Critical Node Identification for Electric Power Communication Network Based on Topology and Services Characteristics

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Abstract. It has an important impact on the overall power communication network reliability to identify the location of critical nodes in the network and further develop protection methods. On the topology layer of power communication network, Node Topology Importance(NTI) is proposed based on calculating the rate of natural connectivity of power communication network after one node being destroyed; A calculation method of power business is presented by considering the power business requirements on the indexes, then taking into account the business layer and topology layer, weighted natural connectivity which fuses the node business information and topology information is defined, accordingly Node Combining Importance(NCI) is proposed to realize the excavation of key node. Finally, taking a real communication network as the simulating example, the simulation results by comparing with other methods show that the proposed method can improve the accuracy of recognition.

1 Introduction

With the rapid construction of smart grid and the continuous expansion of interconnected power grid, the safe and effective operation of the power grid is increasingly dependent on the reliable operation of the power communication network[1]. The communication equipment, that is, network node is indispensable in the power communication network business transmission. And the reliability of the power communication network will decrease immediately, even cause large-scale communication interruption once the key nodes of the network are damaged and fail. It is determined that the risk of the power grid can be reduced only if the importance of the communication network node is identified, the key nodes in the power communication network are identified and the protection is strengthened.

The normal methods for evaluating the importance of nodes include the median method, the node deletion method and the node contraction method. These normal evaluation methods are relatively single which cannot be fully applicable to a dedicated communication network with specific functional requirements such as power communication networks. It is necessary to improve the above methods or introduce new methods to evaluate the importance of nodes. According to the characteristics of the power communication network, researchers have carried out related researches: The paper [2] fused the transmission characteristics and the grid characteristics of the power communication network by using the triangular mode operators to identify the important nodes, but failed to analyze the importance of the nodes in combination with the industry characteristics of the power communication network. In the paper [3], the importance of nodes was analyzed from the special relationship between the power communication network and the power grid, and the key nodes can be identified by integrating grid impact factors and aggregation coefficients. The paper [4] defined the node importance from the static characteristics of node topology and network bandwidth, and used the position and function of the node in the power system as the weight to correct the node importance. In the paper [5], a dual-network coupling model was established based on the topological connections between the power grid and the power communication network, and a method for evaluating the importance of coupled network nodes considering cascade failure was proposed. These methods above focus on the network's topological characteristics, network bandwidth, site category and other indicators. But they don’t take into account the impact of the communication business on the communication node to represent the network operation status accurately.

According to the above analysis, the concept of Node Topology Importance (NTI) based on the change of natural connectivity after node failure in the topology layer is proposed in this paper. Combined with the characteristics of electric power business, the network weighted natural connectivity is defined by fusing the network topology layer and the business layer. And the concept of the Node Combining Importance (NCI) is presented to implement the identification of the key nodes in the power communication network. The proposed method not only considers the contribution of

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nodes to the topology, but also the degree of influence of nodes on the business transmission in the network is discussed, which can be well applied to the mining of important nodes in the power communication network.

2 Node topology importance

When identifying the importance of a node in a network, the degree of damage to the network is usually taken into account after the node fails. The greater the damage brings, the higher the importance of the node is. The degree of damage caused by node failure to the network topology can be measured by multiple aspects, such as the reduction of the number of spanning trees and the reduction of the shortest path between nodes[6]. In fact, there is still a destructive result worth considering, that is, the reduction of alternative path redundancy in the network and the consequent decrease of the network invulnerability. From this point of view, the importance of topological layer nodes is obtained.

