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Power grid security risk assessment based on the comprehensive element influence index

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Abstract. Security risk assessment is of great significance to improve the security operation capability and prevent blackouts of a power system. To overcome the shortcomings of existing security risk assessment methods for component differences, a security risk assessment method based on component comprehensive influence is proposed. Considering flow transferring, the complex network theory and entropy theory are applied to setting up the comprehensive influence index of components. Taking into account the correlation between indicators, the AHP-Cantile weighting method is used to obtain the overall comprehensive severity index. The simulation results of IEEE 30-bus system show that the proposed method can identify N-1 and N-k fault risk reasonably and effectively.

1. Introduction

In recent years, with the increasing complexity of power system and the growth of load demand, blackouts occur frequently [1]. By analyzing several blackouts, it is found that if initial fault set and key links in the known cascading fault sequence can be effectively identified, then corresponding control measures will be taken according to the importance of fault components to minimize the damage of the fault [2,3]. Therefore, how to identify the key components in system and to take more comprehensive and reasonable assessment on a system, are of great significance to prevent the occurrence of blackouts.

Risk assessment [4] is an assessment method considering both the possibility and severity of accidents, and is widely used in power grid security assessment. At present, there are abundant researches on power system security risk assessment both at home and abroad. Literature [5,6] summarizes the state of the art in the methodologies for performing risk assessment of cascading outages caused and proposed presently available tools that deal with prediction of cascading failure events. Literature [7] Starting from system uncertainties, set up a risk assessment model with fuzzy failure rate and fuzzy severity. This model takes into account the randomness of accident risks, but it only measures the accident severity from the operating state of a system, and does not reflect the differences between important components, and can not describe the severity of a system after failure comprehensively. Reference [8] introduces the electrical mediator into the severity model, establishes a component structure importance model, amending the traditional severity model. However, the component importance evaluation index is single, which is not consistent with the multiple characteristics of component attributes. On this basis, a component importance model is established considering the structure and state influences in literature [9]. However, the component importance



index in this paper still does not consider the characteristics of reactive power compensation and power flow transferring uniformity. The accident severity model does not consider the correlation between the indicators and cannot truly reflect actual operation state in power grid.

Based on the above research, this paper proposed a new security risk assessment method based on component comprehensive influence. Firstly, considering flow transferring, complex network theory and entropy theory are applied to establish structure influence index and state influence index. which can make up for the deficiency of current risk assessment. Secondly, the sensitivity index of running state is introduced to overcome the shortage of traditional severity model that only considers operation margin. Thirdly, considering the relativity between indexes, a comprehensive severity model is constructed based on AHP-Cantille weighting method, which further improves the existing risk assessment index set. Finally, the IEEE30-bus system is adopted to verify the reasonability of component influence index, ranking N-1 fault risk, evaluating N-k fault step by step, and comparing this new model with the existing methods.

2. Comprehensive influence of components

2.1. Component structure influence

Based on the complex network theory [10], a structure influence index is established to characterize the differences of topological structure for different components.

In this paper, the branch structure influence index is constructed by branch electrical betweenness [11] and the weighted power flow transmission distribution factor.

$$B_e(l) = \sum_{i \in G, j \in L} \sqrt{\omega_i \omega_j} |I_{ij}(l)| \quad (1)$$

$$G(l) = \sum_{i \in G, j \in L} \sqrt{\mu_i \mu_j} \frac{\Delta P_l}{\Delta P_{ij}} \quad (2)$$

$$T^*(l) = \nu_l \times B_e^*(l) + \psi_l \times G^*(l) \quad (3)$$

Among them, $B_e(l)$ is the branch electrical betweenness; G, L is the set of generators and load nodes; ω_i is the rated capacity or actual output of the generator; ω_j is the actual value or peak value of the load; $I_{ij}(l)$ is the caused current of branch l after adding unit current between the load node pairs (i, j); $G(l)$ is the branch weighted power transfer distribution factor, reflecting the sensitivity of branch l to the change of system power; ΔP_{ij} is the variation of generator load node pair (i, j) power; ΔP_l is the variation of branch l . μ_i, μ_j represent load node fluctuation ability; $T^*(l)$ is the influence of branch structure, the greater the value, the greater possibilities to cause power flow transfer; $B_e^*(l), G^*(l)$ is the normalized branch electrical betweenness and weighted power flow transfer factor; ν_l and ψ_l are the weights of branch electrical betweenness and weighted power flow transfer distribution factor.

