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Research on Vulnerability Identification Algorithm of Power Grid Based on Complex Network

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Abstract. This paper mainly studies the vulnerability of node combination of two kinds of networks, and verifies whether all networks can use the pinning control optimization point selection algorithm. One is the primitive network, in which the nodes correspond to the components in the power grid, and the other is the dual network, in which the nodes are mapped to the nodes of the dual model, It is mapped as an edge, and then the vulnerability of node combination is studied by containment control theory. In the experiment, IEEE57 nodes are used to study the original network, and different combination nodes are used to attack the original network to study the vulnerability. By studying the dual network with IEEE14 nodes, it is found that the eigenvalues of the residual matrix after deleting the control nodes are all zero. Therefore, the dual model of power grid can not use the pinning control theory, and it further shows that not any network can use the pinning control theory to select points.

1 Introduction

With the demand of life, the power system network has become a complex network. The power system presents the characteristics of many kinds and quantities of electronic components, and the transmission line presents the characteristics of complex and cross. Such characteristics make the weak information of topology hidden in the power grid, which is easy to cause large-scale blackouts and chain accidents. Literature[1]points out in the simulation of the power grid between the United States and South Canada that cascaded faults can usually propagate to a long distance from the initial fault, and a few vulnerable lines near the initial fault area play a role in the process of fault propagation[2]. From the perspective of power system security and stability, the search for vulnerable lines is the basis of understanding the propagation path of cascading failures, and plays a decisive role in the propagation of cascading failures. Therefore, how to quickly identify the vulnerable lines in the power grid is of great significance to find the blocking strategy of cascading failures and to prevent the occurrence of blackout. Complex network theory proposes many network properties (such as small world[3] and scale-free property[4]) and component statistical properties to analyze the dynamic behavior of networks. The topology duality theory of power grid is used to realize the correspondence between transmission lines and nodes[5]. In order to further study the vulnerability of power grid, this paper evaluates the vulnerability of power grid combination based on pinning control theory and graph theory. The research on the combination of containment control shows that the combination of two high vulnerability links is not necessarily the optimal combination of the whole network combination. On the contrary, the combination of two medium vulnerability links may be more critical. The key link will lead to large load loss, and even the system will be disconnected after some combination lines are attacked[6]. Therefore, it is worthy of further study to find the identification algorithm of combined vulnerable nodes, and the identification of combined node vulnerability can provide a theoretical basis for the planning and construction of the new generation of power grid.

2 Optimal point selection strategy of power grid control

2.1. Combination of basic theory of containment and control

Assume that the network structure is represented by G, and the node set of G is$V(G)=\{1,\ldots,N\}$controlled node set$S\subset V$,The number of controlled nodes is l, Among them s_1 ,...., s_l Represents controlled node$p_1,\ldots p_{N-l}$Represents the uncontrolled node, and represents the controlled node set $V/_S$ the signw_{pj}Represents a set of controlled nodesSIn place is the controlled nodep_jNumber of edges

$$\lambda_1(L_{N-l}) \leq \frac{\omega_{p1}+\omega_{p2}+\ldots+\omega_{pN-l}}{N-l} \tag{1}$$

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For the deformation of Equation (1), use the signcDenotes the number of edges within the control node setk_{si}Represents controlled nodes$_i$The following relationship is established:

$$\omega_{p1} + \omega_{p2} + \ldots + \omega_{pN-l} = k_{s1} + k_{s2} + k_{s3} + \ldots + k_{sl} - 2e \quad (2)$$

$$K \geq (N - l) \times \lambda_1^* - \sum_{i=1}^{l-1} k_i \quad (3)$$

λ_1^* is the current one$\lambda_1(L_{N-1})$ The maximum. The algorithm of pinching and controlling multiple nodes is optimal $\lambda_1(L_{N-1})$ The specific implementation of the calculation algorithm is as follows: In the process of node combination selection, the first node is selected as the initial controlled node, usually the first node in degree order is selected.