The metrics of the network redundant path can be represented by the natural connectivity of the network. The value of the natural connectivity is equal to the weighted sum of the number of closed paths with different lengths in the network. It can be regarded as a special form of the average eigenvalue with the clear physical meaning and concise mathematical expression, which can be derived from the adjacency matrix eigenvalue set. The power communication devices are referred to the power communication network topology diagram $G=(V, E)$ and the set of nodes $V=\{v_1,v_2,\ldots,v_N\}$. The link between devices is defined as the edge set $E=\{e_1,e_2,\ldots,e_M\}$. Noting $A(G)$ be the adjacency matrix of diagram G, then the element a_{ij} in $A(G)=[a_{ij}]$ is defined as:

$$a_{ij}=\begin{cases}0, \textit{No link or link working state fails between the nodes } v_i \textit{ and } v_j\\ 1, \textit{There are links between the nodes and the working state is normal}\end{cases} \quad (1)$$

Defining λ_j be the eigenvalue of the adjacency matrix $A(G)$, then the natural connectivity of the network can be denoted as[7]:

$$\bar{\lambda}(G)=\ln\left(\frac{1}{N}\sum_{j=1}^{N}e^{\lambda_j(G)}\right) \quad (2)$$

$\bar{\lambda}(G)$ is the natural connectivity of diagram G. The power communication network to pology subnet after the node v_i fails is represented by $G - v_i$. It is assumed that all the links connected to the node fail, while the node remains in the network after the node fails in this paper. It means removing the connected links from the network, not the node. The natural connectivity of the network topology subnet $G - v_i$ is expressed as follows after the node v_i fails.

$$\bar{\lambda}(G-v_i)=\ln\left(\frac{1}{N}\sum_{j=1}^{N}e^{\lambda_j(G-v_i)}\right) \quad (3)$$

The eigenvalue of the adjacency matrix $A(G - v_i)$ is represented as $\lambda_j(G - v_i)$ in this equation.

The natural connectivity is strictly monotone decreasing in regard to the deletion side. The network anti-destructive performance will deteriorate and the natural connectivity value must decrease once the node fails. The more the natural connectivity value decreases, the greater the contribution of the node to the network topology. Defining the vital function of nodes on the topology layer as Node Topology Importance(NTI). The NTI of node v_i is expressed as:

$$NTI_i=1-\frac{\bar{\lambda}(G-v_i)}{\bar{\lambda}(G)} \quad (4)$$

In this equation, NTI_i is the normalized importance of the node v_i. The natural connectivity of the original communication network G is indicated by $\bar{\lambda}(G)$ .The network topology subgraph formed after the node v_i fails is represented by $G - v_i$. $\bar{\lambda}(G-v_i)$ is the natural connectivity of the network $G - v_i$. The higher the NTI_i is， the greater the contribution of the node makes to the topology. Obviously, natural connectivity can be obtained by simple calculations, as well as for the large-scale networks.

3 Power communication network business importance

The power communication network provides communication services and business supports to all aspects of the grid operation through services. According to the different ways of business attributes, security zones and service bearers, the power communication network services can be divided into different types, they have different impacts and the degree of damage on the grid in the event of interruptions or defects. And these impacts are always described by the business importance indirectly. Different types of business result in different importance. Describing and distinguishing the importance of the business accurately is the main content of the evaluation of the power communication network. The influence of the subjective factors such as the expert scoring cannot be eliminated by the existing evaluation methods. And the accuracy of the assessment of the power communication network can be affected by these subjective uncertainties. In order to overcome the subjective uncertainty, the paper [8] proposed a method to evaluate the importance of power business with business performance indicator requirements named feature index evaluation method to replace the expert subjective scoring method. It constitutes a feature indicator of the performance of the power business, mapping different requirements of different businesses to feature indicators into important value sequences and using the important value sequence of the business to build a business relative importance matrix to achieve the business importance evaluation. The feature index method proposed in the paper selects “0, 0.5, 1” when assigning the relative importance of different services under specific performance indicators. While there are many types of business and feature indexes which make this assignment method insufficiently distinguish the importance. Based on this reason, the ratio of relative importance of business is further refined to make the evaluation results more reasonable in this paper.

