Identification of Critical Lines in Power Grid Based on Line Proportion

SUN Zhiyuan[1, a, *], LIU Mosi[1, b], LIU Peng[2, c]

[1]Guangxi Power Grid Electric Power Research Institute, Nanning, China
[2]Guangxi Power Grid Electric Science and Technology Department, Nanning, China
[a]sun_zy.sy@gx.csg.cn, [b]liu_ms.sy@gx.csg.cn, [c]liu_p.sy@gx.csg.cn

Keywords: critical line; power flow transfer; AC/DC hybrid power grid; cascading failures

Abstract: Critical lines in the power grid have an important role in the large-scale cascading failures. In order to improve the accuracy of the critical line identification and to prevent the blackout, a new method for identifying the critical line based on the line proportion is proposed. The proposed method defines a degree of flow transfer connection, weighted lines and then based on the absolute value of the change of the load rate of the tie line caused by the change of the active power of a certain line; the line proportion of each line is calculated and compared. Last, the simulation results show that the proposed method can quantitatively characterize the influence of power flow transfer on the load rate of tie lines due to the disconnection caused by a DC or a AC line fault. It has important significance to identify the weak lines in the power grid effectively and accurately, to determine their roles in the evolution process of self-organized criticality in AC/DC hybrid power grid, and it is of great significance prevent the cascading failure system to the critical state of evolution.

1. Introduction

With the aim of rapid growth of the national economy, State Grid of China is expanding its scale to adapt to the growing load demand; it is becoming more and more complex, and gradually forming a compound AC/DC hybrid power system. Considering the situation of AC/DC hybrid power grid and closely connected operation structure, the margin of safety and stability of the power grid has been decreased in some extent. In recent years, power grid blackout accident frequently happened around the world, such as the ‘7.30’and ‘7.31’ blackout in India, and the ‘8.14’ blackout in the North American. It affected numerous populations and led to irreversible huge economic losses and serious social impact [1-3].

The identification of critical lines is generally based on the assessment of grid vulnerability, which is mainly based on complex network theory [4-10] and Monte Carlo stochastic simulation. The literature [11-12] made a study on the fragile links through the change of the characteristic index of the network from the perspective of grid topology The literature [13] put forward a method of circuit electrical betweenness centrality, this method avoided the defect of assuming that power flow is only transmitted along the shortest path in the past. The literature [14-15] put forward an advice for analyzing the structural fragility of large-scale power grids. The literature [16] uses the number of nodes or branches to measure its criticality. The literature [17-18] considers weighted weights as a vulnerability indicator to identify critical lines. The literature [19] has made further improvements, by using the directional electrical system as an indicator to identify the network critical lines. The literature [20] combined with the power grid topology and system operating state, taking into account the power transmission relationship, the concept of power to quantify the concept of quantitative description of the critical line. The literature [21] puts forward the comprehensive betweenness index, which is considering the topology of power grid, power flow distribution, node voltage offset and relay protection action, to identify the critical lines of power grid.

Although above researches can identify the critical lines of power grid in some extent, the factors considered are incompletely, and only for the identification of the critical lines of AC power grid, it does not compatible with the nowadays AC/DC hybrid power grid.

In a summary, this paper defines the concept of line proportion, which can quantitatively characterize the DC line and quantitatively characterize the influence of the AC line on the surrounding lines, and can accurately identify the critical lines of the AC/DC hybrid power grid. At the same time, the method is applied to the critical line identification of a regional power grid in China Southern power grid, which verifies the validity of the critical line method based on the line proportion.

