{t_0}^{t_1} Q(t)\,dt \tag{11}$$

Formula (8) indicates that with the higher value of S, the capacity to recover to normal state is greater on its own recovery mode, which reflects the adaptability and ability to the disasters respond under fault conditions to a certain extent.

Outage cost can intuitively reflect the impact of the distribution network under meteorological disasters on the economic level. It also reflects the inseparable relationship between its resilience and economy. Therefore, calculate the outage cost of consumers affected by natural disasters, denoted as C, and add it to resilience assessment index of distribution network.

At the same time, assess the abilities of emergency aid of regional Grid Company and the coordination ability of social infrastructure, the assessment value denoted as

$$N = \frac{\lambda_1}{\int_{t_2}^{t_3} l_{CD}\left[1 - Q(t)\right] dt} + \frac{\lambda_2}{(1-p_1)(t_2 - t_1)} \tag{12}$$

where λ_1、λ_2 is weight coefficient, l_{CD} is the distance between the node C and D. The greater value of N reflects the shorter emergency response time and the higher operated efficiency.

These abilities include organizational and command ability, operational efficiency of aid, communication ability, transportation ability, medical aid ability and so on. The strength of such more abilities may impact the duration of responding time after disasters more or less, which cannot be ignored in the total recovery process. In Fig.3, the time t_3-t_1 represents the strength of these abilities, including the emergency response time $t_1 \sim t_2$ and emergency operation time $t_2 \sim t_3$.

With the appropriately weighted to the indexes mentioned above and the analysis of capacity margin of each line, the resilience index can be included as

$$R=\sum_{l=1}^{n} \eta_l \cdot \frac{1}{n} \cdot \sum_{i \in \Omega} f\left(S_i, C_i, N_i\right) \tag{13}$$

Where η is capacity margin, n is the number of total lines, Ω is the set of district of distribution network.

The assessment of economy and resilience on distribution network planning belongs to a problem of multi-objective optimization, which cannot be optimal at the same time. So the method called technique for order preference by similarity to ideal solution (TOPSIS) is chosen to deal with this problem. Obtain optimal solution with the analysis of the assessment value of planning schemes. Decision-making process shows as follows

1) Normalize the index value

The objective function is $f=\left[Q_{iBC}, R\right]$, formula (14) is the normalization formula.

$$a_{i,j}=\frac{A_{i,j}}{\sqrt{\sum_{k=1}^{n} A_{k,j}^{2}}} \tag{14}$$

where $A_{i,j}$ represents the j th objective value of i th solution, n is the number of objective.

2) Calculate the virtual optimal solution J^+, defined as the optimal value of each objective, and virtual worst solution J^-, defined as the worst value.

$$J^+=\left[j_1^+, j_2^+, \cdots \quad \right], \quad \left[\quad \cdots \quad \right] \tag{15}$$

3) Compute the Hamming distance of each solution with optimal solution, also with the worst solution.

$$J_i^+=\sqrt{\sum_{j=1}^{n}\left(a_{i,j}-j_j^+\right)^2}, J_i^-=\sqrt{\sum_{j=1}^{n}\left(a_{i,j}-j_j^-\right)^2} \tag{16}$$

4) Calculate the closeness of each solution with virtual optimal solution, described as M_i

$$M_i=\frac{J_i^-}{\left(J_i^+ + J_i^-\right)} \tag{17}$$

where $M_i \in (0,1)$. If the value is greater, the solution is nearer to the optimal solution namely. The nearest solution will be determined to be the final solution of planning scheme.

3.4 Algorithm

The improved Harmony Search Algorithm (IHSA) is used to solve the problem of distribution network fault recovery.

HSA is a heuristic global optimization algorithm, with each note corresponding to each variable, wonderful harmonies corresponding to the global optimal value, music evaluation criteria corresponding to the objective function. Compared with other intelligence algorithms, HSA has several benefits, such as simple optimization process, fast and easy to find the optimal solution. Optimization steps using HSA are summarized below.