Defining the performance indicator set $Q=\{Q_l\}$ ($l=1,2,\ldots,L$), in which Q_l represents the performance indicators of business and there are a total of L performance indicators; Noting the business set $S=\{S_k\}$ ($k=1,2,\ldots,K$) to express the set of business types and K is the number of business. According to the different requirements of the performance indicators Q_l, the business set S is mapped to the performance importance matrix $B_{kl}=[1,2,...,B_l]$, in which B_l is numerically equal to the total number of different requirement levels of the indicator Q_l. Then, calculating the element $c_{kj}^{(Q_l)}$ of the business relative importance matrix $C^{(Q_l)}$ based on the performance importance matrix B_{kl}:

$$c_{kj}^{(Q_l)}=\begin{cases}1 & B_l\le B_{kl}/B_{jl}\\ \vdots & \vdots\\ 2/B_l & 2\le B_{kl}/B_{jl}<3\\ 1/B_l & 1\le B_{kl}/B_{jl}<2\\ 0 & B_{kl}/B_{jl}<1\end{cases} \tag{5}$$

In this equation, $c_{kj}^{(Q_l)}$ refers to the degree of importance of the business S_k in the performance indicators Q_l compared with the business S_j, in which S_k、S_j ($k,j=1,2,\ldots K$) are all the services in the business set S. As can be seen from equation (5), $c_{kj}^{(Q_l)}$ has a total of B_l+1 values, that is, there are a total of B_l+1 levels for the relative importance, which are 0, $1/B_l$, $2/B_l$, …, 1, and the values are related to B_l. The larger the value of $c_{kj}^{(Q_l)}$, the more important the service S_k is than the service S_j under the performance indicator Q_l. The more performance requirements of the performance indicator Q_l as well as the level of importance, the more accurate when evaluating the business importance values. And the more the performance requirement level of the same performance indicators Q_l and the interval is divided according to the ratio of B_{kl} and B_{jl}, so that the more the $c_{kj}^{(Q_l)}$ value is, and the relative importance assignment of different businesses is refined under the specific performance indicators.

A comprehensive relative importance value matrix C is defined whose element c_{kj} is the value of the business relative importance matrix $C^{(Q_l)}$ summed according to the equation (6) under all the indicators:

$$c_{kj}=\sum_{l=1}^{L}c_{kj}^{(B_l)} \tag{6}$$

The importance values of the same business are summed under different performance indicators, that is, the elements of each row of the matrix C are added to obtain the comprehensive relative importance of the business B_k:

$$c_k^{sum}=\sum_{j=1}^{K}c_{kj} \tag{7}$$

c_k^{sum} is normalized and mapped to the interval [X,1], and the importance α_k of the business S_k is obtained as:

$$\alpha_k=(1-X)\frac{c_k^{sum}-(c_k^{sum})_{\min}}{(c_k^{sum})_{\max}-(c_k^{sum})_{\min}}+X \tag{8}$$

In this equation, $X\in(0,1)$.

Table 1 is the business types, performance indicators and requirements selected in this paper[9]. $c_{kj}^{(B_l)}$ can be calculated from Table 1, and the business importance values of typical power communication network can be obtained from equations (6) to (8) as is shown in Table 1.

4 Node importance combining topology and business

The node importance is the main basis to identify the key nodes. Most of the existing methods for evaluating the node importance of power communication network are to consider the network topology or bandwidth traffic. The types and features of businesses carried by the power communication network have industry characteristics. When evaluating the node importance, not only the topology but also the importance and traffic of the businesses carried by the node should be considered[10]. So it is of more practical significance to study the key nodes of the power communication network by combining the business characteristics and topologies.