Considering the characteristics of reactive power compensation and the correlation between nodes and lines, the node electric betweenness is used to construct the node structure influence index.

$$B_e(n) = \sum_{i \in G, j \in L} \sqrt{\omega_i \omega_j} B_{e,ij}(n) \quad (4)$$

$$B_{e,ij}(n) = \begin{cases} \frac{1}{2} \sum_m |I_{ij}(m, n)| & n \neq i, j \\ 1 & n = i, j \end{cases} \quad (5)$$

$$G(n) = \sum_{i \in G, j \in L} \sqrt{\mu_i \mu_j} G_{ij}(n) \quad (6)$$

$$G_{ij}(n) = \begin{cases} \frac{1}{m} \sum_m \frac{\Delta P_{ij}(m, n)}{\Delta P_{ij}} & n \neq i, j \\ 1 & n = i, j \end{cases} \quad (7)$$

$$T^*(n) = \nu_n \times B_e^*(n) + \psi_n \times G^*(n) \quad (8)$$

Among them, node m is directly connected to node n ; $Be(n)$ is the node electrical betweenness; $G(n)$ is node weighted power flow transmission distribution factor; $T(n)$ is the node structure influence; $B_e^*(n)$ 、 $G^*(n)$ is the normalized node electrical betweenness and power transfer distribution factor; v_n and ψ_n are the weights for node electrical betweenness and node-weighted power transfer distribution factor.

2.2. Component state influence.

Based on entropy theory, the influence index of component state is established to characterize the influence of power flow redistribution process caused by failures.

In this paper, the power flow transfer entropy [12] is applied to constructing branch state influence index

$$H_T(l) = -\sum_1^{N_l} \beta_{mn}(l) \ln \beta_{mn}(l) \quad (9)$$

$$\beta_{mn}^l = \frac{\Delta P_{mn}(l)}{\Delta P(l)} \quad (10)$$

$$H_T'(l) = \frac{1}{H_T(l)} \quad (11)$$

Among them, $\Delta P_{mn}(l)$ is power flow variation caused by the disconnection of line l , $\Delta P(l)$ is the total power flow variation after the disconnection of line, $\beta_{mn}(l)$ is the proportion of power flow variation of line mn to the total value, $H_T(l)$ is the power flow transfer entropy after line L disconnected, and $H_T'(l)$ is the branch state influence index. The larger the $H_T'(l)$ is, the system power flow distribution will become more centralized after l -line goes wrong, which means the system is more likely to break down.

In this paper, the power distribution entropy caused by load fluctuation is used to construct the node state influence index.

$$H_D(n) = -\sum_1^{N_l} \alpha_{mn}(n) \ln \alpha_{mn}(n) \quad (12)$$

$$\alpha_{mn}^n = \frac{\Delta P_{mn}(n)}{\Delta P(n)} \quad (13)$$

$$H_D'(n) = \frac{1}{H_D(n)} \quad (14)$$

Among them, $\Delta P_{mn}(n)$ is power flow variation caused by node load fluctuation; $\Delta P(n)$ is the total variation caused by node n load fluctuation; $\alpha_{mn}(n)$ is the proportion of power flow variation of line mn to the total variation; $H_D(n)$ is the power flow distribution entropy caused by node n load fluctuation; and $H_D'(n)$ is the index of node state influence. The larger the $H_D'(n)$ is, the system power flow distribution will become more centralized after n -node load fluctuation, which means the system is more likely to break down.

2.3. Component comprehensive influence

According to the above indicators, the comprehensive influence index for branched is established:

$$Y(l) = \lambda_l \times T^*(l) + \tau_l \times H_T'(l) \quad (15)$$

Similarly, the comprehensive influence index for nodes should be like this:

$$Y(n) = \lambda_n \times T^*(n) + \tau_n \times H_D'(n) \quad (16)$$

Among them, λ_l 、 λ_n are the structural influence weights for branches and nodes, τ_l 、 τ_n are the state influence weights for branches and nodes. The greater the $Y(l)/Y(n)$ is, the flow transferring after branch l / node n breakouts is more likely to be concentrated in a few lines, the system cascading failure and voltage collapse are easier to occur.

3. A accident severity model

The severity of accident impact on system should be measured by state margin and state sensitivity of system under an accident. However, traditional severity model only considers the former, so this paper introduces the operational state sensitivity index.

