Energy and Power Engineering, 2017, 9, 735-747
http://www.scirp.org/journal/epe
ISSN Online: 1947-3818
ISSN Print: 1949-243X

DC Emergency Power Control Strategy for AC/DC Multi-Channel Interconnected System

Yicong Wang[1], Dejun Shao[2], Zhiqiang Zhang[3], Youping Xu[2], Xiaojie Pan[2], Haishun Sun[1]

[1]State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan, China
[2]Central China Branch of State Grid Corporation of China, Wuhan, China
[3]China Electric Power Research Institute, Beijing, China
Email: yicongwang@hust.edu.cn

How to cite this paper: Wang, Y.C., Shao, D.J., Zhang, Z.Q., Xu, Y.P., Pan, X.J. and Sun, H.S. (2017) DC Emergency Power Control Strategy for AC/DC Multi-Channel Interconnected System. *Energy and Power Engineering*, **9**, 735-747.
https://doi.org/10.4236/epe.2017.94B079

Received: March 29, 2017
Accepted: April 10, 2017
Published: April 17, 2017

Abstract

Inter-regional transmission line fault often results in power flow transferring, tie-line overloading and system islanding. Traditional control methods such asgenerator tripping and load shedding are costly, and also have undesirable impacts on theloadside. In this paper, a new emergency power control strategy is proposed for multi-channel interconnected system by using the overload capacity of non-fault DC lines. First of all, the capacity of emergency power control can be acquired by critical transmission power of a certain tie-line for stability. Secondly, the shortest electric distance can be calculated by Dijkstra algorithm, and then the priority of emergency control of the DC lines can be obtained by the entropy weight method. When the inter-regional transmission power decreases and the effect of single DC line emergency control is poor, the multi-channel cooperative emergency control strategy is proposed to ensure the system stability. Simulation results verify the effectiveness of the method proposed.

Keywords

DC Emergency Control, Critical Stable Transmission Power, Dijkstra Algorithm, Entropy Weight, Multi-Channel Cooperated Emergency Control

1. Introduction

With the rapid development of inter-area transmission connection, the capacity of transmission power increases greatly and the electrical interconnection distance between different areas become closer [1]. In China, more power plants are built in the west, whereas the huge demands for electricity lies in the east. In order to reduce the transmission loses, the high voltage direct current transmission (HVDC) lines have been constructed for power transmission and eventually form the configuration of multiple HVDC connecting different areas.

In order to improve the stability of system operation, multiple HVDC inter-area transmission lines operate in parallel. By the year 2014, three HVDC lines have been constructed connecting Southwest power grid to Huadong power grid while four HVDC lines transmitting power from Huazhong power grid to Huadong power grid. By the year 2018, Yu'e back-to-back HVDC line will be available, thus the connecting tie-line between Southwest power grid and Huazhong power grid will double. More inter-area HVDC tie-lines will be built in the future.

Despite of the benefit of HVDC multi-transmission lines, many challenges and potential risks occur at the same time. If a HVDC tie-line is tripped after a serious fault, it will definitely block a huge amount of power transmission and therefore result in power flow transferring. Many lines will trip because of the over loads and islanding devices may probably take action, separating the whole system into small islands. Then more loads will be lost later.

DC emergency power control technology can improve the capacity of power transmission after a block fault happens, and improve system transient stability [2]. Many studies have been conducted on this field. Reference [3] discusses the optimum controlling start time point and capacity by the derivative of active power, bus voltage and regional relative angle, while reference [4] settles the same problem through neural network method. Reference [5] and [6] focus on the voltage stability and characteristics of loads in emergency control, respectively. Reference [7] designs a new DC emergency control strategy based on the time optimal and auto disturbance rejection tracking control theory. Reference [8] [9] analysis the system transient instability probability model and the economic control cost of DC modulation, generator tripping/load shedding and other emergency measures.

In this paper, a new emergency strategy is proposed to solve the problem that if a HVDC line trips in multi-HVDC transmission system. First of all, a general description of the structure and stability analyses of multi-HVDC transmission system is given. Next, specific control methods such as the time point of start/stop and the capacity of power control will be demonstrated. Furthermore, Dijkstra algorithm has been used to obtain the shortest electric distance, and entropy weight method is established to set the priority of controlling order. Finally, a complete emergency strategy based on multi-channel cooperation is presented and verified by simulations.