Step1: Initialize the parameters of optimization problems and algorithm. Parameters of problem include objective function $f(x)$, variable x_i and its set x, number of variable N, the upper limit U_{xi} and lower limit L_{xi} of each variable. Parameters of algorithm include the size of Harmony Memory (HM) S_{HM}, dimensions of the solution, reference probability of HM R_{HM}, adjust probability R_{PA}, max iteration times N_I and termination conditions.

Step2: Initialize HM. Initial solutions which generated randomly are stored in HM, the objective function value $f(x)$ of each solution is calculated.

Step3: Generate new solution. Choose a random number r_1, if $r_1 < R_{HM}$, then, select a variable in HM, otherwise select a numerical value outside HM randomly. If the value is selected in HM, select another random number r_2. And if $r_2 < R_{PA}$, disturb this value with the disturbance quantity of b_w. The new solution is formed according to the above rules of each variable.

Step4: Update HM. If the new solution is better than the worst solution in HM, then replace the worst solution and store in HM.

Step5: Determine whether the termination condition is satisfied. If satisfied, terminate the circulation of algorithm; otherwise, repeat step3 and step4.

Concluded from steps above, HSA select the new solution with a larger probability R_{HM}, and then disturb it with a smaller probability R_{PA}, so the value of R_{HM} and R_{PA} have a direct impact on the diversity of new particles in algorithm. With this concern, this article put forward the IHSA by assuming the value of R_{HM} and R_{PA} differently, so that value of them adaptively can change following the variation of particle information.

$$K_k=\begin{cases}\dfrac{\sqrt{\left(F_{k0}-\dfrac{1}{L-1}\sum_{i=1}^{L-1} F_{ki}\right)^2}}{F_{k\max}-F_{k\min}} & F_{k\max} \neq F_{k\min} \\ K_{k-1}\,\mathrm{rand}(\ ) & F_{k\max}=F_{k\min}\end{cases} \tag{18}$$

$$R_{\mathrm{HM}k}=R_{\mathrm{HM}\min}+K_k\left(R_{\mathrm{HM}\max}-R_{\mathrm{HM}\min}\right) \tag{19}$$

$$R_{\mathrm{PA}k}=R_{\mathrm{PA}\min}+K_k\left(R_{\mathrm{PA}\max}-R_{\mathrm{PA}\min}\right) \tag{20}$$

where $R_{\mathrm{HM}k}$ indicates the value of R_{HM} at iteration k, $R_{\mathrm{PA}k}$ is the value of R_{PA} at iteration k, R_{HMmax} and R_{HMmin} indicate the maximum and minimum of R_{HM} respectively, R_{PAmax} and R_{PAmin} are so as to R_{PA}, F_{k0} is the fitness value of new solution at iteration k, F_{ki} is the $f(x)$ of other solutions except new solution at iteration k, $F_{k\max}$ and $F_{k\min}$ represent the maximum and minimum of $f(x)$ respectively, rand() means a random number function.

As for intelligence algorithm, the confirmations of initial solution and new solution have a certain randomness, if using the maximum iterations as the criterion, it is not guaranteed that the result is optimal. To compare the global convergence of the algorithm, σ is used to define global optimization rate,

$$\sigma=\frac{R_B}{R_N}\times 100\% \tag{21}$$

where R_B is the times when optimal solution is equal to the global optimum, R_N is the running number of algorithm.

4 CASE STUDYS AND RESULTS

A schematic diagram of a 10kV distribution network area is in Fig 4. It has two substations, each with two feeders. Linetype, contact branches, number of nodes and lines are shown in legend, original ice thickness planning of lines are 10mm. Table 1 represents the power data of each node.