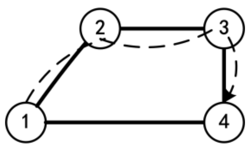

Figure. 1 A simple topology of power communication network

Link is the physical channel between nodes whose business load directly reflects the business load situation of nodes. The coupling degree of bearing relationship d_{ijp} between the link of the nodes v_i and v_j and business p is divided into polar coupling, general coupling and non-coupling. Therefore, d_{ijp} has three values represented by 1, 0.5 and 0: When the routing of business p passes through the link between the nodes v_i and v_j, and the nodes v_i and v_j are the source nodes or sink nodes of business p, the link is coupled with the business and $d_{ijp}=1$; And when the business p passes through the link between the nodes v_i and v_j, and neither of the two nodes is the source node or sink node, the link is generally coupled with the business and $d_{ijp}=0.5$; While the business p does not go through the link between the nodes v_i and v_j, the link is not coupled with the business and $d_{ijp}=0$. The simple topology shown in Figure 1 will be illustrated. The dotted line in the network is a business

Table 1 Selected power business property indexes and their relative importance

Power communication business / Label	Performance indicator requirement / Important level					Business importance
	Business channel	Load mode	Safety zone	Delay	BER：Biterror	
500 kV relay protection/S_1	500 kV and above substation /7	Dedicated channel /6	Ⅰ Zone /4	≤7 ms/8	$\leq 10^{-6}$/3	1.0000
220 kV relay protection /S_2	220 kV and above substation /6	Dedicated channel /6	Ⅰ Zone /4	≤7 ms/8	$\leq 10^{-6}$/3	0.9224
Security system /S_3	Provincial dispatching - Substation; Provincial dispatching - Regional dispatching /3	Dedicated channel /6	Ⅰ Zone /4	≤25 ms /7	$\leq 10^{-7}$/4	0.8609
Dispatching telephone /S_4	Provincial dispatching - Substation /Power plant /4	Dispatching switch network、dispatching data network /3	Ⅰ Zone /4	≤142ms /5	$\leq 10^{-3}$/1	0.5797
Dispatching automation /S_5	Provincial dispatching - Substation; Provincial dispatching - Regional dispatching /3	Dedicated channel、dispatching data network /5	Ⅰ Zone /4	≤94 ms /6	$\leq 10^{-6}$/3	0.6385
Protection information management /S_6	Provincial and municipal substation /5	Dispatching data network /4	Ⅱ Zone /3	≤12 min /2	$\leq 10^{-5}$/2	0.4538
Wide-area phase measurement /S_7	provincial dispatching - Substation /4	Dispatching data network /4	Ⅰ Zone /4	≤25ms /7	$\leq 10^{-9}$/5	0.7748
Lightning location monitoring /S_8	Monitoring center - Monitoring station /1	Integrated data network /2	Ⅲ Zone /2	≤240 ms /4	$\leq 10^{-5}$/2	0.2770
Substation video surveillance /S_9	Provincial dispatching - Substation; Provincial dispatching - Regional dispatching /3	Integrated data network /2	Ⅲ Zone /2	≤142 ms /5	$\leq 10^{-3}$/1	0.2871
Video conference /S_{10}	General dispatching - Provincial dispatching / Regional dispatching /2	Dedicated channel / Integrated data network /3	Ⅳ Zone /1	≤7ms /8	$\leq 10^{-5}$/2	0.3665
Executive telephone /S_{11}	Dispatching center and plant station /4	Integrated data network / Executive exchange /1	Ⅳ Zone /1	≤7ms /8	$\leq 10^{-3}$/1	0.2238
Office automation /S_{12}	General dispatching - Provincial dispatching / Regional dispatching /2	Integrated data network /2	Ⅳ Zone /1	No specific requirement /1	$\leq 10^{-5}$/2	0.0940

path p and in which the nodes v_1 and v_4 are the source nodes or sink nodes, and the business path goes through the nodes v_2 and v_3. Then the links between the nodes v_1, v_2 and the nodes v_3, v_4 are coupled with the business, and d_{12p}=d_{34p}=1; The links between the nodes v_2 and v_3 are generally coupled with business, and d_{23p}=0.5; And the links between the nodes v_1 and v_4 are not coupled with business, and d_{14p}=0.

