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Dynamic analysis method of voltage stability in power system based on power flow betweenness[1]

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Abstract. With the rapid development of power system technology, power system represented by large power grid, large generator unit, long distance and high voltage has become the direction of the future development of power system. Under this background, a method for dynamic analysis of power system voltage stability based on power flow betweenness was proposed in this paper. The common fault analysis methods of power system were expounded in detail; then, the power flow system was simulated by the method of power flow betweenness; finally, the IEEE39 node system was used to validate the method. The results show that the power flow betweenness of the key nodes in the power system can reflect the possible problems in the power system under the influence of voltage and other factors.

Key words. Power system, voltage, power flow betweenness, fault simulation.

1. Introduction

The operation of modern society cannot be separated from the support of energy. Natural gas, oil and electricity are among the most common sources of energy in the society [1]. With the emergence of environmental protection problems, the use of natural resources, such as oil and natural gas, has gradually been limited. Electric energy has been widely used in social production and life. In particular, water, wind, solar, geothermal and other power generation methods are not only environmentally friendly, but also provide a continuous supply of energy for the normal functioning of human society [2]. As a result, electric energy is used more and more widely in current social production and life [3].

At present, large power grid, large unit, long distance and high voltage are the main directions of the development of power technology [4]. These technologies are of great importance to the current energy demand and ecological environment protection, but they bring great problems as well as positive tendency [5]. These

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new technologies pose a major challenge to the safety of power grid systems. For example, the increase of power supply and the limit of power grid have also begun to disturb the power system. Therefore, how to maintain the safe operation of power grid system has become the main research direction in the field of power [6]. In this context, a method for dynamic analysis of power system voltage stability based on power flow betweenness is proposed, which provides a reference for power system operation.

2. State of the art

In power systems, faults are often caused by voltage problems. When the power system fails, it will affect a considerable range of production and life. Therefore, how to judge the fault of power system has become the main problem of power system [7]. In the past, the power system fault diagnosis includes two kinds of computation models: unauthorized topology and weighted topology. The calculation method is similar to the betweenness calculation of communication network in information technology. However, it is built on the shortest route propagation of power flow, which is a fatal flaw. Therefore, the application of the two models has great limitations [8]. Therefore, according to the characteristics of power flow propagation in power grid based on Kirchhoff's law, an electrical betweenness model is designed. The model is more close to the actual situation of power flow propagation [9].

In the electrical betweenness model, the premise of the betweenness is that the power grid is undirected weighted network [10]. Although the electrical betweenness model is more close to the physical characteristics of the power grid than the two models of unauthorized topology and weighted topology, there are some defects in the model [11]. In the model of electrical betweenness, many problems such as the mode of operation of power system, the direction of power flow, the reactive power of grid and the voltage of power grid are not in the model of electrical betweenness. Therefore, there are many problems and defects in the calculation process. The stability research of power system has been continuously improved by many experts and scholars.

3. Methodology

3.1. Calculation of power flow betweenness in power system nodes

In the research of power system stability, from the earliest unauthorized topology and weighted topological model to the electrical betweenness model, the related technology and theory have been constantly changing and improving. However, there are still some defects and problems in these methods. For example, the electrical betweenness model that is closest to the physical characteristics of the power system has considered problems, such as voltage problems in power systems. Therefore, in the study with the method of dynamic analysis of power system voltage stability based on power flow betweenness, the calculation of AC model is added to the calculation of the electrical betweenness model. In other words, when calculating the betweenness of power system, the method of power flow calculation is adopted. The problem of stability of each node in power system is measured by power flow vectors, so as to judge the possible problems and the faults in power system. Nodes in power systems can be divided into three types of power generation, load and connection according to their nature. Supposing that the power flow betweenness of a node n is $B_f(n)$, the following formula can be used to express it:

$$B_f(n) = \sum_{i \in G.j \in L} \sqrt{W_i W_j} P_{ij}(n) \ . \tag{1}$$

Here, G and L in the above formula represent the set of two nodes of the generator and the load, respectively, and (i, j) represents all the "power-load" pairs in the power system. Index i represents the generator node, and index j represents the load node. Symbols W_i and W_j, respectively, represent the weight of the two nodes of power generation and load, and the weight represents the importance of the two nodes of power generation and load in the power system. Finally, $P_{ij}(n)$ represents the active power on the node n in the power system. The power flow betweenness of the power system is basically the same as that of the other betweenness indexes. That is to say, it can reflect the situation of power flow occupancy nodes in the whole power system by quantizing. But the power flow betweenness has more advantages in reflecting the voltage, power flow direction and operation mode of power system.

Before calculating the power flow betweenness of the whole power system, it is necessary to determine the active power flow between the power generation and load, and the power flow path between the two. This process can be achieved by tracing the flow. Fig. 1 shows the flow calculation process.