Then, the $\lambda_1(L_{N-1})$ of this node is calculated as the screening criterion λ^*. according to equation (1):

$$\lambda^* \leq \frac{k_{s1}^* + k_{s2}^* + \ldots + k_{sl}^* - 2e^*}{N - l} \quad (4)$$

If you control the node set$\{s_1, s_2, s_3, \ldots, s_l\}$Ask for a bigger one$\lambda_1(L_{N-1})$

$$\frac{k_{s1} + k_{s2} + k_{s3} + \ldots + k_{sl} - 2e}{N - l} > \lambda^* \quad (5)$$

2.2. Combination point selection algorithm process

The specific algorithm is as follows:

Step 1: Calculate node adjacency matrix A and the degree matrix D of nodes;

Step 2: Write the Laplacian matrix L=D-A;

Step 3: The node with high selectivity is to calculate the eigenvalue of determinant residual matrix after deleting the control node;

Step 4: Substitute the eigenvalues into (3), and screen out the nodes that cannot meet Equation (3) through the degree of nodes;

Step 5: Calculate the eigenvalues of the matrix after deleting the combination of the remaining nodes. If a larger eigenvalue is obtained, it will be used as a new screening criterion, and return to the fourth step to continue the iteration; if a larger eigenvalue is not found, the current eigenvalue is the best.

2.3. Power grid vulnerability assessment index

According to the average path length L in the figure, the network vulnerability coefficient β is defined to reflect the fault degree of the power grid after a key component is attacked [12].

$$\beta = 1 - \frac{\sum_{i \neq j} \frac{1}{d_{i,j(GH)}}}{\sum_{i \neq j} \frac{1}{d_{i,j(GQ)}}} \quad (6)$$

Where $d_{i,j(GH)}$ is the shortest distance between a pair of nodes after node failure; $d_{i,j(GQ)}$ is the shortest distance between a pair of nodes when the power grid is in steady state. The value of vulnerability β is between 0 and 1. With the increase of vulnerability β, the chain fault of the power network also increases. The shortest distance between two nodes is the number of edges in the shortest path between two nodes. Shortest path is the path with the least number of edges connecting the two points.

2.4. Power network duality model

The idea of power grid dual model modeling is as follows:

(1) Establish the adjacency matrix of the original power grid;

(2) Each edge in the original network is assigned a number, assuming that the node corresponding to the dual edge in the original network is a node$\{v_1, v_2, v_3 \ldots v_n\}$;

(3) Gets the cell array of the original network;

(4) find the cell graph of the lines related to the original corresponding head and tail nodes in the cell array to the dual topology;

(5) The dual adjacency matrix is obtained according to the dual cell graph;

(6) According to the dual adjacency matrix.

3 The experimental simulation

3.1 The experimental of original network combination and point selection in power grid

Three node combination and four node combination attack are carried out on IEEE57 to obtain the top 10 nodes with the same node degree. In this paper, the total number of 11 nodes and the corresponding degree of IEEE57 are (9,6) (13,6) (12,5) (15,5) (38,5) (1,4) (4,4) (6,4) (11,4) (49,6) (41,4)

(1) Optimal analysis of three-node control combination:

Table 1 IEEE57 optimal point of three node combination

Node number	Node number	Node number	Minimum eigenvalue	vulnerability
9	13	12	0.047	0.243
9	13	15	0.049	0.278
9	13	38	0.064	0.368
9	13	1	0.048	0.262
9	13	4	0.051	0.287
9	13	6	0.052	0.270
9	13	11	0.049	0.230
9	13	49	0.055	0.263
9	13	41	0.048	0.269

From the optimal analysis of three-node control combination, it can be seen that when the node degree is similar, the vulnerability coefficient with a larger minimum eigenvalue is also larger. Therefore, under the grid network topology, the node combination of {9,13,38} is more important. In case of emergency, the above three nodes should be dealt with first.