2. Modelling the radio of power grid line

According to the accident analysis of the previous blackout accidents, the main reason of the power grid failure is the power flow transfer. The special structure of the large-scale power system network determines that the tie lines in the power grid have anisotropy characteristics in the power transmission task. In the AC/DC power network, most of the DC lines and a small amount of high-voltage AC line have a high load level, can greatly enhance the transmission capacity of the power grid, but also may promote the expanding of the accident when face the chained fault. In the normal operation each line of the power grid has transferred a certain initial load. When a certain power grid failure happened, such as a heavy-duty AC line failure, it may cause commutation failure of the nearby DC system converter which has short electrical distance, and lead to DC line atresia, then the DC line atresia causes the changes of initial power flow distribution. After the power grid restored balance, the power flow redistributed, and it may lead to a few lines in the power grid bearing load which is more than the initial load, and result in overload operation. If these lines after power flow redistribution can’t support this part of the new load, it will lead to the power flow redistributing again, and then lead to other DC lines atresia because of the low voltage, result in the system chained failure, power grid instability, and a large area of power outages will happen. Assuming that the beginning of the accident is a fault on a heavy-duty line, it’s possible that the line near the fault will not be able to bear the excess load which is increasing greatly, and the possibility of a cascading failure will increase [22].

Thus, the connection between the components in the power system is very tight; the operation of each component may affect each other, resulting in unpredictable consequences. The effects of components can be quantitatively described by defining the relationship between the elements and the components. The relationship between components in the grid depends mainly on the following three aspects:

1) The material of lines and its inductance. The higher voltage level lines have smaller inductance and greater the ability to carry power in same length. Taking the reciprocal as the line weight value indicates that the line "position" is the more important in the line set.

2) The correlation of the components in the power variation;
3) The ability of the component bearing power flow.
The connection degree of the power flow transfer is defined as:

$$F_{i,j} = \varpi_j E_j P_i \tag{1}$$

$$\varpi_j = \frac{U_B}{\sqrt{3} I_B X_j l} \tag{2}$$

Equation (1) shows the connection degree of the power flow transfer that line i to the line j (connected by a same node) after the line i has failed. ϖ_j means the weight function of j line, using the reciprocal of the reactance per unit value of the line to express. In the calculation of reactance per-unit value, the reference voltage of the line is taken as the rated voltage U_B and the reference current of the line is taken as the rated voltage I_B, l is the length of the line. E_j is the absolute value of the change in the load rate of line j, which is due to the power change of line i. P_i is the active power standard per-unit value of line i for the normal operation of the grid. The connection degree of the power flow transfer degree is directional, that is $F_{i,j} \neq F_{j,i}$, under normal circumstances.

In actual operation, the DC line is normally operated in constant power mode. Therefore, it is not necessary to consider the change of the load rate of the DC line, so the breaking line around the DC line will not have influence on DC line.

The formula (1) shows that the connection degree of power flow transfer can quantitative repress the impact to the surrounding lines of the AC/DC lines which is after break for failure. The greater the connection degree of power flow transfer between Line i and line j, the deeper the impact of the line i on the line j due to the power flow transfer of the line, the more likely to break the line j, and then lead to the serious effect, power grid will happen major blackout accident because of the cascading failure [4].

In the study of the self-organized criticality of the power grid, the imbalance of the power flow distribution can be quantitatively described by the power flow entropy [23]. In some papers, the load rate of different lines is divided into several intervals, and the probability of each interval is obtained, then the entropy is calculated and the conclusion is drawn that the larger the entropy, the power flow distribution of the power grid is more nonuniform, the more easily the power gird get into the self-organized critical state. But under normal circumstances, the distribution of power flow and the accidents occurring in the case of cascading failure are not necessarily linked. Also, dividing the load rate into several intervals, then measuring the uniformity of the load distribution degree of evolution of the self-organized critical state of the power grid is not accurate enough. A high-load DC line, even if the load rate is relatively low, its fault will cause a huge flow of transfer to the surrounding line, leading to the next level line failure if without regard for cutting load and other control measures. The power grid is likely to have a cascading failure. However, if a high load rate of the line is cut after fault, the flow can be evenly distributed to the surrounding lines, then it will not lead to the surrounding line overload. It will not have a more adverse impact on the spread of the cascading failure. Because the main reason of the power grid failure is the power flow transfer, it is assumed the proportion of the sum of connection degree of power flow transfer that the line i on the surrounding line j and the average of the sum of the connection degree of power flow transfer that all lines to surrounding lines as line proportion, that is:

$$R(i) = N_l \frac{\sum_{j=1}^{N_0} F_{i,j}}{\sum_{i=1}^{N_l} \sum_{j=1}^{N_0} F_{i,j}} \tag{3}$$