2. Structure and Stability Analyses of Multi-Chanel Inter-Connected System

2.1. Structure of Multi-Channel Interconnected System

Regional power grids are often connected by multiple DC lines to improve transfer capability and stability. Typical structure of multi-channel interconnected system can be found in China as shown in **Figure 1**. The centre grid is

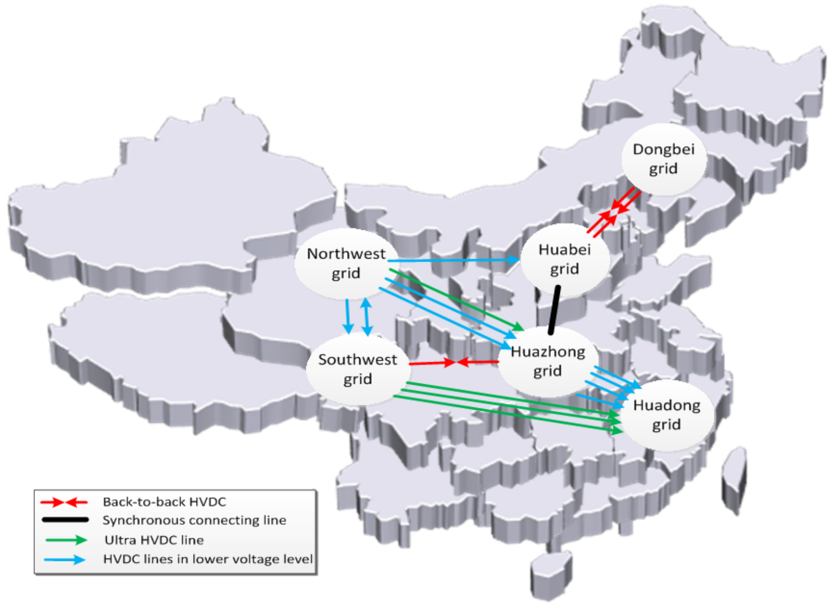

Figure 1. Power grid tie-line diagram of China.

Huazhong power grid, connecting northwest power grid through Hazheng/Lingbao HVDC lines to the west, connecting Huadong power grid through Genan/Longzheng/Linfeng/Yi hua HVDC lines to the east and connecting Huabei power grid synchronously through Changnan line to the north. Besides, another three HVDC lines (Fufeng/Binjin/Jinsu) connect southwest power grid to Huadong power grid, forming a typical hybrid AC/DC power grid configuration.

2.2. Stability Analysis

The power transmission capacity between Huazhong and Huadong power grid will decrease if a block fault happened in Longzheng HVDC line. A huge amount of power electricity will be blocked in Huazhong power grid, resulting in serious power flow transferring and severe power fluctuation on Changnan transmission line. The generator angle of Huazhong power grid gradually goes ahead, islanding devicescut off the Changnan synchronous line when the connected two areas cannot remain synchronous. **Figure 2** and **Figure 3** shows the fluctuation of Changnan transmission line and regional generator relative angle, from which we can observe that the relative angle goes different after the fault. Changnan line opens at 2.6 second. Even though the islanding strategy can prevent the blackout, extra load and generators need to be tripped, and thus causes enormous economic losses.

3. Strategy on Emergency Power Control

3.1. The Capacity of Emergency Power Control

N-1 security criteria shows that power system can stand certain amount of disturbance such as the single line outage. According to N-1 security criteria, if one

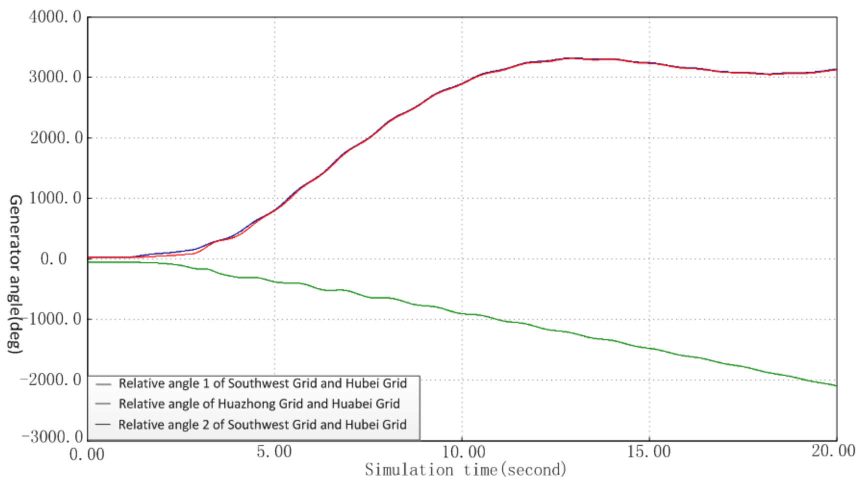

Figure 2. Regional generator relative angle.

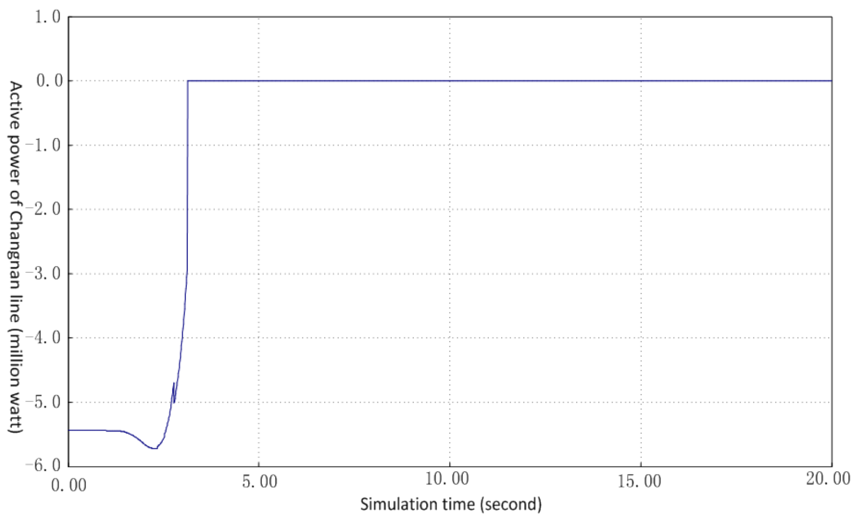

Figure 3. UHV tie-line transmission power fluctuation.

