Importance Evaluation of Nodes in the Power Grid

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Keywords: Power system, Complex network, Importance of nodes.

Abstract. A method is presented in this paper that can easily identify the critical part of the power system. So the critical part can be protected to avoiding damages from nature disasters as well as human factors. This model avoids computing complicated parameters such as the electrical betweenness etc. and it works form the perspectives of the individual characteristics of the power system and the complex network field. Also, the effectiveness and feasibility of the model are verified through the comparison with the traditional method called AHP.

Introduction

It is a practical significance research to estimate the importance of nodes. For instance, in power grid, some nodes plays a significance role in the connectivity, and it will cause huge losses when they breakdown. Previous studies have shown that, the statuses of nodes in the reality network are of great difference. In scale-free networks, it have been proved that when 5% of the core nodes are attacked, the network will fail [1]. Therefore, to identify and focus on the reliability of these nodes becomes increasingly important.

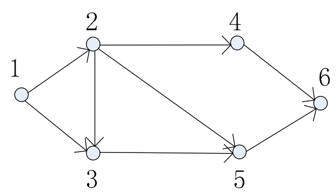
In recent years, the traditional methods of complex network node importance evaluation include the method of betweenness, the method based on the shortest path and the number of spanning tree evaluation, the factor analysis algorithms and the node deletion method [2-6]. The reference [7] uses the Triangle mold operator to fuse the importance of transmission characteristics of the network and characteristics of the nodes, which overcomes the limitations of a single indicator. However, it cannot fully reflect the importance of nodes on backbone telecommunication network [8].

In this paper, we do some preliminary exploration to estimate the importance of the power system node and proposed the estimate model. And to verify its effectiveness and feasibility, we make a comparative analysis on the method and the traditional AHP

Evaluation index on the importance

Topological parameter on the grid

In this paper we consider the power grid as networks which is an ordered pair $G=(N, L)$ comprising a set N of nodes together with a set L of edges. We use the adjacency matrix $A=[a_{ij}]$ to represent the Connections. If there is an edge between i and j, a_{ij}=l. (i.e. $L_{ij} \in L$); Otherwise , a_{ij} =0,which means there is no edge between i and j(i,j=1,2,…,n).There is an example in Figure 1, and the adjacency matrix is A.



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

Fig.1. A simple example

1) The degree of nodes

The degree of node i, represented as is defined as the number of the neighbours of node i. $D(i)$ is the sum of elements in the i-th row and i-th column in directed graph while only the sum of elements in the *i*-th row in undirected graph.

2) The levels of nodes

The levels of generation nodes reflect the influence of the nodes and transmission paths, which can be represented as $L\ (i)$. To acquire the calibration of the levels of generation nodes, we start from the source point, and sequentially search each levels of power supplying nodes on the base of adjacency matrix A. For convenience, we first number the generation nodes and transition nodes at last. Wang Qian [9] has expounded such a search method, nonetheless, the classification of the multiple generation nodes has not introduced. Our improved methods are as follows:

(1) Searching for the 1st level. The first target is to find out the generation nodes, then set it as the first level. If the system has multiple generation nodes, they are all defined as the first level, Then, we make the 2nd searching on the rest of the nodes from the power point separately. In Figure 1, node 1 is the generation node so is the 1st level node.

(2) Searching for the 2nd level. We search the row where the generation node is, and consider nodes with the position index, where the value is 1, are of 2nd level. In Figure 1, node 1 is the 1st level node, so we search the first row in adjacency matrix A, a_1=(0,1,1,0,0,0). For $a_1(1)=1$, $a_1(2)=1$, we obtain the 2nd level nodes is node 2 and node 3.

(3) Searching for the 3rd level. We continue search the 3rd level nodes based on the result above. We know the 2nd level node are node 2 and node 3, so we search the vector in A corresponding node 2 and node 3:a_2=(0,0,1,1,1,0), a_3=(0,0,0,0,1,0). From the same token, we can get:$a_2(3)=1$, $a_2(4)=1$, $a_2(5)=1$, $a_3(5)=1$. So the 3rd level nodes contain node 4 and node 5.

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The strategy to search for the level n nodes is based on the level n-1 nodes. When there are no elements 1 in the vector a_i, all the nodes have been attached with their level. In the search process, the same node that is searched from the same generation node may have different levels. We choose the higher levels (I>II>III……) to meet the "proximity principle"; Last but not the least, we choose the higher levels when we get the different levels for the same node that is searched from different generation node.