In this formula, $F_{i,j}$ means connection degree of power flow transfer that line i to line j, according to the formula (1), N_0 is the sum of lines which connected to line i, N_l is the sum of lines.

3. Identification procedure of critical line

The line identification process of the power grid based on the line proportion is shown in Fig1. The main steps of the method are as follows:

1) Collect the topological information of the power grid;

2) Get the normal operation data;

3) Get the physical parameters of the line, such as the inductance;

4) Calculate the absolute value of the load rate change of line j caused by the change of active power of line i;

5) Calculate the connection degree of power flow transfer by the formula (1) and (2);

6) Calculate the line proportion by formula (3)

7) Determine whether to traverse all lines in the power grid, if satisfied, then turn to step 8), otherwise turn to step 4);

8) Sorting according to the calculation results of the line proportion, get the ranking of the critical lines in the power grid.

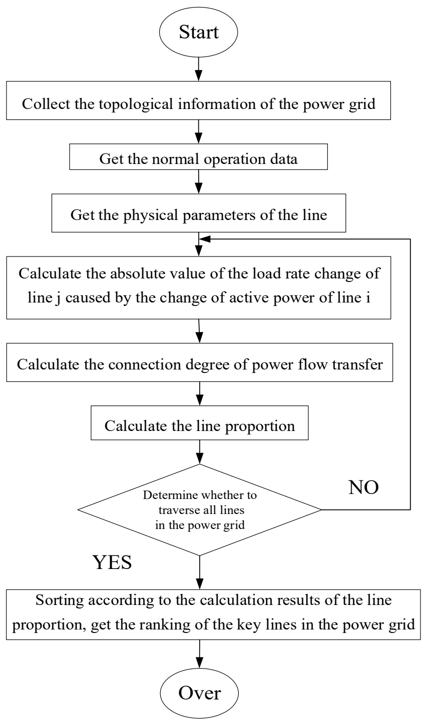

Fig.1 Critical line identification process

4. Example analysis

In order to analyse and verify the correctness and validity of the critical line ranking based on line proportion according to the method in the paper, this paper takes flood season large power flow of a regional power grid in the south to simulate and verified. The PSASP were used to simulate and analyse. According to line proportion of the all DC lines and 500kV AC line in whole power grid, the line proportion of the top 20 results shown in Table 1. These lines in the table are the most important twentieth line of transmission in the power grid. If one of these lines failures, it may cause a major power flow transfer, and then cause cascading failure. Select the Tianguang DC line(Line proportion is 2.78, ranked fifth) and the Congxi-Boluo (line proportion is 0.58, ranked 91th) double-circuit line as comparison objects, the geographical wiring diagram nearby shown in Figure 2 and Figure 3. Tianguang DC bipolar transmission power is 1800MW, Congxi-Boluo AC double-circuit line transmission power is 1991MW, the power is similar; and Taichung DC is the DC transmission lines, Congxi-Boluo AC is the AC transmission lines, the electrical distance is similar, they fit as comparative objects. Disconnect the Tianguang DC bipolar and the Congxi-Boluo AC double-circuit line respectively, and observe the change of the power flow of the surrounding DC lines. The results are shown in Table 2, Table 3, Figure 4 and Figure 5 (assuming a rated load factor of 1).

