Fault Clearance Strategy and Simulation of VSC-HVDC by DC Breaker

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Summary

This paper presents the fast fault clearance strategy of VSC-HVDC system by DC breaker.

Nowadays, more and more renewable energy is developing and it is the main stream to constitute multi-terminal VSC-HVDC or VSC-HVDC grid for renewable energy evacuation. And the key barrier is fast and selective fault clearance, especially for transmission line or cable fault.

The DC breaker can isolate fault transmission line/cable or fault terminal without blocking healthy terminals, namely the healthy terminals can keep in operation. Consequently, it has minimum adverse influence to both AC gird and DC system during fault clearance and restarting.

The structure and principle of NR's hybrid DC breaker are introduced in this paper and also the fault clearance strategy of transmission overhead line and cable. The comparison of fault characteristics and fault isolation requirement between transmission line and cable are also made.

The effectiveness of this strategy is proven by simulation in PSCAD/EMTDC application, the parameter of simulation models are based on real operated project – the 5-terminal Zhoushan project.

Keywords

VSC-HVDC, DC Breaker, Fault Clearance

1. Introduction

Nowadays, VSC-HVDC transmission becomes more and more popular due to it is an effective method of renewable power access to grid. In situation of multi-terminal power resources or/and multi-terminal load centers, both multi-terminal VSC-HVDC and DC grid could be applied. Compared to point to point VSC-HVDC, multi-terminal or DC grid reduces quantity of VSC-HVDC converter stations[1]. So multi-terminal and DC grid are hot topics and under vigorous research and development worldwide[2]. The "Super Grid" was presented in 2008 in Europe[3-4], which aims to enhance access to grid of renewable power and constitute pan-European electricity market. Meanwhile, the concept of "Grid 2030" was issued in 2011 in US, it is planned to apply VSC-HVDC grid as backbone and integrate with superconductor technology, power storage technology. Grid 2030 will interconnect east coast and west coast of US, Canada and Mexico.

In existing VSC-HVDC projects, 2-level voltage source converter (VSC) and half bridge modular multilevel converter (HBMMC) are mainly applied. Both 2-level VSC and HBMMC have no inherent capability of DC fault clearance[5-6]. So DC breaker is necessity in multi-terminal and DC grid with valve technologies above.

Compared to AC grid, VSC-HVDC has lower damping, consequently the fault developing process is faster. It's put higher demand to control and protection system for detecting and insolating fault promptly. It should ensure that the healthy converter doesn't block and fault current doesn't exceed the breaking capability.

This paper does the research and simulation of fault clearance strategy by DC breaker. In chapter 2, a new topology of DC breaker is introduced; in chapter 3, fault clearance strategy by DC breaker is presented and in chapter 4, the fault clearance strategy is simulated in PSCAD/EMTDC application base on Zhoushan 5-terminal VSC-HVDC project which was put into service in 2014.

2. Commutation-based hybrid HVDC breaker

Hybrid DC breaker is composed of three parallel connected branches, namely main load branch, breaker branch and MOV dissipation branch. It applies mechanical switch for conduction of normal operation current (main load branch) and uses electronic switch for breaking fault current (breaker branch). It provides reliable current breaking capability, prompt speed of action and low loss of normal conduction.

In reference [7-10], all the topology of breaker branch applies anti-parallel connected semiconductor branch which is composed of a quantity of series connected IGBT. Only one IGBT branch is active for current breaking and voltage withstanding. It makes low utilization of IGBT units and uneconomic.

NR Electric developed commutation-based type hybrid DC breaker which uses bridge type commutation model to constrain current to go through breaker branch from single direction. Thanks to this new topology, only half quantity of IGBT is required, it helps to make DC breaker more economic.

By NR's unique design, the DC breaker has features of reliability, compact structure, fast re-close and double breaking capability.

This new topology has got verification of type tests of 535kV DC circuit breaker by DNV.GL. The main parameter is as table 1.