The scale scheme of node topology factors used in this paper is as follows: The rows represent degree, and the columns level.

Table 1 the scale scheme of the node topology factors

L \ D	≧5	4	3	2	1
1	0.1	0.2	0.3	0.4	0.5
2	0.2	0.3	0.4	0.5	0.6
3	0.3	0.4	0.5	0.6	0.7
4	0.4	0.5	0.6	0.7	0.8
≧5	0.5	0.6	0.7	0.8	0.9

There are the principles in Table 1, that importance of node is positive correlative with its degree and negative with its level.

The attributes parameter of the grid

1) The capacity of nodes

We use the load capacity per unit to reflect its capacity based on the scale of the grid.

2) The type of the nodes

The types of nodes are divided into two categories: the generation node and the substation node.

The model of importance evaluation

The network model of the power system

Power system is a large and complex system. In order to analysis in network view, some simplifications must be made according certain principles and logical relationships between the different parts. The principles of simplifications are as follows [10][11]:

(1) Only concern about power plants and high-voltage power transmission in power system, and simplify the remaining part of the distribution into one node;

(2) Regard the main wiring system of the power plants and substations as the nodes in the network graph, and the transmission as a directed edge connecting two adjacent nodes in the network graph;

(3) No matter how many circuits between power plants and substations, they are regarded as only one.

Power system can be simplified into the network model that contains only nodes and edges according to the principles above, which reflects the topology and logical relationships of power system.

The importance evaluation model of AHP

AHP: Analytic Hierarchy Process is a practical method for making a multi-factor decision.

Generally speaking, power plants should be the most important nodes, although its degree is very low. As it is shown in Figure 2

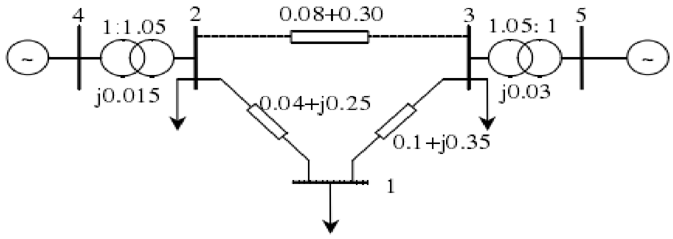

Fig.2. 5 bus system

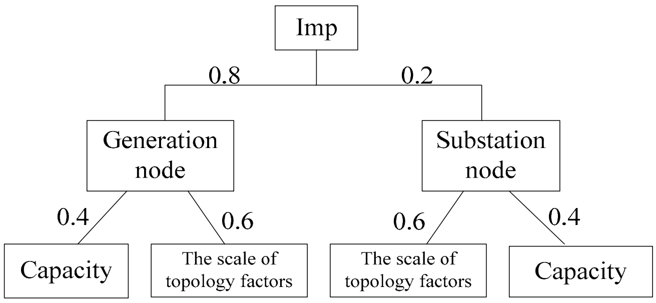

Fig.3. the analysis model of hierarchy evaluation weight

Note: The scale of topology factors is shown in Table 1.

We can find nodes with highest degree are node 2 and node 3. However, node 4 and node 5 are more essential to power system as they are the generator nodes, while they have lower degree.

Taking into account the "2-8 Principles" in economics (i.e.20% nodes would contribute 80% in the system), we assume the weights of generator nodes ω_1=0.8 while substation nodes ω_2=0.2. They are called the 1st level weight. In addition, the 2nd level weight contains degree, level and capacity. Among them, the degree and level are the topological properties, and the capacity is individual attributes. Their value should be determined according to their influences on the node importance. In this paper, tentative values are: ω_d=0.4, ω_l=0.4,ω_s=0.2. We can make the appropriate adjustments based on the scale of practical grid, the actual engineering features as well as the expert advice.

Figure 3 is the analysis model of hierarchy evaluation weight.

The comprehensive importance evaluation model

AHP establishes the index scale, and when there are too many nodes, the solution process will be cumbersome and difficult to defined hierarchy. Also there is a time-consuming problem. So, the paper presents a new model for importance evaluation, which makes up part of the shortages in AHP.