The business weight of business p is represented as γ_p, then the element w_{ij} of the business weight matrix $W(G)$ of the link is as follows:

$$w_{ij} = \sum_{p=1}^{P} d_{ijp}\gamma_p \tag{9}$$

In this equation, $\gamma_p = \sum_{k=1}^{n_p} \alpha_k \beta_{pk}$, in which np refers to the number of business types loaded between the p-th source and sink node pairs, and α_k represents the importance value of business B_k, while the number of business B_k runs between the p-th source and sink node pairs is represented as β_{pk}.

The non-zero elements of the adjacency matrix are all 1, while the element wij of the business weight matrix is

easy to ignore the influence of topology characteristics on the importance evaluation of nodes based on its various values and large differences. Then w_{ij} is normalized. The normalization function is as follows:

$$h_{ij} = \frac{w_{ij}}{\max_{i,j=1}^{N}\{w_{ij}\}} \tag{10}$$

h_{ij} is used as the element corresponding to the position of the weighted adjacency matrix $H(G)$. It can be seen from equations (9) and (10) that h_{ij} represents the normalized business weight value of the link between the nodes v_i and v_j.

In the topology, the impact of the middle node on the network invulnerability reflected by the natural connectivity can reasonably evaluate the node topology importance[11]. Assuming that the eigenvalue of the weighted adjacency matrix $H(G)$ is λ_j'(G). Then the definition of the weighted natural connectivity of the power communication network is given by combining the topology and business characteristics in this paper.

$$\overline{\lambda}'(G) = \ln\left(\frac{1}{N}\sum_{j=1}^{N} e^{\lambda_j'(G)}\right) \tag{11}$$

The topology of the power communication network and the transmission of network services will be damaged by the failure of node v_i. And the value of the weighted natural connectivity of the power communication network becomes smaller. The Node Combining Importance(NCI) can be obtained by calculating the change of the weighted natural connectivity of the network before and after the failure of the node. The expression is as in equation (12).

$$NCI_i = 1 - \frac{\overline{\lambda}'(G - v_i)}{\overline{\lambda}'(G)} \tag{12}$$

In this equation, NCI_i is the normalized combining importance of node v_i; The weighted natural connectivity of the original network topology graph G is represented as $\overline{\lambda}'(G)$; And $\overline{\lambda}'(G - v_i)$ is defined as the weighted natural connectivity of the subnet G - v_i. The smaller the $\overline{\lambda}'(G - v_i)$ is, the larger the NCI_i can we get, and the more important the node v_i is.

The Node Combining Importance (NCI) takes into account the node topology characteristics and power service characteristics comprehensively[12]. While reflecting the impact of the node on the invulnerability of the topology layer, combining the contribution degree of the business layer to the business operation status at the same time. Thus the key node can be identified more accurately.

5 The case analysis

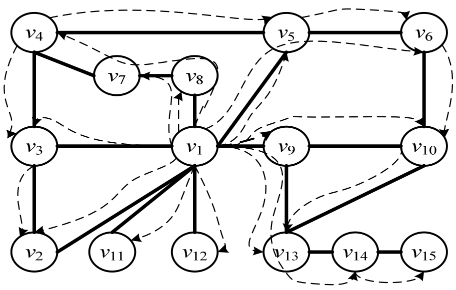

Figure. 2 Topology and routing distribution of a power communication network

A power communication network and business path model are shown in Figure 2. The network contains 15 nodes and 19 links, and the dotted lines in the network represent the business path[13]. Abstractly, the provincial dispatching is the node v_1, the regional dispatching is expressed as the node v_{14}, the 500kV substations are nodes v_5 and v_9, and the 220kV substations are all represented as other nodes. The business types and numbers loaded by node pairs are shown in Table 2.