Tab.1 Top 20 critical lines of a southern regional power grid

No.	Type	Line	Power(MW)	Proportion
1	DC	Niucong DC line	6400	5.17
2	DC	Chuhui DC line	5000	4.29
3	DC	Puqiao DC line	5000	4.11
4	DC	Xing’an DC line	3000	3.37
5	DC	Tianguang DC line	1800	2.78
6	DC	Gaozhao DC line	3000	2.49
7	AC	Guilin-Xianlingshan	3101	2.33
8	AC	Xianlingshan –huandu	2433	2.25
9	AC	Yunlin-Maoming	2197	2.11
10	AC	Nanning- Yunlin	2075	2.02
11	AC	Wuzhou-Luodong	1616	1.98
12	AC	Hezhou-Luodong	2508	1.94
13	AC	Pingguo-Laibin	1995	1.82
14	AC	Laibin-Wuzhou	1911	1.80
15	AC	Huadu-Beijiao	1787	1.77
16	AC	Luodong-Beijiao	1153	1.70
17	AC	Shunde-Xiangshan	1230	1.67
18	AC	Tian’er-Pingguo	1753	1.63
19	AC	Longtan-Shatang	2410	1.63
20	AC	Luoping-Baishe	2224	1.59

In Table 2, Tian’er220-Tianer is the three-winding transformer, the load rate in the table refers to the actual capacity and rated capacity proportion. From Table 2 , Table 3 , Figure 4 and Figure 5 we can tell that after Tianguang DC failure, the surrounding AC line load rates have improved, like Mawo-Tian’er220 AC line load rate has reached 1.418, Tian’er220-Tianer transformer has also exceeded the rated capacity, so Tianguang DC line failure has a great impact on the surrounding AC line load rate, it’s likely to trigger the failure of next level and eventually lead to cascading failure; compared with this, after the failure of Congxi-Boluo AC line, only the load rate of Congxi-Huadu AC line and Congxi-Canyuan AC line have increased, the other lines’ load rate remain unchanged or even decline, therefore, the effect on the power grid of the failure of Congxi-Boluo AC line is small.

Tab.2 The Change of AC Line Load Rate around Tian-Guang HVDC Line before and after the fault

No.	Line	Load Before Fault	Load After Fault
1	Mawo-Tian’er220	0.136	1.418
2	Tian’er 220-Tian’er	0.053	1.122
3	Huadu-Beijiao	0.678	0.886
4	Beijiao-Luodong	0.279	0.765
5	Mawo-Baishe	0.408	0.620
6	Mawo-Tian’er	0.115	0.428

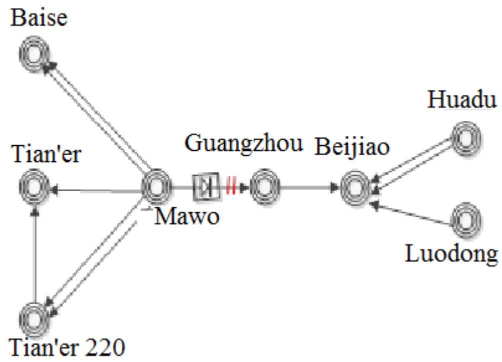

Fig.2 Geographical Connection Diagram of Tian-Guang DC Line

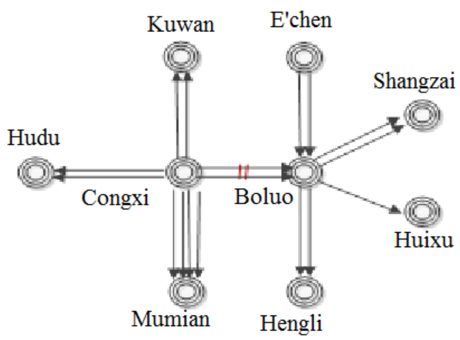

Fig.3 Geographical Connection Diagram of Congxi-Boluo AC Line

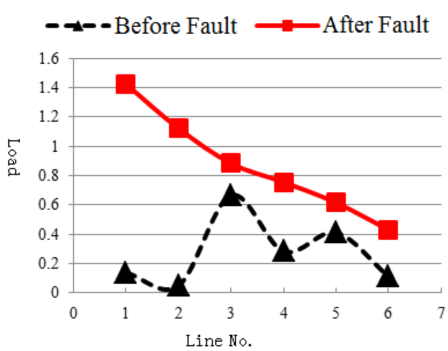

Fig.4 The Change of AC Line Load Rate around Tian-Guang DC Line before and after the fault