(2) Optimal analysis of four-node control combination:

Table 2 IEEE57 optimal point of four node combination

Node number	Node number	Node number	Node number	Minimum eigenvalue	vulnerability
9	13	12	15	0.050	0.317
9	13	12	38	0.0638	0.401
9	13	15	38	0.0642	0.459
9	13	1	4	0.0521	0.330
9	13	1	38	0.0641	0.425
9	13	1	15	0.0495	0.316

It can be seen that {9,13,15,38} and {9,13,1,38} node combinations are important nodes in the power grid. When attacking these four nodes at the same time, the vulnerability coefficient of power grid increases, and the power grid is prone to cascading failure.

3.2 Experiment and simulation of power network duality model

The original network topology connection of IEEE14 node is shown in Figure 1 below. The schematic diagram of the dual model of IEEE14 node is shown in Figure 2. The nodes of the dual model are the transmission lines of the original network, and the edges of the dual model are the component nodes of the original network.

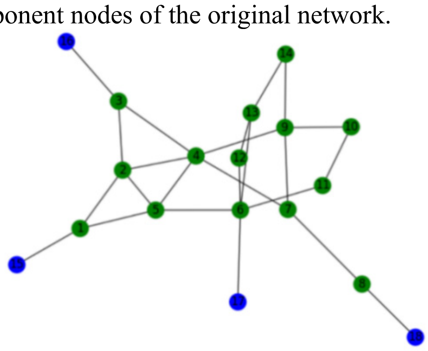

Figure1. IEEE14 node topology diagram

The original IEEE14 node network has 14 nodes and 20 edges. The green node is the component node, and the generator is represented by the blue node for clear representation. In the IEEE14 node specification, the generator is connected with the node {1,3,6,8}.

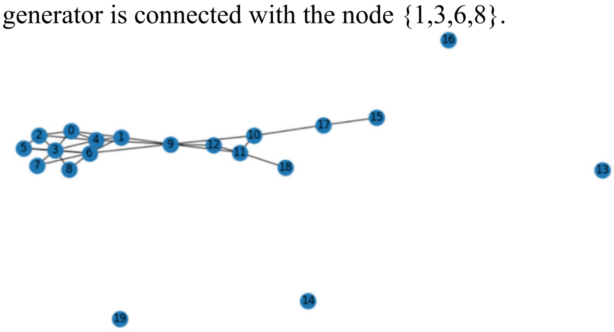

Figure2. IEEE14 Dual Model Topology

The number of edges in the dual model of 14 nodes is the same as the number of nodes in the original network, with a total of 14 edges. The number of nodes in the dual model is equal to the number of edges in the original network, with a total of 20 nodes. Dual Model Node Degree Sort:

(0,3)(1,4)(2,3)(3,4)(4,5)(5,3)(6,3)(7,2)(8,2)(9,3)(10,3)(11,1)(12,2)(13,0)(14,0)(15,1)(16,0)(17,0)(18,1)(19,0).The node degree is arbitrarily selected for the node degree ordering of the 14-node dual model, and the experiment verifies that the minimum eigenvalue after any combination of two nodes is zero.

4 conclusion

This paper mainly studies the combined vulnerability of power grid topology. The vulnerability of nodes is found through the power grid topology with components as nodes and transmission lines as edges. The results show that the combined vulnerability has nothing to do with the degree. The combination of any two nodes can be determined according to the minimum eigenvalue of the deleted matrix. The larger the eigenvalue is, the greater the vulnerability is. Secondly, the dual model is established on the original network. The nodes of the dual model are the edges of the original network. The topological data show that the eigenvalue of the deleted matrix is zero, which indicates that the pinning control theory is not universally applicable. There are still many shortcomings in this paper. At present, we only study the combinatorial vulnerability in static networks. How to identify the combinatorial nodes in dynamic networks needs further research.

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