3.1. severity index for power flow

The line overload offset is shown in Figure 1. For line L , its line overload offset function can be expressed as:

$$S_p(P_l) = \begin{cases} \frac{P_l - P_d}{P_{lim} - P_d} & P_l \geq P_d \\ 0 & P_l < P_d \end{cases} \quad (17)$$

Among them, P_l is the current active power of line l ; P_d is the overload risk warning threshold, generally taking 90% of line limit transmission capacity; P_{lim} is the overload risk threshold, taking the line limit transmission capacity.

For line L , its line state sensitivity can be expressed as:

$$S_b(P_l) = \begin{cases} \frac{P_l - P_l^0}{P_N} & P_l \geq P_l^0 \\ 0 & P_l < P_l^0 \end{cases} \quad (18)$$

Considering the comprehensive influence and the severity of operation state, the global power flow severity index is established as follows:

$$S(P) = \sum_1^N Y(l) \times (S_p(P_l) + S_b(P_l)) \quad (19)$$

In the formula, N represents the set of all lines in system, $S_p(P_l)$ and $S_b(P_l)$ are normalized overload offset and power flow sensitivity.

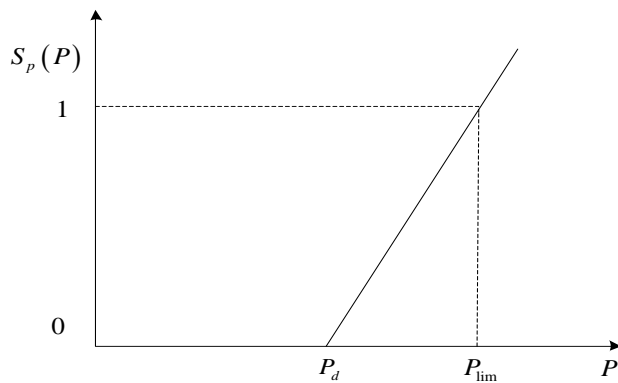


Figure 1. Overload status offset of lines.

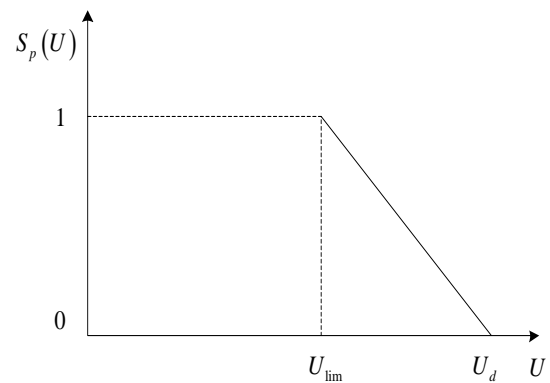


Figure 2. Low voltage state offset.

3.2. severity index for voltage

The node low voltage state offset is shown in Figure 2.

For node n , its low voltage state offset function can be expressed as:

$$S_p(U_n) = \begin{cases} 0 & U_n \geq U_d \\ \frac{U_d - U_n}{U_d - U_{lim}} & U_n < U_d \end{cases} \quad (20)$$

Among them, U_n is the current voltage amplitude of node n ; U_d is the low voltage risk warning threshold of node n , that is, the rated voltage value; U_{lim} is the low voltage risk threshold, generally taking 90% of the node rated voltage.

For node n , its voltage state sensitivity can be expressed as:

$$S_b(U_n) = \begin{cases} \frac{U_n^0 - U_n}{U_N} & U_n^0 \geq U_n \\ 0 & U_n^0 < U_n \end{cases} \quad (21)$$

Considering the comprehensive influence and the severity of operation state, the global voltage severity index is established as follows:

$$S(U) = \sum_1^M Y(n) \times (S_p(U_n)' + S_b(U_n)') \quad (22)$$

Among them, M is the set of all nodes in system, $S_p(U_n)'$ and $S_b(U_n)'$ are normalized low voltage offset and voltage sensitivity of node n .

3.3. severity index for load loss

Considering the load type and importance, the severity function of load loss is established:

$$S_{load} = \begin{cases} \frac{\eta}{\eta_{lim}} & \eta < \eta_{lim} \\ 1 & \eta \geq \eta_{lim} \end{cases} \quad (23)$$

$$\eta = \frac{\sum_{i \in L} \varepsilon_i P_{lossi}}{\sum_{j \in L} P_j} \quad (24)$$

$$\varepsilon_i = \varepsilon_{i1} \frac{L_{loss1}}{L_{loss}} + \varepsilon_{i2} \frac{L_{loss2}}{L_{loss}} + \varepsilon_{i3} \frac{L_{loss3}}{L_{loss}} \quad (25)$$

Among them, η is the load loss proportion; L is the set of load nodes; L' is the set of load-loss nodes; ε_i is the important factor of node i ; P_{lossi} is the loss value of node i ; P_j is the load value of node j before the accident; S_{load} is the load loss severity, η_{lim} is the set threshold of load loss, generally taking 20% of the total load value. L_{loss1} 、 L_{loss2} 、 L_{loss3} are the total loss value of primary load, secondary load and tertiary load of node i , ε_{i1} 、 ε_{i2} and ε_{i3} are the importance coefficients of the first, second and third load. The load loss severity model is shown in Figure 3.