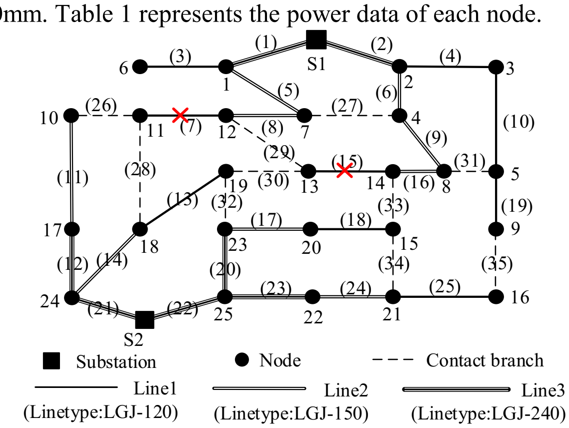

Fig 4. A schematic diagram of a 10kV distribution network area

Table1. Power Data of Each Node/kW

Node	Power	Node	Power	Node	Power
1	60	10	45	19	180
2	0	11	210	20	120
3	90	12	200	21	210
4	120	13	210	22	200
5	100	14	160	23	120
6	120	15	200	24	90
7	200	16	120	25	0
8	210	17	100		
9	90	18	240		

Recognize the weaknesses of lines in distribution network above, length of lines, weakness indexes and its ranking are given in Table 2.

Choose ice disaster to demonstrate as a typical natural disaster. The historical meteorological data and actual natural influence on distribution network lines are investigated to estimate the relations between line outage probability and ice force using the method of Monte-Carlo simulation, based on failure theoretical model of natural disasters. Ice force represents the designed ice thickness multiple to ordinary thickness planning. Relation Curve is in Fig 5.

Table2. Weakness Index and Length of Each Line

Line	T_l	Length/km	Line	T_l	Length/km
5	1.3031	1.214	11	0.6669	0.509
14	1.2887	0.784	3	0.6595	1.031
23	1.2229	1.034	7	0.6229	0.798
4	1.1237	0.534	16	0.6171	0.240
21	1.0015	0.557	15	0.5795	0.837
9	0.9737	0.737	19	0.5679	0.338
6	0.9479	1.158	10	0.4471	0.617
22	0.9246	1.202	18	0.4372	0.780
25	0.9149	0.522	24	0.3887	1.237
20	0.8929	0.426	12	0.2955	1.055
13	0.7987	0.716	17	0.2821	0.344
2	0.7941	0.509	8	0.2637	0.993
1	0.7611	0.954			

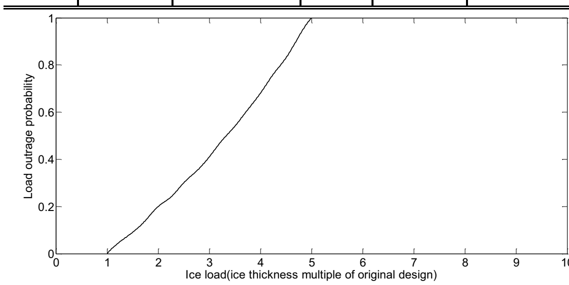

Fig 5. Relation Curve of line outage probabilities and ice force

Discussing the sub-extreme disaster situation as an example, select the line outage probability of 0.8 as the cut-off point. Randomly generated numbers are used to simulate the process. The generated number is between 0 and 1. If the number is bigger than 0.8, that means this line is outage in disasters, otherwise the line is normal running. Generate the number randomly, line 7 and line 15 are outage in the ice disaster, then using IHSA algorithm to recover distribution network fault. Parameters chosen here are $R_{\mathrm{HM}}=8$, $R_{\mathrm{HMmin}}=0.7$, $R_{\mathrm{HMmax}}=0.9$ and $N_I=300$. The default of load weight is 1. The network schematic diagram after reconfiguration is proposed in Fig 6.