of the interconnected channels is cut off after a fault, the whole interconnected system can remain synchronized if the capacity of transmission power is above a certain minimum value. This minimum value can be defined as the critical transmission power ($P_{i,min}$) for stability , and can be calculated through off-line simulation as follows.

To find the $P_{i,min}$ of line *i* and reduce the transmission power of HVDC line *i* gradually as a disturbance, until the connected two system cannot keep synchronized. The critical remaining transmission power is $P_{i,min}$ shown in **Figure 4**.

Suppose line *I* trips for the sake of a fault. If the other paralleling HVDC lines are able to transmit more power instantly than $P_{i,min}$ in total as an emergency control, then the system can remain synchronized.

Therefore, we can get the power capacity of emergency control by Equation (1).

$$P_{i,\varepsilon} = P_{i,\min} \times \alpha \tag{1}$$

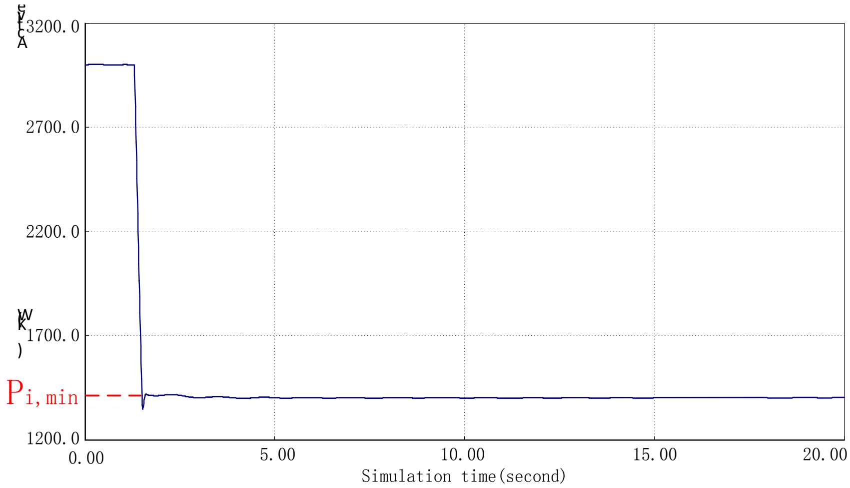

Figure 4. Single DC line critical stable transmission power.

where $P_{i,c}$ indicates the capacity of emergency control. To improve the effect of emergency control, the capacity is often a little bit more than $P_{i,min}$, which means the value of α should be 1.2 - 1.3.

3.2. Time for Start and Stop

1) When to start

If the blocking faults happen on transmission lines, not only the generation angle will become different but also its operating point will deviate from the original one. Therefore, the emergency control should take effect as quickly as possible after the fault, otherwise, it will lose its effect.

To demonstrate the viewpoint above, the case of bipolar blocking fault in Longzheng HVDC is given. Linfeng HVDC line increases transmission power at different time point as emergency control. In **Figures 5-7**, it is shown that the later emergency control starts, the larger the relative angle, the lower bus voltage and the more severe power fluctuation will be. Emergency control will fail if it is started later than 2 seconds after the fault.

However, take the signal transmission time into consideration, the emergency control strategy is often demonstrated 0.3 second delay after the fault [2].

2) When to stop

To diminish the bad influence when regional relative angle swings back from the peak point, the regional relative angle should be monitored by the PMU devices on both terminals of Changnan transmission line, and a signal should be sent to stop the emergency control when the relative angle reach the peak point (shown in **Figure 8**) at the first time.

4. Multi-Channel Cooperated Emergency Controlling Strategy

4.1. Parameters for Priority Control Order

To define the priority control order parameter, two aspects should be considered: HVDC available transmission power and the electrical distance.

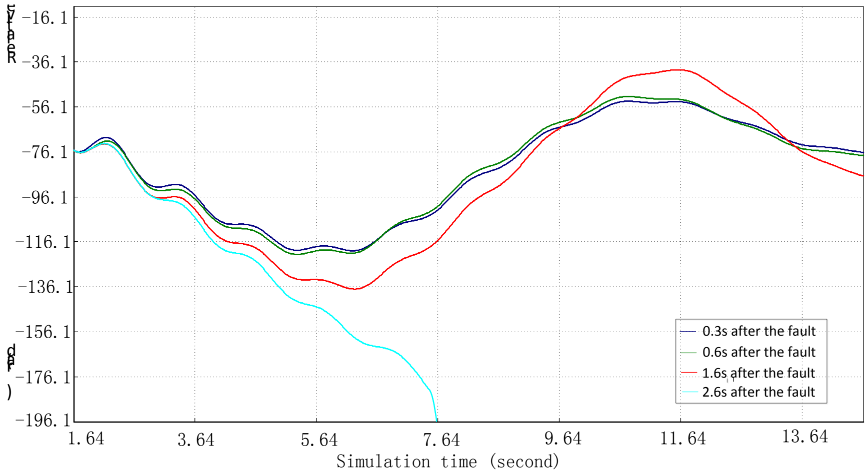

Figure 5. Generator relative angle.