Table 1 Parameter of DC breaker

Items	Value
Rated Voltage	535KV
Rated Current	3KA
Breaking Current	25KA
Breaking Time	≤3ms

The topology of commutation-based hybrid HVDC is shown as figure 1. The main load branch is composed of high speed mechanical switch S1 and series connected conduction valve Q1. Breaker branch includes bridge type commutation model and single direction breaking model. 4 identical commutation valves (D1-D4) constitute bridge type commutation model. D1-D4 is composed of a quantity of series connected diodes respectively. Single direction breaking model Q2 is composed of series connected IGBT. The MOV dissipation branch becomes conductive when transient voltage exceeds setting value during current breaking process.

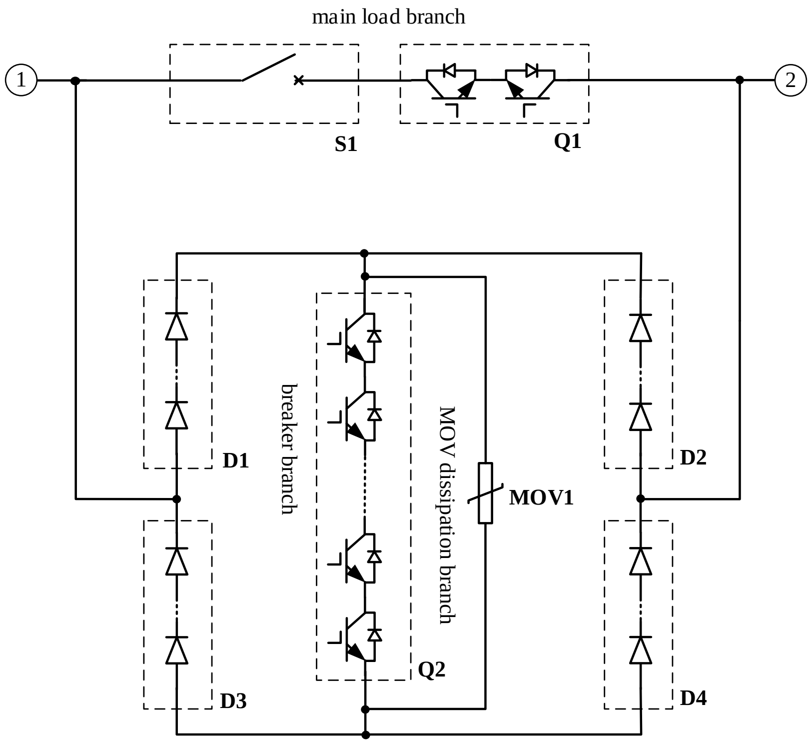


Figure 1 Topology of commutation-based hybrid HVDC breaker

The current breaking procedure is 4 steps:

1) In normal operation, current goes through main load branch.
2) When fault occurs, Q1 blocks, breaker branch is triggered to be conductive for fault current. Breaking model Q2 can be controlled to switch on/off in ultra short time.
3) When fault current goes through breaker branch completely, open mechanical switch S1, block breaking model Q2. Meanwhile, the buffer circuit of breaker branch is charging to increase terminal voltage of MOV.
4) The MOV becomes conductive when terminal voltage exceeds action setting. Finally the fault current is dissipated by MOV branch and fault current is completely breaking.

3. Fault clearance strategy by DC breaker[5]

VSC-HVDC is low-inertia system, DC line fault impacts whole system instantaneously, it will cause steep fault current increasing of converter. The semiconductor of converter has limited over current withstanding capability. So DC breaker is necessity for breaking fault current promptly.

The fault clearance includes 3 steps: fault detection and line selection; fault isolation, it should ensure only isolate faulty zone and keep healthy part in operation; reclosure of DC breaker. When overhead line is applied, it helps to recover HVDC link instantaneously after transient fault, increases system availability consequently.

The steps show as figure 2.