Now the importance of indicators definition of nodes is as follows:

$$imp = W \times \left[\left(\frac{1}{d_i} \times \frac{1}{\omega_d} + l_i \times \frac{1}{\omega_l} \right)^{-1} + S_N \times \omega_s \right] \tag{1}$$

Where, *imp* is the importance degree of nodes;

d_i, l_i are degrees and levels separately (unscaled);

W is the weights of nodes type (when the node is a generation node, W=0.8; and when it is substation node, W=0.2)

S_N is the node capacitance per unit; Meanwhile, in the right parenthesis formula, topological factor also be made by the normalization process to make it easy for summation;

Weights: ω_d=0.4, ω_l=0.4, ω_s=0.2.

The process of importance evaluation is shown in Figure 4:

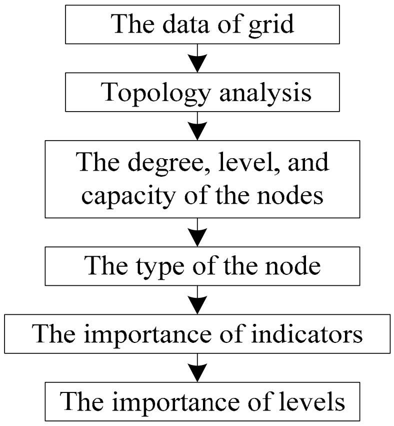

Fig.4. Evaluation process based on a comprehensive evaluation

The case analysis

Let the IEEE-14 nodes model for an example. Our method neglect the direction of edges in topology, the simplification of the model is shown in Figure 5. IEEE-14 nodes system benchmark capacity is 100MVA in the distribution network, and the initial load values of nodes are shown in Table 2.

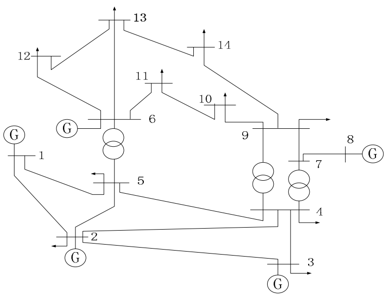

Fig.5. The analysis case model

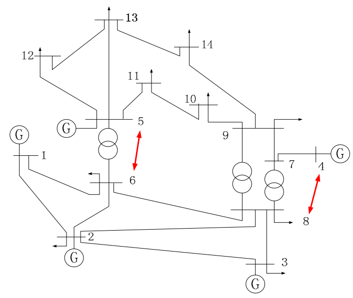

Fig.6. Case model after adjusted

To make it easy to number, we number generation node first. The adjustment is as follows: $4 \leftrightarrow 8$, $5 \leftrightarrow 6$. Model after the adjusted is shown in Figure 6:

Table 2 The initial load values of nodes

Node	P	Q	S	Node	P	Q	S
1	0.000	0.000	0.000	8	0.478	-0.039	0.479
2	0.217	0.127	0.251	9	0.295	0.166	0.338
3	0.942	0.190	0.961	10	0.090	0.058	0.107
4	0.000	0.000	0.000	11	0.035	0.018	0.039
5	0.112	0.075	0.135	12	0.061	0.016	0.063
6	0.076	0.016	0.078	13	0.135	0.058	0.147
7	0.000	0.000	0.000	14	0.149	0.050	0.157

Node 1 is the balanced node; node 2~5 are PV nodes; node 6~ 14 are PQ nodes; the shaded parts are the generator nodes; the rest are substation nodes. (Data taken from [13])

Calculating importance degree with each node by AHP model

The adjacency matrix of the system is as follow:

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

According to the search method modified in chapter 1.1.2, we carried out the levels search. To start with, we search from node 1.

I level search:Node1: 2,6

(As node 2 is in the generate node, the search after that no longer search the generating node)

II level search: Node 6: 8

III level search: Node 8: 6,7,9

IV level search: Node 7: 8,9; Node 9 : 7,8,10,14

V level search: Node 10: 9,11; Node 14: 9,13

VI level search: Node 11: 10 ; Node 13: 12,14

VII level search: Node 12: 13

Likewise, we search from all the generator nodes (node 2 to node 5), and the final level of each node is as follows:

I level Node: 1, 2, 3, 4, 5

II level Node: 6, 7, 8, 11, 12, 13

III level Node: 9, 10, 14

In the power system, due to distributed power, levels of node could not too high. It also means our calibration criterion is feasible.