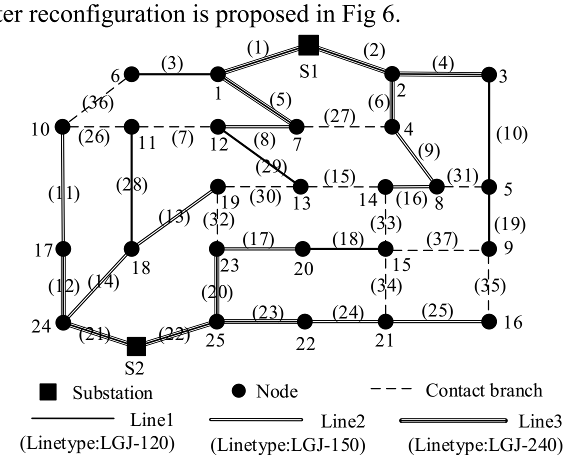

Fig 6. A schematic diagram of a distribution network area after reconfiguration

The running number is 100, and its optimal value distribution shown in Fig 7. The worst solution is 144.7kW,

η is 30%, representing a better global optimization capability.

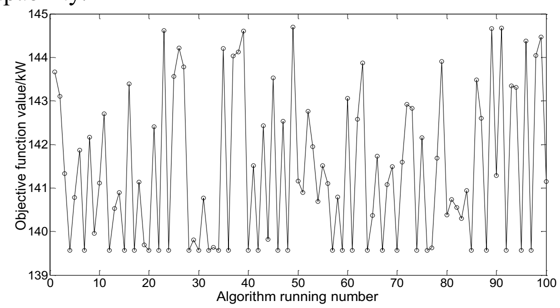

Fig 7. Distribution of IHSA algorithm optimal value

Based on the planning analysis above, plan1 to plan 32 can be achieved. Then assess the index of economy and resilience of each planning scheme respectively, each index value is displayed in Fig 8. Comprehensive cost of each planning scheme are listed in Table 3.

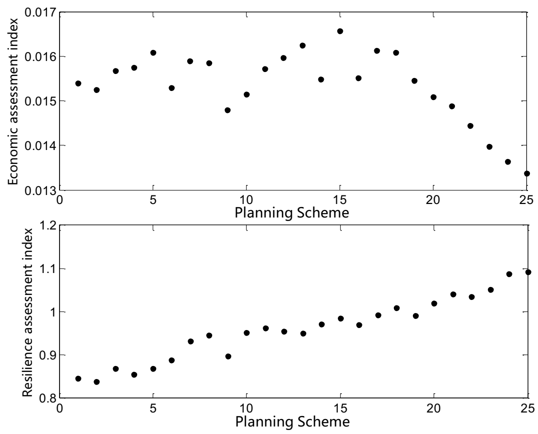

Fig 8. Economic and resilience index value of each scheme

Table3. Comprehensive Cost of Each Planning Scheme

Planning Scheme	Comprehensive Cost per km
Line expansion of LGJ-240	80 thousand yuan
Line expansion of LGJ-150	60 thousand yuan
Strengthen anti-ice thickness of 20mm	1000 thousand yuan
Strengthen anti-ice thickness of 30mm	2000 thousand yuan
Strengthen anti-ice thickness of 40mm	3500 thousand yuan
Construct the contact switching station and its ancillary equipment	100 thousand yuan per unit

After standardization, virtual optimal and worst solution is [0.21563,0.22696] and [0.17412,0.17406], the maximum of M_i is 0.73051 when i=18. That is to say, the plan 18 are determined to be the optimal solution. Line 5, 4, 6 alter to LGJ-240; line 14, 25, 13, 7 alter to LGJ-150; Strengthen the anti-ice thickness of 30mm of line 5, 23, 21, 4, 6, 22, 20, 2, 1; Strengthen the anti-ice thickness of 20mm of line 14, 9, 25, 13, 11, 3, 16, 15; construct the contact switching station at position of line 36 and 37 shown in Fig 6. With the planning scheme above, the ability of responding to natural disasters can be improved effectively.

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