A method of power grid partition based on influence law of component reliability

Wenzhu Zhang¹, Yong Wang², Ying Ding³

¹²Key Laboratory of Power System Intelligent Dispatch and Control of Ministry of Education (Shandong University), Jinan, China
³State Grid of China Technology College, Jinan, China
940024322@qq.com

Abstract. In view of the increasing scale of power network and the complexity of reliability calculation, how to divide large power grid to reduce computational complexity is an urgent problem to be solved. In this paper, a partition method based on the rule of reliability influence between components is proposed to judge the area division of power network. By calculating the influence of component outage on the reliability index of other components, we can analyse the strength of the system regional relation, and partition the power system at the weakly connected nodes to reduce the computational complexity of reliability. At the end of the paper, we use the IEEE-RTS79 system model to simulate and calculate. By analysing the data and comparing with the partition results of other algorithms, we can verify the rationality of the proposed method.

1. Introduction
With the rapid development of science and technology in the modern era, the scale of China’s power grids has expanded and the degree of interconnection has been continuously improved. The problem of safe and reliable power system operation has become increasingly prominent. How to quickly and accurately assess the reliability level of the power system has important significance for system planning and safe operation. However, the reliability assessment of large power grids is very complex, involving a wide range of equipment components, a huge number of grid structures at various levels, and the operating environment is complex and changeable, so there is an urgent need to find a suitable method to reduce the computational complexity[1-3].

The actual large-scale power system is formed by the gradual development and interconnection of a number of local power grids. The internal connection of local power grid is close, but the connection between regional grid is weak, which is usually connected by a few tie lines. Therefore, it can be used to calculate the reliability of large power network in different areas, which can reduce the complexity of calculation and accord with the actual operation of power system at the same time[4-5]. Most of the existing researches on the structural characteristics of power systems are based on classical complex network models, which analyze the structural characteristics of power systems and their effects on fault propagation from the point of view of network topology. Among them, the community structure in complex networks is applied to study the topological segmentation of large power grids. The identification of the structure of the community is to simplify the elements and lines of the power grid to a topological structure, and identify the characteristics of the nodes and lines in the diagram, then divide the set of nodes and lines into a set[6]. In previous studies, some studies use the spectral
clustering algorithm to identify the power grid partition\cite{7}, some construct weighted directed power network models based on the connection impedance and power flow direction, and discover key nodes, vulnerable lines and topological partitions by digitized network mining\cite{8}. In addition, there are some researches on how to divide the region from the electrical connection of the system itself. One kind of method is to sort the nodes with some static voltage stability index, so as to determine the weak nodes and the weak areas composed of these nodes\cite{9}. Another method is to divide the system into several regions with single stability by analyzing the Jacobian matrix of power flow. The max-min electrical distance method\cite{10} and the mapping partition algorithm\cite{11} are also applied to the power network partition. Based on the above research, many current power grid partitioning methods are based on reactive power and voltage, but the results of this method do not necessarily accord with the actual situation of reliability calculation. Therefore, it is necessary to combine the reliability analysis index to find a suitable partition method.

This paper takes the power grid node as the research object, and carries out the reliability analysis of the power system by Monte Carlo method. We calculate the load loss of other nodes when each node is out of service, and then compare the load loss expectations of the same node under the condition of no outage. By analyzing and processing the data, we can partition it according to the law of its influence.

2. The basic theory and index of reliability analysis

The reliability calculation or adequacy calculation of large power network is a complex calculation, which includes three aspects: the acquisition of the system state and the analysis of the system under that state. Then a series of reliability indexes are calculated to quantitatively reflect the power transmission capacity of the network system. As far as the analytical enumeration method is used to calculate the reliability of the large power grid system, the formation of each index needs to enumerate a large number of system failure states, and then the system analysis of the failure states is carried out. This includes the basic flow calculation, judging whether there is component overload, judging whether the system dissolves, and the calculation of load reduction. Finally, the reliability index of the system and load points is formed.

Power system reliability analysis is the probability analysis and evaluation of the power system’s ability to supply continuously and uninterruptedly to each load point to meet the voltage quality required by the regulation within a specified time and under certain conditions by using the reliability index and find out the key link that affects the system reliability. The reliability analysis and evaluation of power system have different emphases, so the reliability index is different, but it can be expressed as the expected value of a measure function, as shown in the formula:

\[ E[f] = \sum_{x \in X} f(x)p(x) \]  

(1)

In the form, \( X \) is a collection of all the possible scenarios in power system reliability analysis. \( f(x) \) is a reliability measure function under scenario \( x \); \( p(x) \) is the probability of a scene happening.