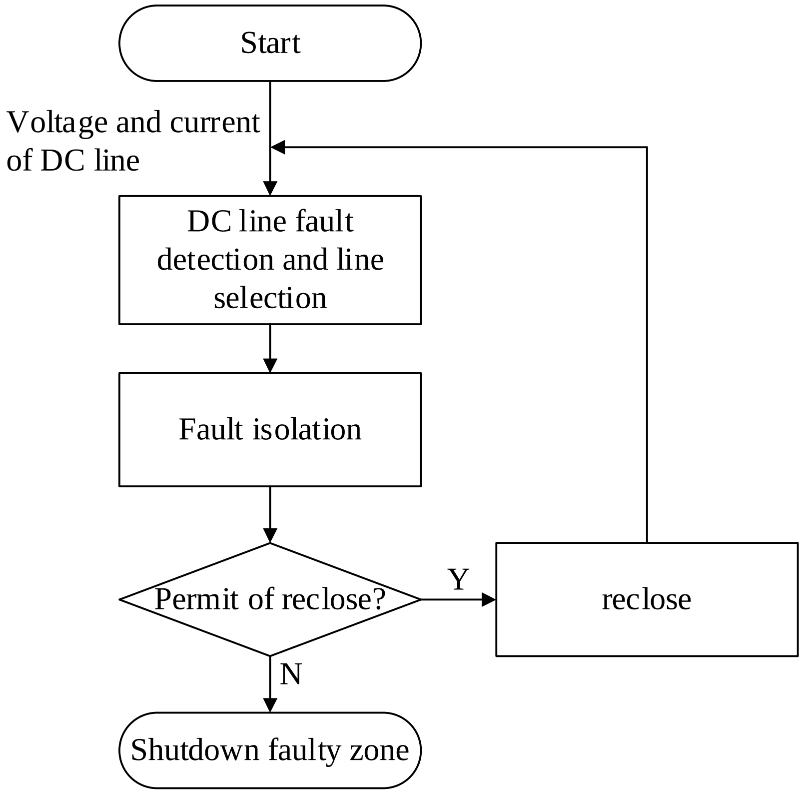


Figure2. Fault clearance strategy by DC breaker

The detailed description of 3 steps are as below：

1) Fault detection and line selection

The fault within converter station can be detected reliably by differential protection and then block and isolate faulty zone. After this, the healthy part of HVDC system could be recovery to operation.

But for DC line fault, it's more difficult for fault detection due to inconspicuous difference of electrical measurements between two terminals and delay of communication caused by long distance. So fault characteristics of VSC-HVDC system should be supplemented for suitable fault detection and line selection.

a) Single pole fault

When DC single pole fault occurs, since AC system is earthed, bridge arm capacitance of faulty pole and DC fault point and AC earthing point constitute capacitor discharge circuit. Take for instance the positive pole earthing fault, the fault circuit is shown as figure 3 circuit ①. Voltage of faulty pole decreases promptly and voltage of healthy pole increases quickly, the surge arresters of healthy pole act consequently, and then the fault current pumps to fault point through bridge arm which is shown as figure 3 circuit ②.

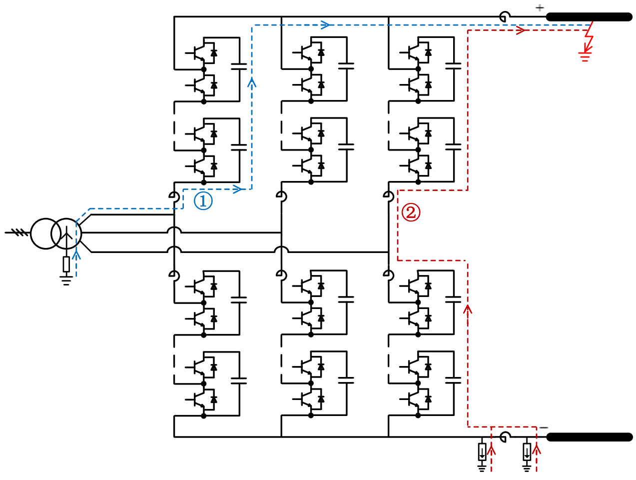


Fig.3 Fault circuit of single pole earthing fault

The features of single pole earthing fault include:

- Voltage of faulty pole decreases and voltage of healthy pole increases
- The fault current of two terminals of fault line is non-through current
- When surge arresters act in healthy line due to overvoltage, the current of two terminals of healthy line is also non-through current. So only current difference criteria may cause maloperation.
- Fault current is relatively small, low demand on speed of fault isolation.