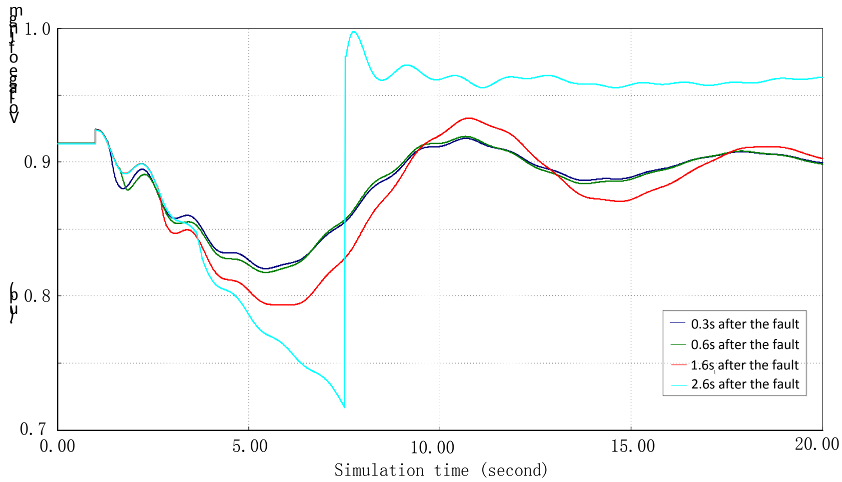

Figure 6. Voltage of Bus Jingmen.

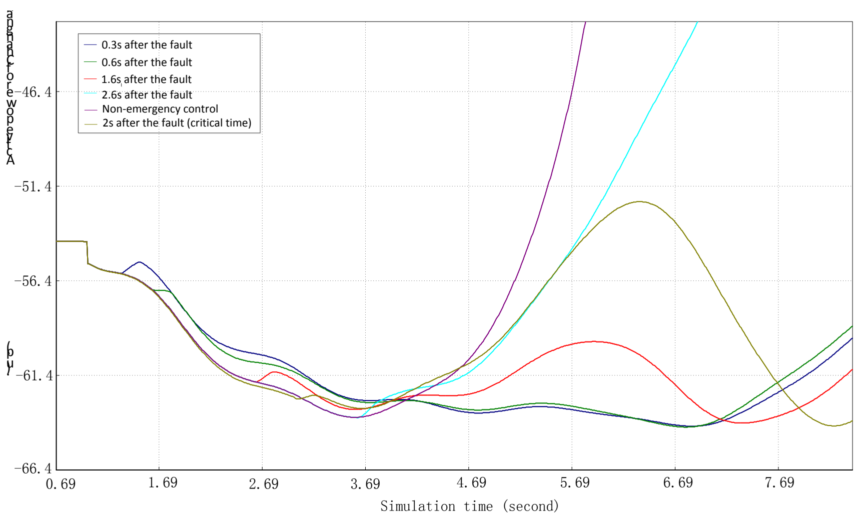

Figure 7. UHV tie-line transmission power fluctuation.

1) HVDC available transmission power

HVDC available transmission power (ATP) indicates the overload capacity of non-fault DC lines. A normal HVDC line can sustain 1.5 times rated power overload for 3 to 10 seconds and 1.1 times up to 2 hours [10]. Making full use of the overload capacity can increase interconnecting transmission power after block faults happens.

2) The shortest electrical distance

The electrical distance indicates the electrical contact among different nodes in a power system [11]. However, it is hard to calculate the electrical distance accurately between two nodes if the system structure is complex. When two nodes are connected through a tie line, the electrical connection is strong and thus the electrical distance is little and vice versa. Therefore, the shortest electrical distance (SED) can be utilized to make a comparison of the electrical contact between two nodes easily [12].

The SED problem can be deemed to find the shortest path of a certain network, where the impedance is the weight of lines. Then, SED of two nodes can be calculated by Equation (2) based on the Dijkstra algorithm.

$$d = \sum_{e_i \in l} w(e_i) \tag{2}$$

where $V = \{v_1, v_2, \ldots, v_n\}$ and $E = \{e_1, e_2, \ldots, e_m\}$ stand for a set of bus nodes and transmission lines separately. $w(e_i)$ indicates the weight of e_i as impedance of transmission line.