Table 2 Business type and number between node pairs

Node pair	Business type × number
(v_1, v_2)	$S_3\times3+S_4\times3+S_5\times3+S_6\times1+S_7\times3+S_8\times2+S_9\times1+S_{10}\times1+S_{11}\times1+S_{12}\times2$
(v_1, v_3)	$S_3\times5+S_4\times4+S_5\times8+S_6\times2+S_7\times6+S_8\times8+S_9\times2+S_{10}\times4+S_{11}\times1+S_{12}\times4$
(v_1, v_4)	$S_3\times5+S_4\times4+S_5\times6+S_6\times2+S_7\times4+S_8\times4+S_9\times2+S_{10}\times4+S_{11}\times1+S_{12}\times4$
(v_1, v_5)	$S_3\times5+S_4\times4+S_5\times6+S_6\times2+S_7\times6+S_8\times7+S_9\times2+S_{10}\times4+S_{11}\times1+S_{12}\times4$
(v_1, v_6)	$S_3\times4+S_4\times4+S_5\times8+S_6\times2+S_7\times6+S_8\times7+S_9\times2+S_{10}\times4+S_{11}\times1+S_{12}\times4$
(v_1, v_7)	$S_3\times3+S_4\times3+S_5\times2+S_6\times2+S_7\times4+S_8\times2+S_9\times2+S_{10}\times4+S_{11}\times1+S_{12}\times4$
(v_1, v_8)	$S_3\times2+S_4\times2+S_5\times5+S_6\times1+S_7\times2+S_8\times3+S_9\times1+S_{10}\times1+S_{11}\times2+S_{12}\times4$
(v_1, v_9)	$S_3\times6+S_4\times5+S_5\times10+S_6\times6+S_7\times9+S_8\times4+S_9\times1+S_{10}\times3+S_{11}\times5+S_{12}\times2$
(v_1, v_{10})	$S_3\times5+S_4\times5+S_5\times9+S_6\times6+S_7\times8+S_8\times4+S_9\times1+S_{10}\times3+S_{11}\times4+S_{12}\times2$
(v_1, v_{11})	$S_3\times4+S_4\times3+S_5\times5+S_6\times2+S_7\times4+S_8\times3+S_9\times2+S_{10}\times1+S_{11}\times2+S_{12}\times2$
(v_1, v_{12})	$S_3\times4+S_4\times4+S_5\times6+S_6\times2+S_7\times5+S_8\times5+S_9\times2+S_{10}\times1+S_{11}\times4+S_{12}\times1$
(v_1, v_{13})	$S_3\times2+S_4\times2+S_5\times3+S_6\times1+S_7\times3+S_8\times1+S_9\times2+S_{10}\times2+S_{11}\times2+S_{12}\times1$
(v_1, v_{14})	$S_3\times4+S_5\times7+S_8\times2+S_9\times3+S_{10}\times2+S_{11}\times2+S_{12}\times1$
(v_3, v_2)	$S_1\times1+S_8\times1+S_{11}\times1$
(v_4, v_3)	$S_1\times1+S_8\times1+S_{11}\times1$
(v_4, v_5)	$S_1\times1+S_8\times1+S_{11}\times1$
(v_5, v_6)	$S_1\times1+S_8\times1+S_{11}\times1$
(v_6, v_{10})	$S_1\times1+S_8\times1+S_{11}\times1$
(v_{10}, v_{13})	$S_1\times1+S_8\times1+S_{11}\times1$
(v_{14}, v_{15})	$S_3\times1+S_4\times1+S_5\times1+S_6\times2+S_7\times1+S_8\times2+S_{10}\times1+S_{11}\times1+S_{12}\times2$

The node set of the network model in Figure 2 is $V = \{v_1, v_2, v_3, v_4, v_5, v_6, v_7, v_8, v_9, v_{10}, v_{11}, v_{12}, v_{13}, v_{14}, v_{15}\}$. And the adjacency matrix *A(G)* is obtained from the network topology:

$$A(G) = \begin{bmatrix}
0 & 1 & 1 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 & 0 & 0 \\
1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0
\end{bmatrix}$$