The whole calculation process is divided into six steps. The power flow needs to be calculated according to the basic parameters of the power system. Therefore, before the power flow calculation, the basic parameters of the whole power system should be determined. The first step of the power flow calculation is to calculate the AC flow in the power system by using the Newton-Raphson method. According to the calculation results, the power loss and the charging power of the whole power system are judged, and the magnitude and direction of the power flow in all the lines of the power system are determined.

In the second step, the power flow direction of the power system is judged according to the first step, and the power loss in each loop of the power system is incorporated into the power flow terminal node by the equivalent load. The charging power in the grid is incorporated into the nodes at both ends of the line in the same way.

The third step is to determine the shunt ratio of each node in the power system. Supposing that the injection power is for node i in the whole power system, the calculation method of the shunt ratio $K_{j,i}$ at the node J is as follows.

$$K_{j,i} = \frac{S_{O,j}}{\sum_{j=1}^{N} S_{O,j}} \ . \tag{2}$$

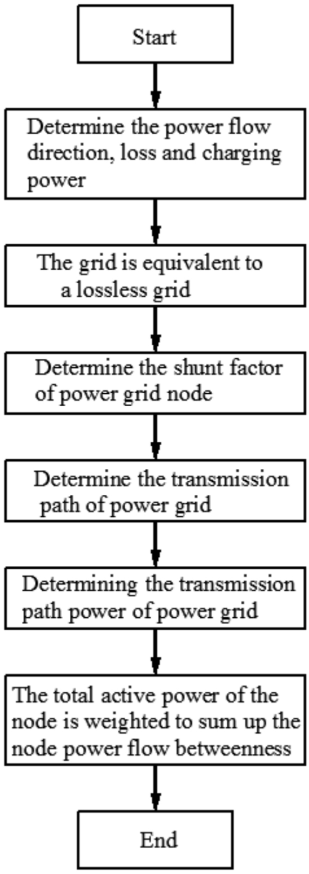

Fig. 1. Calculation procedure of power flow betweenness

In the above formula, $S_{O,j}$ represents the active power flowing out of the circuit system node J, M represents the number of injected power branches associated with the node, and N represents the number of branches that flow out at the node position.

The fourth step is to search the whole load node of the whole power grid from the starting point of the power system, which is the generator node, along the direction of the power flow, and to determine the transmission path between the two.

The fifth step starts from the initial node, calculates the load allocation of all generators in the power grid according to the results obtained in the third step, and then determines the power in each transmission path of the grid. Assuming that the transmission branch is i, the formula for the allocation $S_{j,i}$ of the injected power at the Jth branch is

$$S_{j,i} = K_{j,i} S_{I,i} \,. \tag{3}$$

Here, $K_{j,i}$ in the above formula is the allocation factor of third steps, and $S_{I,i}$ represents the active power injected on the ith branch.

The sixth step is to sum up all the active power of the nodes, and finally get all the power flow betweenness of the node. Through the power flow betweenness of the node, the fault of the node can be determined.

3.2. Power grid simulation based on power flow betweenness

After defining the calculation method and procedure of power flow betweenness, power system based on power flow betweenness is simulated in this paper. The simulation also considers the voltage of the grid in the power system as a whole. The possible problems in the whole power system are judged by simulation. In the process of power flow simulation based on power flow betweenness, the optimal load shedding model is adopted in this paper. The model can be expressed in the formulas.

$$\min C_{\mathrm{p}} = \sum_{i \in N} C_{\mathrm{p}i}\,, \tag{4}$$

$$\begin{cases} P_{\mathrm{g}i} - P_{\mathrm{d}i} - U_i \sum U_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}\right) = 0, \\ Q_{\mathrm{g}i} - Q_{\mathrm{d}i} - U_i \sum U_j \left(G_{ij} \sin\theta_{ij} - B_{ij} \sin\theta_{ij}\right) = 0, \\ \left(P_{\mathrm{d}i} - C_{\mathrm{p}i}\right) / \left(Q_{\mathrm{d}i} - C_{\mathrm{q}i}\right) = P_{\mathrm{d}i}/Q_{\mathrm{d}i}, \\ P_{\mathrm{g}i} \min \le P_{\mathrm{g}i} \le P_{\mathrm{g}i,\max}, Q_{\mathrm{g}i,\min} \le Q_{\mathrm{g}i} \le Q_{\mathrm{g}i,\max}, \\ U_{i,\min} \le U_i \le U_{i,\max} \\ 0 \le C_{\mathrm{p}i} \le P_{\mathrm{d}i}, 0 \le C_{\mathrm{q}i} \le Q_{\mathrm{d}i}, \\ P_{ij}^2 + Q_{ij}^2 \le T_{ij,\max}^2. \end{cases} \tag{5}$$