With the formula (3), the proportion of Tianguang DC line is calculated at 2.78, the proportion of Congxi-Boluo line is 0.58. The larger the line proportion, the more important the line is in the evolution and propagation of the cascading failure.

Tab.3 The Change of AC Line Load Rate around Congxi-Boluo AC Line before and after the fault

No.	Line	Load Before Fault	Load After Fault
1	Echeng-boluo	0.707	0.700
2	Congxi-Huadu	0.148	0.502
3	Boluo-Huixu	0.568	0.453
4	Congxi-Mumian	0.405	0.386
5	Congxi-Kuwan	0.092	0.161
6	Boluo-Hengli	0.524	0.131
7	Boluo-Shangzhai	0.056	0.013

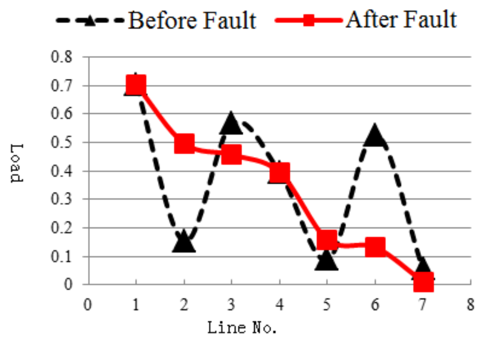

Fig.5 The Change of AC Line Load Rate around Congxi-Boluo AC Line before and after the fault

Tab.4 The first 10 critical lines from south grid

No.	Type	Line	Proportion	Status after DC Line Blocked
1	DC	Niucong	5.17	Multiple lines overload and unstable
2	DC	Chuhui	4.29	Multiple lines overload and unstable
3	DC	Puqiao	4.11	Multiple lines overload and unstable
4	DC	Xing'an	3.37	Multiple lines overload
5	DC	Tianguang	2.78	Multiple lines overload
6	AC	Gaozhao	2.49	Multiple lines overload
7	AC	Guilin-Xianlingshan	2.33	Stable
8	AC	Xianlingshan –huandu	2.25	Stable
9	AC	Yunlin-Maoming	2.11	Stable
10	AC	Nanning- Yunlin	2.02	Stable

5. Conclusions

This paper put forward the concept of line proportion. The method takes the electrical distance into account, and can be applied to AC and DC hybrid power system. The importance of the line is determined by the influence of the power flow transfer on the load rate of the peripheral line due to the interruption of a line of the power grid. The greater the impact, the greater the line proportion. And the influence of the fault on the power flow of the surrounding lines is greater, the greater the possibility of further cascading trip and then lead to cascading failure.

Based on the test of a regional grid system, it is verified that the critical lines of the power grid identified by the line proportion identification method, it can find the weak lines in the hybrid power grid and prevent the system to the critical state of the cascading fault. It has an important practical value.

References

[1] YIN Yonghua, GUO Jianbo, ZHAO Jianjun, et al. Preliminary analysis of large scale blackout in interconnected North America power grid on August 14 and lessons to be drawn[J]. Power system technology, 2003, 27(10):8-11.

[2] XUE Yusheng.The way from a simple contingency to system-wide disaster[J].Automation of Electric Power Systems,2003,27(18): 1-6(in Chinese).

[3] ALBERT R,ALBERT I,NAKARADO G L.Structural vulnerability of the North American power grid[J].Physical Review E,2004,69(2): 025103/1-025103/4.