The set of the power business carried is $S = \{S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8, S_9, S_{10}, S_{11}, S_{12}\}$. According to the business path shown by the dotted line in Figure 2 and the business types and numbers between the nodes given in Table 2[14], the weighted adjacency matrix *H(G)* of network obtained by the equation (10) is as:

$$H(G)=\begin{bmatrix} 0 & 0.286 & 0.576 & 0 & 0.807 & 0 & 0 & 0.669 & 1.000 & 0 & 0.397 & 0.475 & 0 & 0 & 0 \\ 0.286 & 0 & 0.039 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.576 & 0.039 & 0 & 0.039 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.039 & 0 & 0.039 & 0 & 0.235 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.807 & 0 & 0 & 0.039 & 0 & 0.311 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.311 & 0 & 0 & 0 & 0 & 0.039 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.235 & 0 & 0 & 0 & 0.397 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.669 & 0 & 0 & 0 & 0 & 0 & 0.397 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1.000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.155 & 0 & 0 & 0.273 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.039 & 0 & 0 & 0.155 & 0 & 0 & 0 & 0.039 & 0 & 0 \\ 0.397 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.475 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.273 & 0.039 & 0 & 0 & 0 & 0.142 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.142 & 0 & 0.137 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.137 & 0 \end{bmatrix}$$

The NTI and NCI values of each node can be calculated through the matlab simulation. Taking the node deletion method (method 1) and the node contraction method (method 2) as the comparison algorithms to verify the validity and accuracy of the method proposed in this paper[15]. And programming to achieve each algorithm simulation. Table 3 lists each algorithm in accordance with the NCI algorithm ranking.

Table 3 The ranking result of the value of node importance in Figure.2

Node	Method 1		Method 2		NTI algorithm		NCI algorithm	
	Importance value	Rank	Importance value	Rank	NTI	Rank	NCI	Rank
v_1	1.000	1	0.584	1	0.359	1	0.876	1
v_9	0.923	6	0.367	2	0.150	3	0.348	2
v_5	0.925	4	0.251	6	0.130	4	0.236	3
v_8	0.741	10	0.010	12	0.079	9	0.185	4
v_3	0.880	8	0.237	7	0.165	2	0.111	5
v_{12}	0.000	13	0.069	14	0.047	13	0.074	6
v_{11}	0.000	13	0.069	14	0.047	13	0.052	7
v_7	0.741	10	0.010	12	0.068	11	0.049	8
v_2	0.627	12	0.128	11	0.118	7	0.029	9
v_{13}	1.000	1	0.368	2	0.118	6	0.024	10
v_6	0.770	9	0.176	9	0.062	10	0.024	11
v_4	0.925	4	0.237	7	0.109	8	0.013	12
v_{14}	1.000	1	0.276	5	0.050	12	0.008	13
v_{10}	0.923	7	0.313	4	0.121	5	0.007	14
v_{15}	0.000	13	0.155	10	0.022	15	0.004	15

As it can be seen from the simulation results, among the top seven nodes, the coincidence rate of NTI and the node contraction method are as high as 71.4%. Meanwhile, the evaluation results of both algorithms are that node v_1 has the highest degree of importance, and the nodes v_{11} and v_{12} are ranked lower, indicating the effectiveness of NTI. If the network is not connected after the node fails, then the node deletion method is unavailable and the method fails[16]. While the NTI algorithm does not require the network connectivity after the node fails, which effectively overcomes the limitation of the node deletion method. Another disadvantage of the node deletion method is the inability to distinguish the importance of all nodes in the network. For example, the importance of nodes v_1, v_{13} and v_{14} calculated by the node deletion method is 1, which is not consistent with the actual situation of the network. However, the importance of all nodes in the network can be completely distinguished according to the NTI algorithm. In the experimental results in Table 3, the importance of nodes v_7, v_8 and nodes v_9, v_{13} cannot be distinguished by the node contraction method, while NTI can distinguish the importance of the two groups of nodes, indicating that the NTI evaluation has higher accuracy[17].