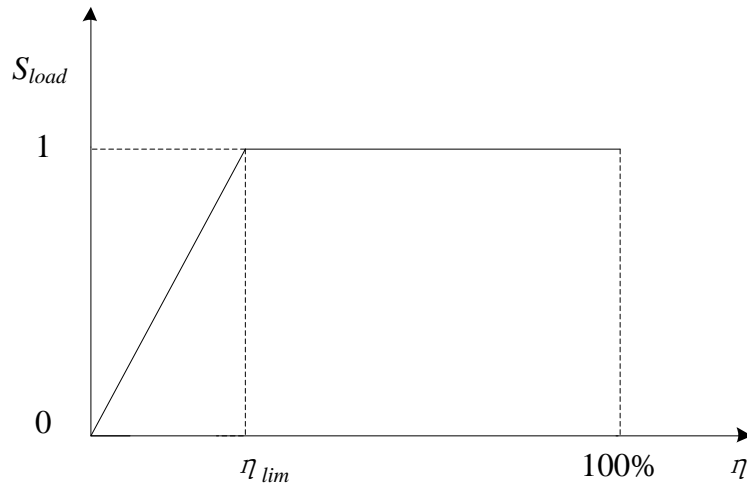


Figure 3. Severe load loss function.

4. Risk assessment model based on comprehensive influence

4.1. Comprehensive severity model after accidents

This paper adopts AHP-Cantilly comprehensive weighting method [13], the global comprehensive severity index is obtained as follows:.

$$S_i = \rho_p S_i(P) + \rho_U S_i(U) + \rho_L S_{i\text{load}} \quad (26)$$

$$\rho = \kappa \zeta + (1 - \kappa) \varphi \quad (27)$$

Among them, ρ is the comprehensive weight, κ is the subjective preference coefficient, ζ is the subjective weight, φ is the objective weight, ρ_p , ρ_U , ρ_L are the corresponding comprehensive weight of each index, i represents the level i fault.

4.2. Failure probability model.

In this paper, the non-sequential Monte Carlo method is used to calculate the N-1 failure probability. When the number of samples is large, the sampling frequency can be used as an unbiased estimate of its probability. Therefore, the probability of failure [6] can be expressed as:.

$$P(E_i) = \frac{m(E_i)}{M} \quad (28)$$

$$P(E_i) = P(E_{i-1})P(E_i|E_{i-1}) \quad i > 1 \quad (29)$$

Among them, $P(E_i)$ is the failure probability; M is the total number of sampling; $m(E_i)$ is the number of occurrences of state E_i . $P(E_i|E_{i-1})$ is the probability of occurrence of level i fault under the occurrence of $i-1$ failure.

4.3. safety risk assessment model

Considering the failure probability and the global comprehensive severity after accidents, the security risk index is established:

$$R_i = P(E_i) \times S_i \quad (30)$$

The flow chart of safety risk assessment is shown in Figure 4.

5. Example analysis

The IEEE30 node system is used to simulate the power grid, which consists of 30 nodes and 41 lines. All nodes in the system adopt single-bus connection mode. In the simulation process, the probability of main protection action is 0.85 and the probability of error protection is 0.05[14]. The system connection diagram is shown in Figure 5.

5.1. Comprehensive influence analysis.

According to the comprehensive influence analysis after branch L1 breakdown. the top 10 branches and nodes are shown in Table 1 and table 2 respectively.

As can be seen from Table 1, the comprehensive influence of each branch varies greatly. The first 10 branches are all important paths for energy transmission. For example, L4 and L2 are the key branches which constitute the basic framework of the power grid, bearing heavy transmission tasks. What is more, The L6 and L8 which can not be identified by the structural impact index and L41 which can not be identified by the state impact index can be identified by the comprehensive impact index. The same analysis for Table 2 Therefore, the comprehensive influence index proves to be reasonable and effective.