The reliability of power system calculated by Monte Carlo simulation method can be expressed in the form of the following formula:

\[ E[f] = \sum_{x \in X} f(x) \cdot \frac{n_x}{n} = \frac{1}{n} \sum_{x=1}^{n} f(x) \]  

(2)

\( n \) is the total number of simulations, and \( n_x \) is the number of scenes \( x \) appears in the simulation process.

In this paper, the lost of load probability (LOLP) is chosen as the system reliability index. For each sub-sample of the system, the reliability measure function is defined as follows:

\[ f_{\text{LOLP}}(k) = \begin{cases} 1, & P_k > 0 \\ 0, & P_k \ll 0 \end{cases} \]  

(3)

\( P_k \) is the total power that cannot be satisfied in the system. When the simulation times meet the error requirement, the reliability index of the system can be obtained by substituting the reliability measure function of each sub-sample of the system into the formula.
3. Optimal Load Curtailment in Power System Reliability Evaluation

3.1. Load reduction in reliability analysis
Reliability evaluation of composite generation and transmission system consists of three parts: System state selection, system state analysis and system reliability index accumulation. System state analysis includes power flow calculation of selected system states to determine whether the system is in violation of operational constraints (node voltage constraints and line capacity constraints) and remedial measures are taken to adjust the system operating state. If the system can’t be restored to a safe state after adjustment, the system state is a failure state. As a final remedy, the system load reduction will be carried out. In system state analysis, these remedial measures are included in the optimal load reduction model. It can be seen that the optimal load reduction model is the most important part of reliability evaluation. For the formation of reliability adequacy index, only the state at this time will have the final impact. The optimal load reduction models discussed in this paper are linear DC models which not only satisfy the reliability accuracy but also ensure the calculation speed.

3.2. Optimal load reduction model
The template is used to format your paper and style the text. All margins, column widths, line spaces, and text fonts are prescribed; please do not alter them. You may note peculiarities. For example, the head margin in this template measures proportionately more than is customary. This measurement and others are deliberate, using specifications that anticipate your paper as one part of the entire proceedings, and not as an independent document. Please do not revise any of the current designations.

In the actual load reduction, the following two important load reduction principles are usually considered:
1) load relative to faulty component bus should be reduced as far as possible. (proximity principle)
2) load reduction should take into account the importance of the load.(Principle of reduction in importance)

These two practical reduction principles can be realized by adding weighting factors to the above optimal problems. The models used in this article are as follows:

\[
\min \sum_{i \in \text{ND}} W_i \cdot P_{ci} \tag{4}
\]

s.t
\[
TL = A \cdot (PG - PD + P_c) \tag{5}
\]
\[
\sum_{i \in \text{NG}} PG_i - \sum_{i \in \text{ND}} P_{ci} = \sum_{i \in \text{ND}} PD_i \tag{6}
\]
\[
PG_i^{\text{min}} \leq PG_i \leq PG_i^{\text{max}} \quad (i \in \text{NG}) \tag{7}
\]
\[
0 \leq P_{ci} \leq PD_i \quad (i \in \text{ND}) \tag{8}
\]
\[
|TL_i| \leq TL_i^{\text{max}} \quad (i \in \text{NL}) \tag{9}
\]

In the form, \( W_i \) is the weight coefficient of node \( i \), \( P_{ci} \) is the power that Node \( i \) cannot satisfy. ND is the load node set; TL is the transmission line active power flow column vector, A is the correlation matrix between transmission line power flow and node net injection, PG is a nodal generator output column vector, PD is a nodal generator output column vector, \( P_c \) is the column vector corresponding to the unsatisfied power of the node; \( PG_i \) is nodal generator output, NG is generator set, \( PD_i \) is the net injection of node i active load: \( TL_i \) is the active power flow of the transmission line of section I; \( TL_i^{\text{max}} \) is the maximum transmission capacity of line I. NL is a collection of transmission lines. In the actual calculation, different values of \( W_i \) can be used to simulate different strategies of power system rescheduling in order to meet the practical requirements.
4. Power system partition method based on component reliability index

4.1. Instructions on the method
For the large power system, the electrical connection between the node and the node is very weak, and the influence of the same element on the reliability of other elements is different. We can find an index to measure the influence of a generator node or line outage on the reliability index of other nodes, and use this index as the criterion of partition.