So single pole earthing fault can be detected by unbalance of DC voltage and then distinguish fault line by making current difference of the voltage reducing line.

As in figure 4, Udp is positive voltage, Udn is negative voltage, Idp is positive line current, Idp_op is positive line current of opposite side converter station, the forward direction is defined as from positive pole bus to line. Idn is negative line current, Idn_op is negative line current of opposite side converter station, the forward direction is defined as from line to negative pole bus.

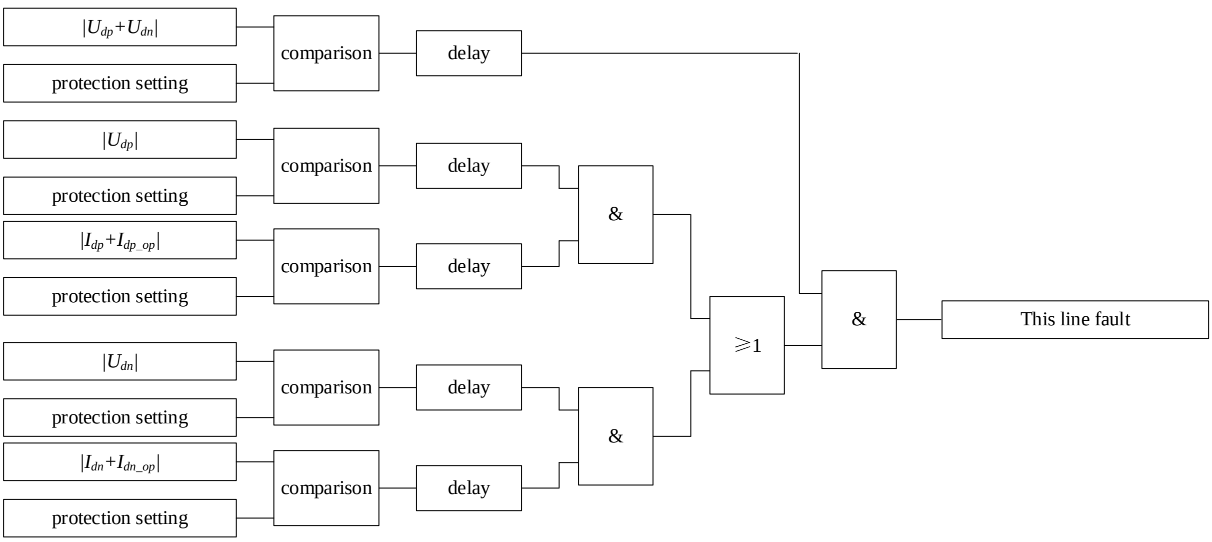


Figure 4 Single pole fault detection and faulty line selection

When proper smoothing reactors are installed at two terminals of line, it can achieve faulty line selection by single terminal travelling wave protection.

b) Inter-pole fault

When Inter-pole fault happens on VSC-HVDC that applies half bridge MMC topology, fault current increases steeply. For protection purpose, the converter is blocked when bridge arm current exceeds protection setting. The features of fault are divided into pre-block and post-block.

- Pre-block

The fault current is composed of capacitor discharging current of sub-module(circuit ①) and feeding current of AC power source(circuit ②), the former is predominantly at the beginning of fault.

- Post-block

When converter is blocked, capacitor discharging current stops. The current of bridge arm reactor keeps on pumping current to fault point through diode of sub-module.