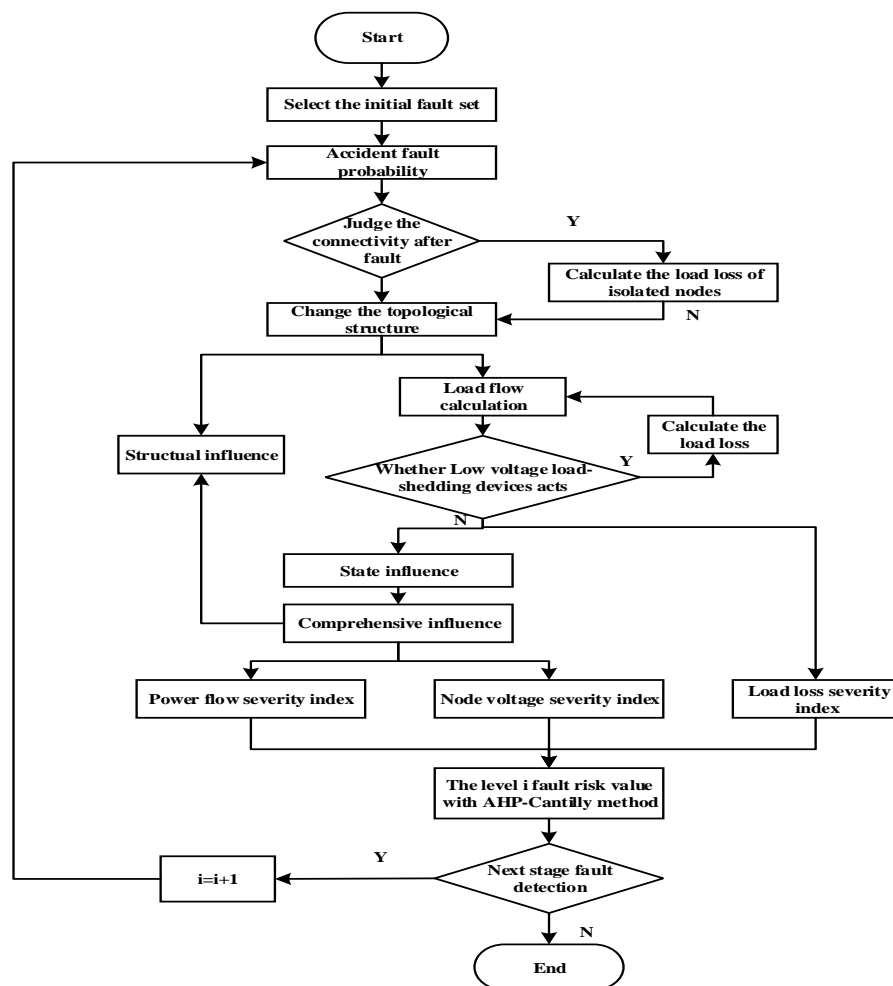


Figure 4. Flow chart of risk assessment.

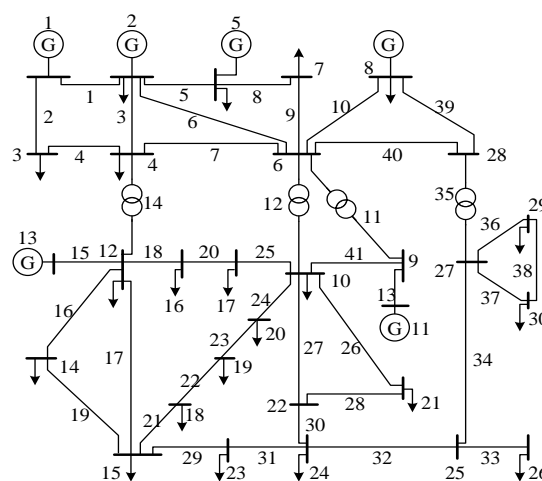


Figure 5. Connection diagram of IEEE 30 node system.