3) Prioritycontrol parameter (PCP)

When the block faults occurs on DC transmission line, the non-fault DC line with less SED and larger ATP should be assigned with the top priority. Less SE-Dindicates that non-fault DC line is near to the faulted line, which can limit power flow transferring to the minimum degree. While the DC line with "larger ATP" will be likely to transfer more power, contributing the system to reach $P_{i,min}$ and remain synchronized. Then a prioritycontrol parameter (PCP) for synthesizing SED and ATP together is proposed based on entropy weight method, this procedure is shown as follows.

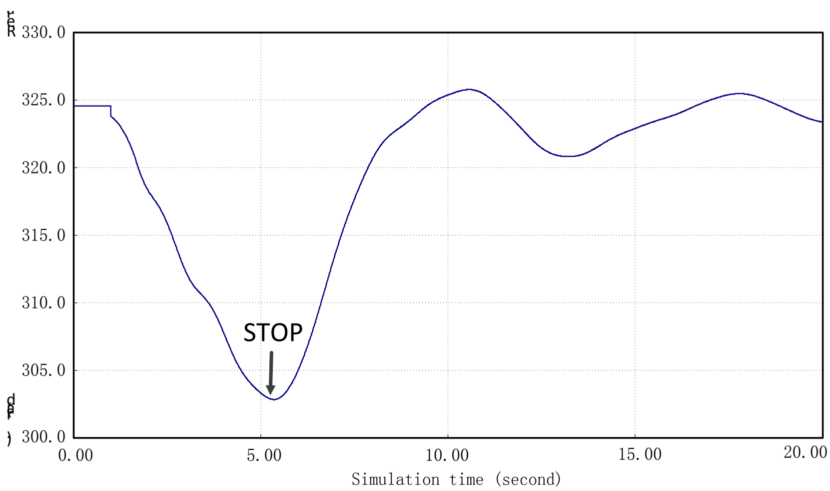

Figure 8. Relativeangle on both terminals of the tie-line.

Firstly, normalize ATP and SED parameters to the same unit as

$$x_{i2}^{'} = \frac{x_{i2} - \min(x_{12}, x_{22}, \cdots, x_{n2})}{\max(x_{12}, x_{22}, \cdots, x_{n2}) - \min(x_{12}, x_{22}, \cdots, x_{n2})} \times 100 \quad (3)$$

$$x_{i1}^{'} = \frac{\max(x_{11}, x_{21}, \cdots, x_{n1}) - x_{i1}}{\max(x_{11}, x_{21}, \cdots, x_{n1}) - \min(x_{11}, x_{21}, \cdots, x_{n1})} \times 100 \quad (4)$$

Therefore, the ratio of the two parameters above of line *i* can be derived as.

$$P_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}}, (i = 1, 2, \cdots, n,\ j = 1, 2) \quad (5)$$

Thus the entropy of ATP and SED are available below

$$e_j = -k \sum_{i=1}^{n} p_{ij} \ln(p_{ij}) \quad (6)$$

$$k = 1/\ln(n) \quad (7)$$

The weight w_j can be calculated as.

$$w_j = \frac{g_j}{\sum_{j=1}^{2} g_j}, (j = 1, 2) \quad (8)$$

Finally, the factor PCP can be obtained as.

$$s_i = \sum_{j=1}^{m} w_j \bullet p_{ij}, (i = 1, 2, \cdots, n) \quad (9)$$

4.2. Multi-Channel Emergency Control Strategy

If the loss of inter-area transmission power is so huge that a single HVDC line cannot meet the requirement, the multi-channel emergency control strategy should be applied and coordinate all non-fault paralleling HVDC lines in a proper way. However, the total overload capacity of all the non-fault paralleling HVDC lines should be above $P_{i,c}$ to make sure the emergency strategy is feasible.

Since the power increase of non-fault HVDC line is costly, the principle of the emergency control is to make full use of the overload capacity of each HVDC line and minimize the number of total controlled lines. Hence, those HVDC ranked at the highestpriority should operate at 1.5 times overload and the one ranked at second assumes the rest of transmission power requirement. The flow chart for the coordination is shown in **Figure 9**.

5. Simulation Results

Two case studies are given by using power system analysis software package (PSASP). The structure of Triple HUA AC/DC hybrid transmission system in **Figure 10** shows that the power flow transmits from Changzhi to Nanyang through Changnan line.