In this paper, based on the second optimal load reduction model and the method of generating system state by Monte Carlo random sampling, a reliability evaluation program for large power system is developed. The algorithm is used to analyze the reliability of the network and calculate the load loss of other nodes when a certain component is out of operation. The data are analyzed and processed by comparing the load loss expectation under the condition of no outage. According to the specific network structure to judge its influence law and carry on the division.

4.2. Algorithm flow
The specific steps of the program developed on the MATLAB platform are as follows:

1) Start the program, initialize the running state of the line and the unit, and initialize the failure probability of the equipment;
2) The iteration number i is set 1, and the result of node load loss is initialized to n(n for node number) × 1 zero matrix Loadloss. The number of simulations is defined as N;
3) Monte Carlo simulation is carried out to generate a number of random numbers that are uniformly distributed in 0 ~ 1, and compared with the failure rate of the equipment one by one, the fault state of the system is obtained: if the random number is less than the failure rate, the device will fail in this iterative simulation;
4) The topological parameters of the updated system are read, and the linear programming model of node load loss is solved by using the Cplex software package of IBM. The concrete model is shown in the second paragraph of this paper;
5) Obtain the node load loss matrix lol corresponding to the node number;
6) Update the node load loss result matrix (Loadloss = Loadloss + Lol);
7) update i = i + 1; determine whether the iteration number I is larger than the maximum number of simulation times N, if not, jump to step 3 to continue the simulation, if so, jump out of Monte Carlo simulation to step 8;
8) Calculate node expected loss of load: lolp = \frac{\text{Loadloss}}{N};
9) Setting up node I outage, that is, corresponding parameter is 0, repeat step 2 ~8, get the system and each node lose load expectation when discontinue node I;
10) Calculate the influence ratio of the node i outage on the load loss expectation of other nodes:
\[ P_{\text{Lost}} = \frac{\text{lolp}_1 - \text{lolp}_0}{\text{lolp}_0} \]
draw lists to visualize the results;
11) Terminate the procedure.

5. Cases
In this paper, the IEEE-RTS 79 network structure is used to analyze the partition method to verify the feasibility. At this time, the Monte Carlo random sampling times N is set to 30000 times, and the load capacity of each bus bar is set to 40%. The specific algorithm is shown above. Through the generator node outage experiment of the system, it is found that there is a certain regularity on the expected load loss of the other nodes when the generator node is disconnected. The data are as follows:
Table 1. Partial display of impact of Node 1~13 outage

| Initial result | Outage node 1 | $P_{lost}$ | Outage node 2 | $P_{lost}$ | Outage node 13 | $P_{lost}$ |
|----------------|--------------|------------|--------------|------------|----------------|------------|
| Node1          | 0.00119      | 0.04531    | 37.076       | 0.00469    | 2.941          | 0.05307    | 43.597    |
| Node2          | 0.00085      | 0.00692    | 7.141        | 0.19599    | 229.879        | 0.02723    | 31.035    |
| Node3          | 0.00856      | 0.11821    | 12.807       | 0.08125    | 8.492          | 0.21359    | 23.952    |
| Node16         | 0.03507      | 0.02615    | -0.254       | 0.03621    | 0.033          | 0.02924    | -0.166    |
| Node18         | 0.00605      | 0.00987    | 0.631        | 0.01067    | 0.764          | 0.02730    | 3.512     |

Because of the large number of data, this table selects part of the data display. It can be seen from the table data that when the nodes of 1 / 2 / 7 / 13 are out of operation, the LOLP of most nodes in the system will be affected, and the LOLP ratio of node 1~13 will be greatly affected. Combined with the system diagram, it is found that these nodes are basically in the system area of 138kv.

For the remaining nodes, the data is displayed in Table 2.