Table 1. Top 10 of Branch comprehensive influence.

ranking	structure influence	State influence	Comprehensive influence	Comprehensive influence Value
1	L4	L4	L4	1.0000
2	L2	L2	L2	0.8853
3	L5	L3	L5	0.6364
4	L7	L8	L7	0.5171
5	L41	L5	L35	0.4582
6	L14	L6	L3	0.4571
7	L35	L9	L9	0.4471
8	L9	L35	L8	0.3702
9	L10	L7	L10	0.3637
10	L11	L10	L6	0.3163

Table 2. Top 10 of Node comprehensive influence.

ranking	structure influence	State influence	Comprehensive influence	The value of Comprehensive influence
1	6	4	6	0.8285
2	4	6	4	0.7519
3	10	2	10	0.6744
4	12	5	12	0.6339
5	24	3	3	0.4365
6	9	7	9	0.3972
7	3	9	2	0.3377
8	29	10	5	0.3343
9	20	12	24	0.3317
10	26	8	7	0.3308

5.2. Identification of $N-1$ accident critical links.

The security risk of $N-1$ accident is analyzed considering the comprehensive influence of components and the system state severity model after faults. The ranking result is obtained and compared with literature [8], literature [9] and traditional method [7].

Table 3. Top 10 of $N-1$ contingency risk value.

ranking	Risk value/ 10^{-5}	Method in this paper	Method in reference [8]	Method in reference [9]	Traditional method [10]
1	5.6835	L1	L1	L1	L1
2	4.4621	L2	L2	L2	L2
3	4.3124	L4	L4	L35	L8
4	2.8936	L35	L7	L24	L5
5	2.5924	L5	L11	L4	L11
6	2.1367	L10	L8	L5	L4
7	1.8113	L7	L12	L7	L24
8	1.5836	L6	L9	L41	L10
9	1.4549	L41	L5	L11	L7
10	1.3851	L11	L24	L8	L32

As can be seen from Table 3, the top 10 routes of risk ranking obtained by this method have many similarities with the results of literature [8], literature [9], and traditional method [7], especially in identifying the risk values of the most critical branches. For example, branches L1, L2, which are directly connected with the No. 1 generator, once in fault, are very likely to lead to the separation between the generator and the main network. Therefore, method in this paper is effective and correct. The main difference between the proposed method and the traditional method is in branches L35, L41, L6, because the traditional method only considers the running state of the system after failure, ignoring the differences of components. The main difference between the proposed method and the reference [8] method is that branches L10, L35, L41 and L6 only consider the contribution of the component in power transmission process, not reflecting the multiplicity of component attributes. Reference [9] considers the sensitivity of operation state on the basis of reference [8], but it does not contain the characteristics of reactive power compensation and power flow transfer uniformity. Compared with the methods mentioned above, branch L10 is directly connected to the generator, supplying the No. 8 node which bears heavy load. Once in fault, it will lead to branch L39 power flow reverse, and the load rate of branch L40 will be greatly increased, which will greatly affect the security operation. L35 is a main transformer branch, which has a large power supply range. Blackouts will overload branches L30 and L32, cause the nodes N24-N30 disconnected with the system, resulting in a large area of power failure. Therefore, this method can identify the initial high risk faults.

5.3. Identification of $N-k$ accident critical links

According to the $N-k$ risk assessment method mentioned above, the fault sequence L5-L6-L3-L2/L4 is assessed step by step, and the risk increment for each stage is calculated to identify the key link in the $N-k$ fault.

As can be seen from Table 4, after the fault of L6 and L3 branches, system security deteriorates greatly, system risk increases sharply, and eventually leads to blackouts. It shows that branch L5, L6 and L3 are important branches, and L6, L3 are the key links of the fault sequence. The reason is that the above three lines are directly connected with the No. 2 generator. The three lines complement each other in the topology of the power grid and bear heavy power transmission task. Any of them get a fault, the other two lines will appear overload.

Table 4. Critical link identification of $N-k$ contingency series with initial fault of L5.

fault sequence	Composition Risk value/ 10^{-5}	Risk increment/ 10^{-5}
L5	2.5924	2.5924
L6	8.7540	6.1616
L3	14.8348	6.0808

6. Conclusions

Based on the present security risk assessment theory, this paper proposes a security risk assessment method. It introduces the electrical mediator and power flow entropy into the traditional severity model, establishing a component comprehensive importance model, which amends the traditional severity model and improves the existing security risk assessment index set. Simulation results prove the degree of innovation brought by the proposed method. Firstly, from the point of power flow transfer, considering the multiple attributes of components and regional influence of reactive power, this method uses complex network theory and entropy theory to establish the comprehensive influence index, which is more suitable for the actual situation of power grid. Secondly, The state sensitivity index is introduced into the severity model to overcome the deficiency of traditional severity model which only considers state margin. At last, Taking account of the correlation among the indicators, we use the AHP-Cantille weighting method to get the global comprehensive severity model. The results of this method can identify the high-risk set and the key links of cascading faults correctly and effectively, which is of practical significance to improve the security of power grid.

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