Now, we set the node 1 for an example to calculate the importance of index:

$$(0.7\times 0.8+0.000\times 0.2)\times 0.8=0.448$$

Likewise, we obtain an importance index of each node in Table 3.

Table 3 The results of the importance index by AHP

Node	D	L	Scaling	Capacity	Imp	Node	D	L	Scaling	Capacity	Imp
1	3	I	0.7	0.000	0.448	8	6	II	0.8	0.479	0.147
2	6	I	0.9	0.251	0.616	9	5	III	0.7	0.338	0.126
3	4	I	0.8	0.961	0.666	10	3	III	0.5	0.107	0.084
4	2	I	0.6	0.000	0.384	11	3	II	0.6	0.039	0.098
5	5	I	0.9	0.135	0.598	12	3	II	0.6	0.063	0.0985
6	5	II	0.8	0.078	0.131	13	4	II	0.7	0.147	0.118
7	3	II	0.6	0.000	0.096	14	3	III	0.5	0.157	0.086

Note: Type 1 is the generator node, while type 0 is substation node. Each node data is shown by the histogram is as Figure 7:

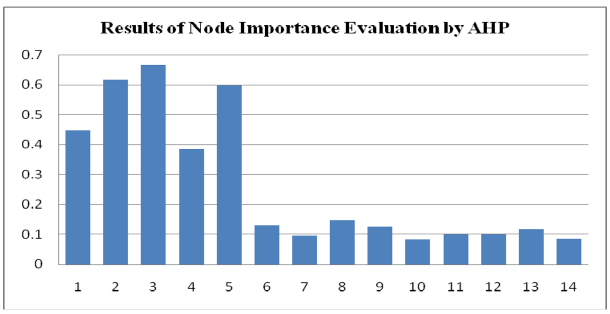

Fig.7. Results of Node Importance Evaluation by AHP

From Table 3 and Figure 6, the importance index generator nodes in descending order is:3>2>5>1>4 and the importance of substation in descending order is: 8>9>6>13>12>11>7>14>10; The degree of importance of the whole system node is:3>2>5>1>4>8>9>6>13>12>11>7>14>10.

The degree of importance of each node by comprehensive evaluation model

Based on formula (1), we use the node 1 as an example to compute the importance index:

$$imp\ 1 = 0.8 \times \left[\left(\frac{1}{3} \times \frac{1}{0.4} + 1 \times \frac{1}{0.4} \right)^{-1} + 0 \times 0.2 \right] = 0.240$$

Likewise, we obtain an important index of each node, and the results are shown in Table 4.

Table 4 the results of the important indicator

Node	D	L	Capacity	Imp	Node	D	L	Capacity	Imp
1	3	1	0.000	0.240	8	6	2	0.479	0.079
2	6	1	0.251	0.314	9	5	3	0.338	0.064
3	4	1	0.961	0.410	10	3	3	0.107	0.044
4	2	1	0.000	0.213	11	3	2	0.039	0.050
5	5	1	0.135	0.288	12	3	2	0.063	0.0502
6	5	2	0.078	0.060	13	4	2	0.147	0.059
7	3	2	0.000	0.048	14	3	3	0.157	0.046

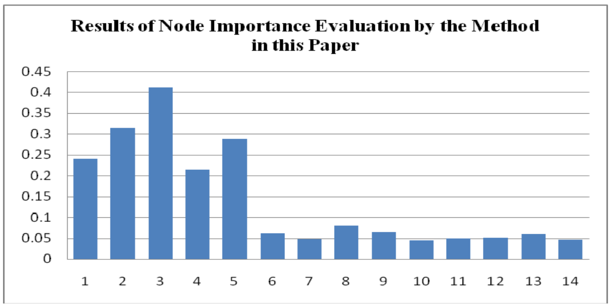

Fig.8. Results of Node Importance Evaluation by the Method in this Paper

As apparent from Table 3 and 4, the importance index of generator nodes in descending order is: 3>2>5>1>4. And substation nodes in descending order is:8>9>6>13>12>11>7>14>10; The importance index of all nodes in descending order is: 3>2>5>1>4>8>9>6>13>12>11>7>14>10.The results are consistent with the AHP.

The importance index curves by the two methods are drawn in the Figure 9.