Table 2. Partial display of impact of Node 14~23 outage

| Initial result | Outage node 16 | $P_{lost}$ | Outage node 21 | $P_{lost}$ | Outage node 23 | $P_{lost}$ |
|----------------|---------------|------------|---------------|------------|----------------|------------|
| Node1          | 0.00119       | 0.00269    | 1.261         | 0.00362    | 2.042          | 0.04188    | 34.193    |
| Node2          | 0.00085       | 0.00128    | 0.506         | 0.00213    | 1.506          | 0.02337    | 26.494    |
| Node3          | 0.00856       | 0.00735    | 0.141         | 0.00613    | 0.284          | 0.13852    | 15.182    |
| Node15         | 0.00419       | 0.03124    | 6.456         | 0.02388    | 4.699          | 0.10899    | 25.012    |
| Node18         | 0.00605       | 0.03577    | 4.912         | 0.03223    | 4.327          | 0.07582    | 11.532    |

At this point, we can see that when the nodes 15 / 16 / 18 / 21 / 22 / 23 are out of operation, there may be great changes in the nodes 1~13 and 14~24, and the main effect is greater in the 14 / 24 nodes. According to the system structure diagram, these nodes belong to the system area of 230kv, so the law of influence is similar. Because these nodes are located in the high voltage 230kv region and may be transmitted to the low voltage region, the nodes in the lower voltage region may also be affected.

The data of Table 1 and 2 are clustered from large to small, and the influence range of each node can be obtained. In this paper, we use the principle of proximity to merge isolated nodes into regions with direct electrical connection or regions with similar voltage levels. The result of the partition is as shown in the Fig.2:
This result is consistent with the result that the electrical distance defined by the node impedance matrix is a partition standard. From this it can be seen that the node with similar influence law can be divided into a region by the change of the node load loss index so that it can be roughly partitioned so as to facilitate the subsequent reliability calculation. More precise partitioning boundaries can be found by defining more precise partitioning metrics, coupled with special processing of isolated nodes.

6. Conclusion
In this paper, a new way of dividing the power system is proposed. By using the optimal load reduction model to calculate the reliability of the power network, the change of the reliability index of the node is obtained. In this way, the influence relation among the components in the system is analysed to find the basis of the partition in the power network. After defining the criterion of partition, the area with strong electrical connection is divided by clustering. At the end of this paper, the IEEE RTS79 model is verified by partition, and the feasibility of this method is illustrated by comparison and analysis.

Acknowledgment
This work was funded by Power Grid Corporation of Guangxi (0002200000029827).

References
[1] Guo Y. RELIABILITY OF POWER SYSTEMS AND POWER EQUIPMENT [J]. Automation of Electric Power Systems, 2001.
[2] Jing Z, Kang C, Xia Q, et al. POWER SYSTEM RELIABILITY IN ELECTRICITY MARKET CURRENT STATUS AND FUTURE PROSPECTS[J]. Automation of Electric Power Systems, 2004, 28(5):6-10.
[3] Wang C, Zheng X U, Gao P, et al. Reliability Index Framework for Reliability Evaluation of Bulk Power System[J]. Proceedings of the CSU-EPAS, 2007, 19(1):42-48.
[4] Jiang M, Wu W, Zhang B, et al. A multi-area coordinated power dispatch method for provincial power grid[J]. Automation of Electric Power Systems, 2009, 33(22):10-14.

[5] Wei Y, Qiang G, Juan Y U, et al. An Algorithm for Hierarchical and Partitioned Regulation of Voltage and Reactive Power in Transmission Network[J]. Power System Technology, 2011, 35(2):71-77.

[6] Shi J, Tu G Y, Luo Y. Complex network characteristic analysis and model improving of the power system[J]. Proceedings of the Csee, 2008, 28(25):93-98.

[7] Zhao J, Yixin Y U. Determination of Power System Voltage Stability Regions and Critical Sections[J]. Automation of Electric Power Systems, 2008.

[8] Musirin I, Rahman T K A. Voltage stability based weak area clustering technique in power system[C]// Power and Energy Conference, 2004. PECon 2004. Proceedings. National. IEEE, 2004:235-240.

[9] Musirin I, Rahman T K A. Voltage stability based weak area clustering technique in power system[C]// Power and Energy Conference, 2004. PECon 2004. Proceedings. National. IEEE, 2004:235-240.

[10] Lei L I, Huang Y Q, Dong J D, et al. Optimization method of power network partitioning based on voltage/var control[J]. Power System Protection & Control, 2010.

[11] Zhao J, Liu F, Deng Y, et al. Network partitioning for reactive power/voltage control based on a mapping division algorithm[J]. Automation of Electric Power Systems, 2010, 34(7):36-40.