[4] LIU Xiaoli,MAO Yi,LIANG Shan, et a1. Identification of vulnerable lines in power grid based on comprehensive betweenness index[J]. Power SyStem Protection and Control, 2016, 44(2): 116-121.

[5] ALBERT R, JEONG H, BARABASI A L. Error and attack tolerance of complex networks[J]. Nature, 2000,406(6794): 378-382.

[6] WATTS D J, DODDS P S, NEWMAN M E J. Identity and search in social networks[J]. Science, 2002,296(5571): 1302-1305.

[7] DODDS P S, MUHAMAD R, WATTS D J. An experimental study of search in global social networks[J]. Science,2003, 301(5634): 827-829.

[8] NEWMAN M E J. The structure and function of complex networks[J]. Nature, 2003, 45(2): 167-256.

[9] CAO Yijia, CHEN Xiaogang, SUN Ke. Identification of vulnerable lines in power grid based on complex network theory[J]. Electric Power Automation Equipment. 2006, 26(12):1-5,31.

[10] LIANG Ying, FANG Ruiming, LU Xiaofen, et al.Research status of power system vulnerable line identification based on complex-network theory[J].Power System Protection and Control, 2012, 40(20):151-155.

[11] JU Wenyun, LI Yinhong. Idectification of critical lines and nodes in power grid based on maximum flow transmission contribution degree[J]. Automation of Electric Power System, 2012, 36 (9): 6-12.

[12] NI Xiangping, MEI Shengwei, ZHANG Xuemin. Vulnerability assessment on transmission lines based on complex network theory [J]. Automation of Electric Power Systems, 2008, 32(4): 1-5.

[13] LIU Ying, WANG Tao, GU Xueping. Screening of critical lines in power systems based on the edge tenacity index[J]. Power System Protection and Control, 2012, 40(6):92-103.

[14] XU Lin, WANG Xiuli, WANG Xifan. Electric betweenness and its application in vulnerable line identification in power system[J]. Proceedings of the CSEE, 2010, 30(1): 33-39.

[15] CHEN Xiaogang, SUN Ke, CAO Yiyij. Structural Vulnerability Analysis of Large Power Grid Based on Complex Network Theory[J]. Transactions of China Electrotechnical Society, 2007,22(10):138-144.

[16] KINNEY R, Crucitti P, ALBERT R, et al. Modeling cascading failures in the North American power grid[J]. The European Physical Journal,2005,46(1):101-107.

[17] MOTTER A E, LAI Y-C. Cascade-based attacks on complex networks[J].Physical Review E,2002,66(2):1-4.

[18] DING Ming, HAN Pingping. Small-world topo－logical model based vulnerability assessment algorithm for large-scale power grid[J]. Automation of Electric Power System, 2006, 30(8): 7-10, 40.

[19] LIU Yaonian, SHU Qian, KANG Kefei, et al. Identification of vulnerable lines in power grid based on the weighted reactance betweenness index[J]. Power System Protection and Control, 2011, 39(23): 89-92, 100.

[20] ZHANG Fuchao, XIE Chengrong, SHEN Lixin, et a1. Identification of power grid critical lines based on path chains and transmission betweenness[J]. Power System Protection and Control, 2015, 43(21):7-12.

[21] WANG Tao, GAO Chengbin, GU Xueping, et al. Power betweenness based identification of power grid critical links [J]. Power System Technology, 2014, 38 (7): 1907-1913.

[22] HE Jun.The analysis of power system cascading failure based on complex network theory[D].Beijing：Northeast Electric Power University, 2013.

[23] LIU Wenying, CAI Wantong, DAN Yangqing, et al. The evolution of grid's self-organizing critical state based on entropy theory under the circumstance of large scale wind power connecting to grid centrally[J]. Power System Technology, 2013, 37(12): 3392-3398.