The red curve shows the result by AHP and the blue one by our method. The two curves fit very well. We believe that the importance of one node is positive correlative with its degree and the capacity and the closer it is to the generator node, the more important it is. Therefore, our method can better distinguish importance of nodes. Besides, it can achieve progressive evaluation of the importance and respectively show the importance of the nodes in different levels. Since the method we have proposed does not involve meticulous level division, and it avoids deciding the topology scale by the degrees and levels. Meanwhile it prevents to construct overcomes fuzzy judgment matrix when the number of factors exceeds the upper threshold. So, in a large grid, the importance evaluation will be greatly simplified and accurate.

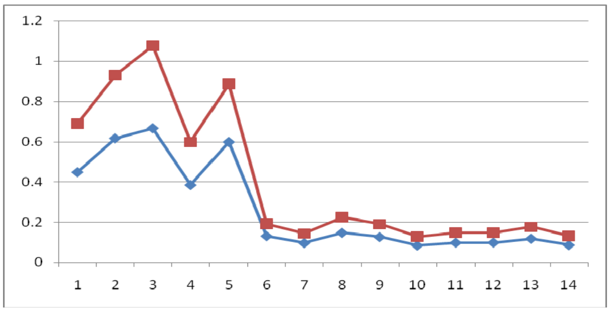

Fig.9. The results comparison of Assess the importance of the node

Summary

This paper has done some preliminary discussion in the evaluation of importance in the power system, and proposed a model to assess the importance. Meanwhile, it also provides a theoretical basis on the system for the identification of key nodes, which should be well protected. In addition, through a case study to verify its validity, drawing the following conclusions:

(1)The feasibility to identify the critical nodes in power system is verified in this paper. The critical nodes can be damaged by nature disasters as well as human factors, which lead to the problem of power flow or avalanche effect, and at last cascading failure occurs and results in widespread blackouts. So it is so important to identify the important nodes and focus on protecting them to decline the risks.

(2)The result of the experiment shows that our method of identifying critical nodes is efficient to the nodes that are of the same type as well as of the different type in the same level. The result of estimating can tell us which part should be focused on protected to prevent widespread blackouts. It is useful to reinforce the nodes of high importance or improve redundancy before the nature disasters or negative human factors appear.

References

[1] Callaway D S,Newman M E J,Strogatez S H,et al.Network robustness and fragility: percolation on random graphs. Phys. Rev. Lett. , 2000,85 (25) : 5468-5471.

[2] WANG Jia-sheng, WU Xiao-ping, LIAO Wei. Improved Method of Node Importance Evaluation in Weighted Complex Networks.Computer Engineering, 2012, 38(10): 74-76.

[3] WANG Xiao-guang, WANG Feng, LI Sen. Node Importance Evaluation of Communication Network Based on Betweenness Influence Matrix [J]. Journal of Air Force Engineering University, 2012, 13 (5): 80 - 84.

[4] Zhang Minqing,Wu Xuguang. Evaluating node importance in complex networks based on factor analysis [C]//International Conference on Computer Science and Network Technology (ICCSNT), 2011.

[5] Jun Hu,Bing Wang,Deyi Lee.Evaluating Node Importance with Multi-Criteria [C] // Green Computing and Communications (Green Com) ,2010.

[6] Chen Y, Hu A Q, Hu J, et al, A method for finding the most vital node in communication networks [J], High Technology Letters,2004,14(1):573-575.

[7] WU Run-ze, HU Xiu-yuan, TANG Liang-rui. Node importance evaluation strategy based on triangle module applying to optical communication network for power grid [J].Journal of North China Electric Power University, 2011, 38 (4) : 28 -32.

[8] ZENG Ying, WANG Ying, DONG Xi-jie, et al. Node importance evaluation strategy on electric power communication backbone network [J]. Journal of North China Electric Power University, 3012, 40(5).

[9] WANG Xi. Research on Seismic Function Failure Analysis and Security Control of Power Supply System [D]. Dalian University of Technology, 2012.

[10] FENG Fei. Analysis of Seismic Security and Control of Power Supply System [D]. Dalian University of Technology, 2006.

[11] LI Xiu-ju. Research on Seismic Function Failure of Power Supply System [D].Harbin, China earthquake administration institute of engineering mechanics, 2003.

[12] Liu Chun-guang, LI Xiu-ju. Studies on seismic function failure of electric power supply system [J].Eathquake Engineering and Engineering Vibration, 2010, 30(3).

[13] WANG Xi-fan. Analysis of Modern Power System [M].Science Press, 2003.3