5.1. Emergency Power Control for Unipolar Blocking Fault

A block on Fulong HVDC unipolar occurs at 1 s. Emergency control strategy

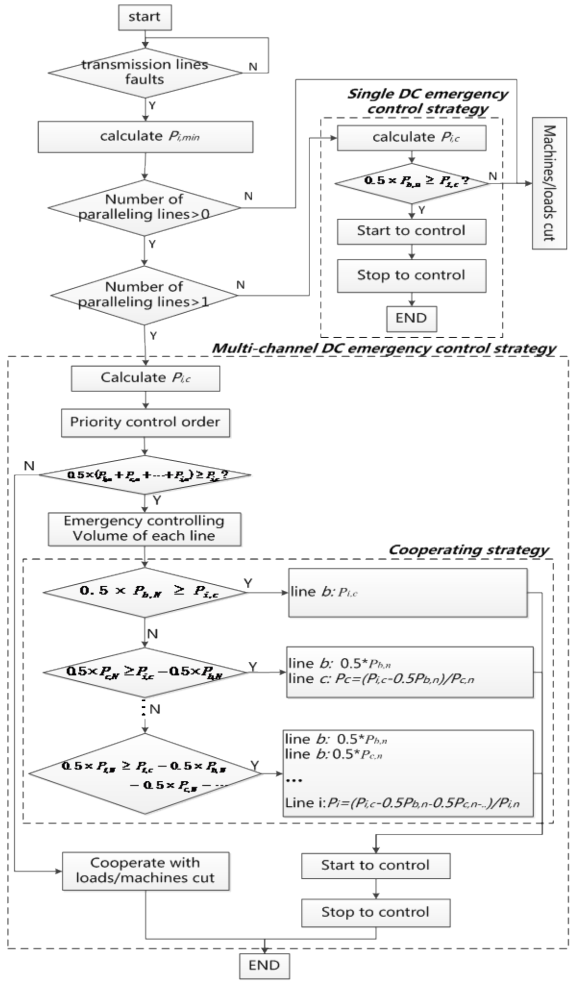

Figure 9. Diagram of Multi-DC cooperated emergency control.

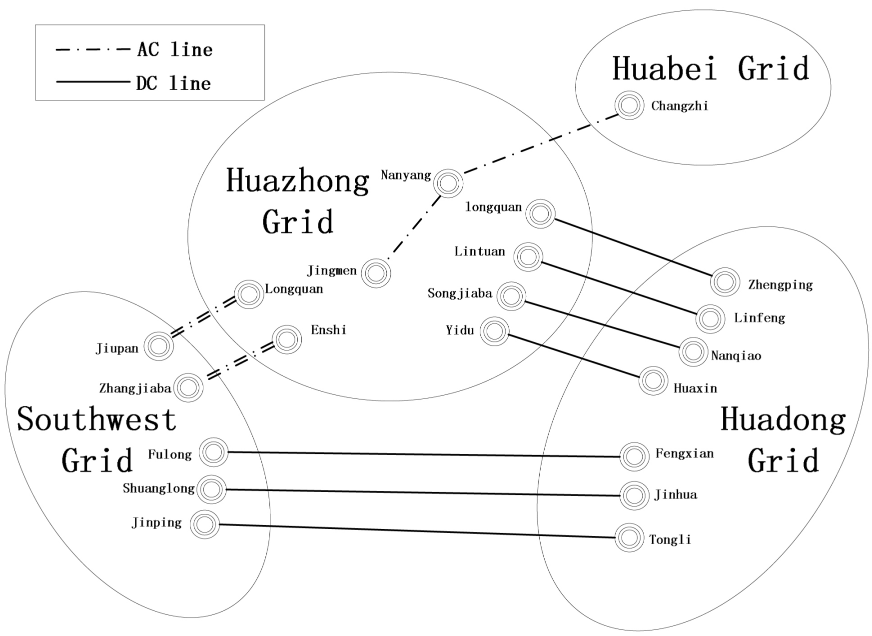

Figure 10. Triple HUA AC/DC hybrid transmission system.

takes effect instead of traditional controlstrategy. Transmission line structure of Sichuan province is shown as **Figure 11**.

In this case, non-fault HVDC links are: non-fault unipolar of Fulong HVDC, Binjin HVDC and Jinping HVDC line. After calculating the SED and ATP of each link above, the priority control order can be made depending on PCP. Detailed results can be seen from **Table 1**.

It can be seen that the highest priority of controlling HVDC is Binjin HVDC. The $P_{i,min}$ of Fufeng HVDC can be get to 1400 MW through simulation. Then $P_{i,c}$ should be 1950 MW (where the value of α is 1.3). Therefore, the emergency control strategy should be: Binjin HVDC line increase 1950 MW power, starting at 1.3 second and ending at 4.63 second.

Figure 12 shows the comparison among non-strategy, traditional cutting strategy and emergency power controlling strategy, from which we can see that both of the latter two strategies can preserve the system synchronous operation and avoid islanding. Additionally, the emergency controlling strategy avoid loads shedding and generator tripping, which reduces the economic and energy cost.

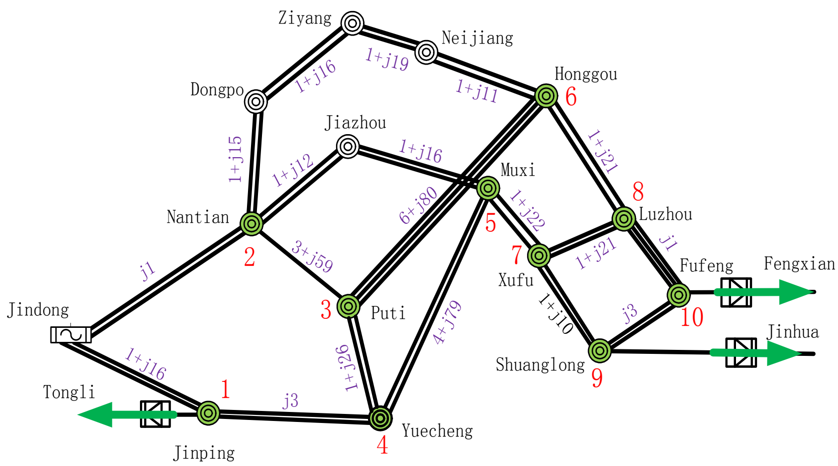

Figure 11. Transmission line structure of Sichuan province.