In formula (4), $_{\mathrm{p}i}$ represents the total load shedding for each load node in the grid and $_{\mathrm{p}i}$ represents the reduction of the active load at the node i. In formula (5), $P_{\mathrm{g}i}$ and $P_{\mathrm{d}i}$ represent the active power and active load at the node, $Q_{\mathrm{g}i}$ and B_{ij} represent the reactive power generation and reactive power load, $C_{\mathrm{q}i}$ represents the reactive load curtailment of the node i, G_{ij} and B_{ij} represent the real and imaginary parts of the element at the row i and column j of the admittance matrix, P_{ij} and Q_{ij} represent the active power and reactive power on the power network branch$i-j$, $P_{\mathrm{g}i,\max}$ and $Q_{\mathrm{g}i,\max}$ indicate the active power upper limit of the starting node (generator) i and the upper limit of reactive power output, $P_{\mathrm{g}i,\min}$ and $Q_{\mathrm{g}i,\min}$ represent the active power lower limit of the starting node (generator) i and the lower limit of reactive power output, $\theta_{ij} = \theta_i - \theta_j$ represents the difference of the phase angle at the two ends of the branch $i-j$, and $T_{ij,\max}$ represents the rated capacity of the branch $i-j$. The constraints in the formula are the constraints of node active power, reactive power, and the constant power factor before and after the load shedding, the output range of the generator set, the upper and lower limits of the node voltage, the node clipping load and the power flow of the grid lines.

4. Result analysis and discussion

In order to verify the applicability of power flow simulation method based on power flow betweenness, IEEE39 node system is used in this paper to verify. The degree of node in power system has a great influence on the fault of power system. If the degree of the node is relatively high, the number of transmission paths through the node will be relatively more, and the power flow betweenness will be relatively large. Fig. 2 shows the statistics of the cumulative distribution of the power flow betweenness in the IEEE39 node system. As can be seen from the diagram, the power flow betweenness is relatively high among several critical nodes in the IEEE39 node system. According to the statistical results, the nodes with more than 50 of the power flow account for only 6.79 % of the IEEE39 node system. The results show that the power flow node can reflect the importance of nodes in the power system. The voltage of these parts should be paid more attention to, and then the possible faults in the power system are warned in advance. In addition to these small number of key nodes, nearly 80 % of the node's power flow betweenness is between 0–30, which shows that the voltage concerns of these nodes can be lower than those of the critical nodes.

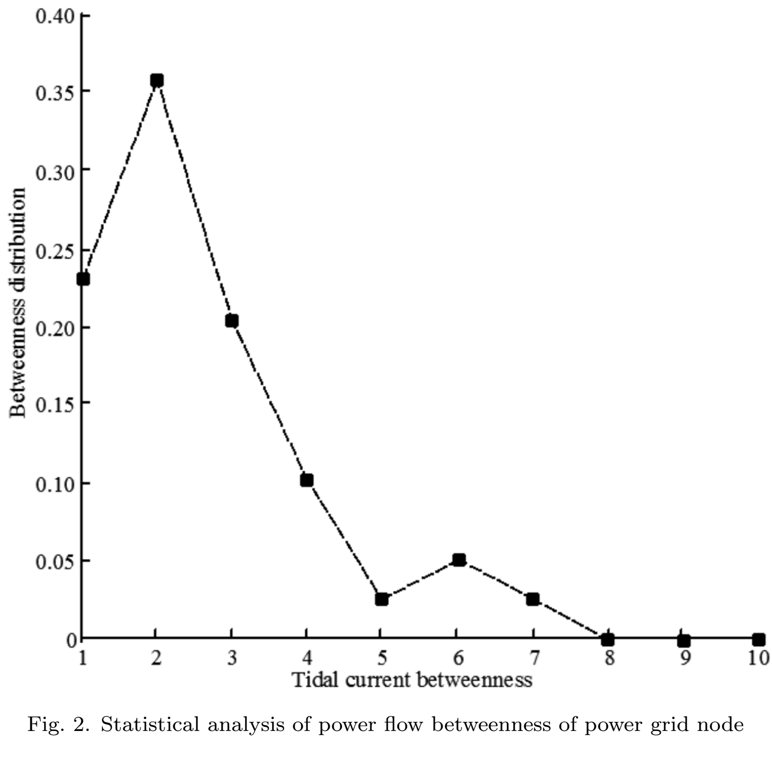

Fig. 2. Statistical analysis of power flow betweenness of power grid node

Table 1 shows the statistical results of the influence of the removal of nodes with different power flow betweenness on cascading failures. From the statistics in the table, it can be seen that in the simulation of power system faults based on power flow betweenness, the overall load shedding after power system failures is small. This kind of results can reflect the actual situation of power system more than the simple electric betweenness. The main reason for the results is that the power flow direction and the voltage of the power system are taken into account in the calculation of the flow betweenness. In other words, the power flow betweenness combines the actual conditions of the voltage of the power system, which can reflect the possible problems of power system more practically. The results also show that the voltage is larger when the flow is larger, and the contact node has a greater impact on the power system.