The node importance obtained by the NCI algorithm is quite different from the calculation results obtained by the other three algorithms from the comprehensive analysis of the data in Table 3. The NCI algorithm not only takes the network topology into account, but also the business characteristics loaded by the nodes. The importance of node v_1 is much higher than that of other nodes, and this result highlights the central position and the important role of node v_1 as a provincial dispatching. Comparing the four algorithms, it can be seen that NCI significantly improves the importance ranking of nodes directly connected to node v_1, such as nodes v_5, v_8, v_{11} and v_{12}. Because these nodes are necessary for the provincial dispatching nodes and some other nodes to transmit business, which carrying a large number of important services, being of high importance and conforming to the actual situation of the power communication network. It indicates the rationality of the NCI. NTI and NCI reduce the importance of node v_{14}, because node v_{14} is at the edge of the topology and transmits less business. From the above, the node importance ranking obtained by the NCI algorithm proposed in this paper is closer to the actual operation of the power communication network, which can effectively identify the key sites and reduce the business loss.

Taking the business failure rate as the indicator, the deliberate attack method is adopted to attack each node one by one according to the descending order rank of the node importance of the node contraction algorithm, NTI and NCI[18]. Then the relationship between node failure and business loss is analyzed, and the result is shown in Figure 3.

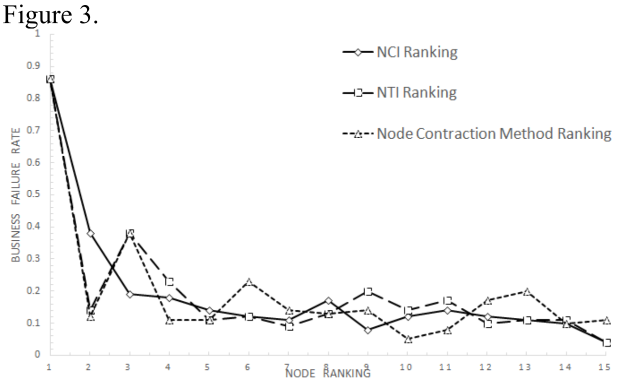

Figure. 3 Corresponding network business failure rates of three attacks

From the results of Figure 3, it is obvious that the polyline of business loss rate obtained by attacking each node according to the descending order ranking of NCI shows an overall decrease and the change range is not large. The business loss rate of network caused by the failure of node v_1 and node v_9 is 0.3 or more, while that of other nodes is less than 0.2. The degree of the impact on the grid risk is relatively low, so the ranking of the node importance is relatively backward, which verifies the rationality of the NCI. The proposed NCI algorithm not only considers the business characteristics of the network load, but also well reflects the contribution of the node topology, so the NCI polyline in the figure is not strictly monotonic decreasing[19]. Taking nodes v_3 and v_7 as an example, the business failure rate caused by the failure of node v_7 is greater than that of node v_3. However, it can be seen from the topology diagram that the topological position of node v_3 is more important than that of node v_7. Combining the effects of the two nodes, the proposed NCI algorithm shows that node v_3 is more important than node v_7. The business failure rates of the other two attack modes in the figure are irregular. The main reason is that only the impact of the topology is considered, while the contribution of the network bearer business to the importance of the node is not considered. Therefore, analyzing the actual operation of the network has no practical significance.

6 Conclusion

In this paper, the change of the natural connectivity of the power communication network is calculated under the condition of node failure, and the Node Topology Importance (NTI) is defined; On the business level, the quantization method of the business importance of the power communication network is detailed firstly, and then the weighted adjacency matrix is obtained by integrating the type, importance and number of the business carried by the link. By combining the topology and the business characteristics, the eigenvalues of the adjacency matrix in the natural connectivity are replaced by the eigenvalues of the weighted adjacency matrix, and the Node Combining Importance (NCI) is defined. Based on the actual operation of the power communication network, and compared with other existing algorithms, the node importance can be calculated and the key nodes of the power communication network can be excavated by NCI more effectively and reasonably.

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