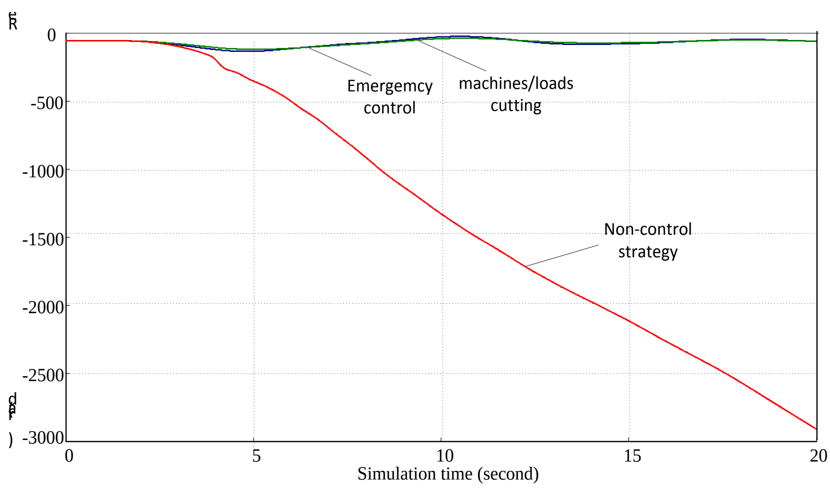

Figure 12. Relative angle of generators in Huazhong and Huabei district.

5.2. Emergency Power Control for Bipolar Blocking Fault

Simulation works on the Three Gorges multi-channel cooperating strategy is done with a block on Longzheng HVDC bipolar occurring at 1 seconds. The transmission structure and parameters are given in **Figure 13** and **Table 2**, from which we can see the priority controlling order is Linfeng, Yihua and Genan HVDC line.

The $P_{i,min}$ of Longzheng HVDC line is 1400 MW, then $P_{i,c}$ should be 1820 MW (where α is 1.3). Since the requirement on $P_{i,c}$ is larger than the available overload of any single HVDC line, the multi-channel cooperating strategy should be established. Specifically, Linfeng and Yihua HVDC improve 1500 MW and 320 MW respectively at the same time, starting at 1.3 second and stopping at 4.12 second. From **Figure 14** we can see that the multi-channel cooperating strategy prevents the system from islanding.

Table 1. Priority control results of Multi-DC transmission line in Sichuan province.

Name of DC	SED	APT/MW	PCP	Priority order
Fufeng non-fault unipolar	0	1200	0.2507	3
Binjin	76.5	4000	0.5184	1
Jinsu	75	3600	0.2771	2

Table 2. Priority control results of Multi-DC transmission line in the three gorges.

	SED	APT/MW	PCP	Priority order
Linfeng	36	1500	0.6243	1
Genan	87	580	0.706	3
Yihua	122	1500	0.2051	2

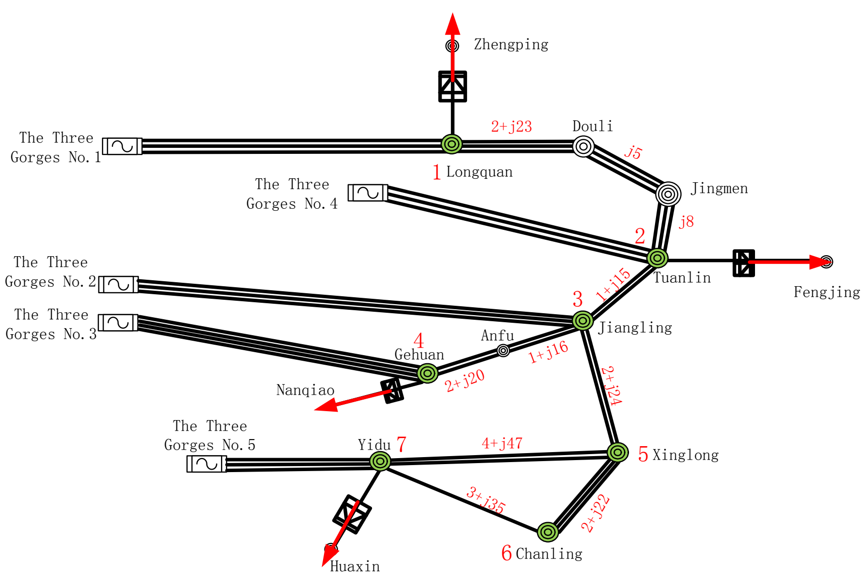

Figure 13. Transmission line structure of Hubei province.