Table 1. Influence of different betweenness on power system faults

Node number	Betweenness sorting	Tidal current betweenness	Percentage of minimum load loss	node number	Betweenness sorting	Tidal current betweenness	Percentage of minimum load loss
1	30	10.17	1.66	21	19	16.70	11.01
2	17	19.85	0.21	22	9	29.36	13.22
3	28	12.00	5.15	23	15	20.69	11.54
4	8	32.15	8.00	24	24	14.32	13.34
5	4	46.02	10.36	25	20	16.60	6.82
6	1	66.60	26.64	26	31	8.94	5.01
7	16	20.53	3.74	27	34	7.60	10.99
8	6	34.51	8.35	28	36	6.40	3.29
9	39	2.85	0.10	29	25	12.77	8.42
10	2	50.57	7.19	30	32	8.04	5.80
11	11	28.30	10.02	31	5	38.43	5.97
12	37	5.33	0.14	32	3	50.57	3.59
13	14	22.26	8.82	33	13	26.74	10.47
14	22	16.10	9.29	34	38	5.08	7.49
15	18	18.63	18.99	35	10	29.36	9.02
16	7	32.96	14.09	36	33	8.03	9.11
17	27	12.15	12.52	37	212	16.60	2.75
18	29	10.80	6.65	38	26	12.77	32.60
19	12	26.74	17.90	39	35	7.47	17.65

Figure 3 shows the influence of margin coefficients on power system failures. When the power system fails due to voltage or other reasons, the effect on other nodes in the power system is mainly determined by the betweenness threshold of the nodes.

As can be seen from Fig.3, with the increase of the margin coefficient of different tidal currents, the percentage of minimum load loss in power system shows a downward trend. Moreover, for different fault nodes, when the margin factor is greater than 1.7, the minimum percentage of loss between the three essentially assumes a linear state, i.e., the percentage of minimum load loss is no longer changing. The results show that the power system is sensitive to single node faults when the margin coefficient is lower due to voltage and other reasons. With the increase of the margin coefficient, the resistance of the power system to the fault is improved to a certain extent.

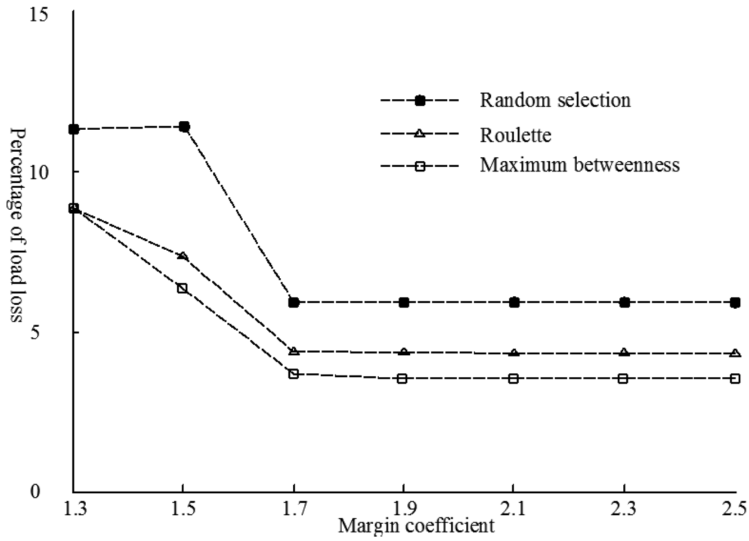

Fig. 3. Influence of margin coefficient on power system failure

5. Conclusion

With the increasing awareness of environmental protection, the application of fossil fuels represented by oil and natural gas in the production and life of human society has been more and more limited. Clean energy, such as power energy, has gradually been favored by all countries, and has been vigorously developed. However, electric power has many defects and problems while satisfying the requirements of human society for environmental protection. Therefore, in this context, the dynamic analysis method of voltage stability in power system was proposed in this paper. Various nodes in the power system were calculated by the power flow betweenness and the actual voltage in the power system. The influence of voltage and other factors on the fault of power system was analyzed by calculating the results. The method was validated by IEEE39 node system. The verification results show that the key nodes in the power system have the greatest impact on the power system, such as voltage and other factors. Therefore, the voltage of these nodes should be paid more attention to ensure the normal operation of the power system.

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