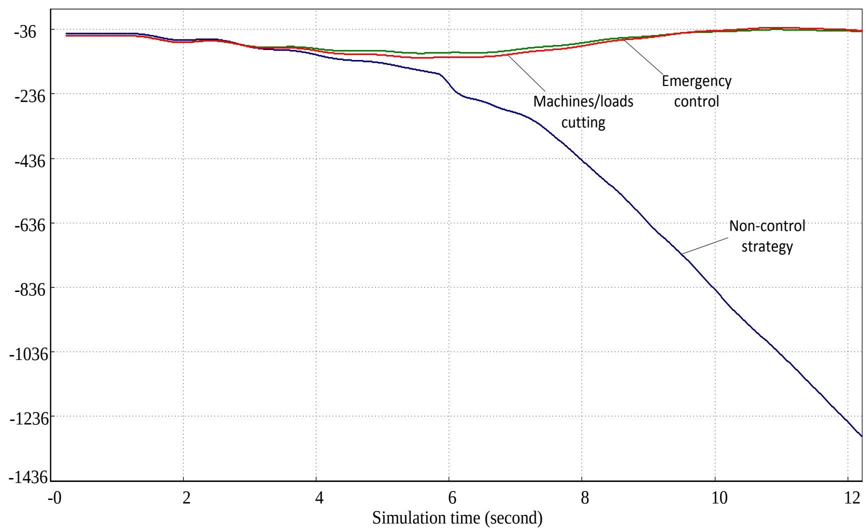

Figure 14. Relative angle of generators in Huazhong and Huabei district.

6. Conclusion

In AC/DC hybrid power system, a sudden huge decrease in inter-area transmission power will make the system collapse. A new emergency control strategy based on the overload capacity of HVDC line is proposed in this paper to enhance system stability and prevent out-of-step islanding. This emergency control should start as quickly as possible and stop at the first peak of regional relative angle. If the number of paralleling HVDC line is above three, the priority control order can be judged by entropy weight method considering SED and ATP. Besides, the multi-channel cooperating strategy should be applied if the demanding controlling capacity is huge.

References

[1] Fang, Y.J. (2011) Analysis on Trends in Emergency Control Technology of Cross-Regional Interconnected Power System. *Automation of Electric Power Systems*, **15**, 1-5, 77.

[2] Xie, H.F., Zhang, Y. and Xia, C.G. (2008) Study of UHV Emergency DC Power Support Strategy. *Electric Power Automation Equipment*, **8**, 1-7.

[3] Zheng, C., Miao, T. and Ma, S.Y. (2016) Transient Stability Identification and Emergency Control Based on the Convex Characteristic of the Key Branch's Disturbed Trajectory. *Proceedings of the CSEE*, **10**, 2600-2610.

[4] Siddiqui, S.A., Verma, K., Niazi, K.R. and Fozdar, M. (2015) Artificial Neural Network Based Early Detection of Real-Time Transient Instability for Initiation of Emergency Control through Wide-Area Synchrophasor Measurements. *International Conference on Computer*, *Communication and Control* (IC4), Indore, 1-6.

[5] Wang, K., Yang, S. and Yao, J. (2011) Multi-Circuit HVDC System Emergency DC Power Support with Reactive Control. *Power Systems Conference and Exposition (PSCE)*, 2011 *IEEE/PES*, 1-5. https://doi.org/10.1109/psce.2011.5772475

[6] Zhang, K.J., Yin, X.G., Chen, D.S. and Zhang, Z. (2008) Dynamic Simulation Experiments for Internal Fault Protection of Large Hydro-Generators. *Automation of Electric Power Systems*, **6**, 41-45, 90.

[7] Xie, H.F., Zhang, Y., Lin, L.X., Zhong, Q. and Deng, Q.S. (2010) Emergency DC Power Support Control Based on Time-Optimal Control and Auto-Disturbance Rejection Control. *Transactions of China Electrotechnical Society*, **8**, 145-153, 173.

[8] Chen, J., Liu, D.C., Liao, Q.F. and Liu, J.K. (2013) Assessment Index of Emergency DC Power Mutual Support for HVDC Transmission System with Multiple Sending Ends. *Power System Technology*, **9**, 2416-2421.

[9] Zhang, J., Song, X.F. and Xue, F. (2013) Study of HVDCs Emergency Power Support Strategy Based on Multiple Principles. *Proceedings of Chinese Society for Electrical Engineering in* 2013.

[10] Wang, J.M., Sun, H.D., Zhang, J., Ren, D.W., Yin, Y.H. and Bu, G.Q. (2012) Stability Characteristics and Coordinated Control Strategy of Interconnected Grid Integrated with UHVDC Transmission Line from Jinping to Sunan. *Power System Technology*, **12**, 66-70.

[11] Li, Y.K., Lv, F.P., Jiang, K., Chen, X. and Hu, Y.P. (2010) Method for Power System Operation Mode Combination Based on Shortest Electrical Distance. *Power System Protection and Control*, **15**, 24-27, 37.

[12] Wang, H.X., Liu, R., Zhao, C.H. and Li, W.D. (2008) Power Loss Allocation Based on Power Flow Tracing With Consideration of the Electrical Distance between Buses. *Power System Technology*, **S2**, 196-201.