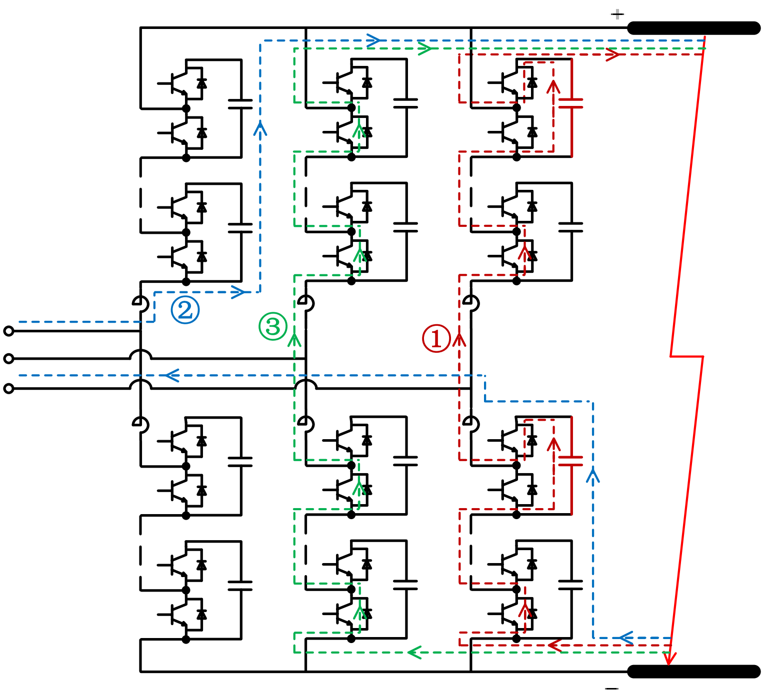


Fig.5 Fault circuit of Inter-pole fault

The features of Inter-pole fault include:

- Inter-pole voltage drops
- In pre-block stage, capacitors of sub-modules discharge speedily, converter supplies current to fault point through DC line.
- In multi-terminal VSC-HVDC, the fault current of two terminals of fault line is non-through current; the fault current of two terminals of other healthy lines are through current.

During Inter-pole fault, the two terminals' difference current is large and both are injecting to fault point. So it can achieve instantaneous trip by criteria of directional overcurrent, as shown in figure 6, the forward direction is from bus to line. In this case, the installation of line smoothing reactors is necessary so as to limit the increasing rate of fault current, the final purpose is to ensure the fault current doesn't exceed the breaking capability of DC breaker.

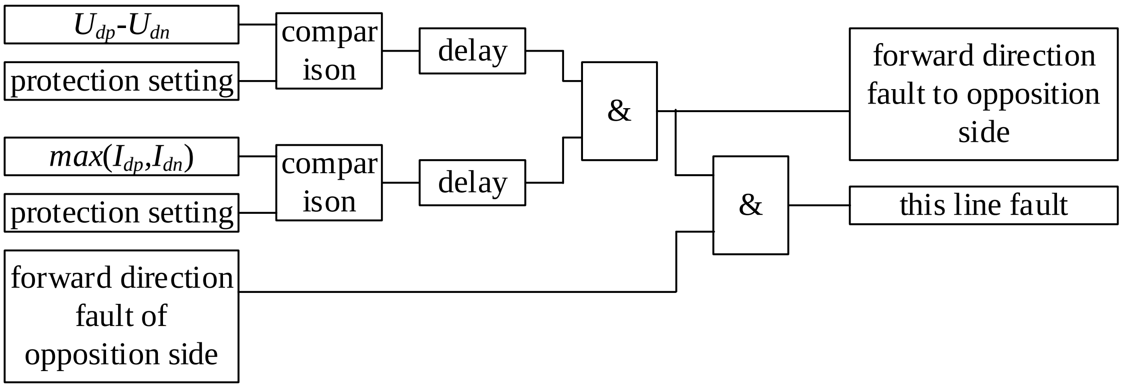


Fig.6 Fault line detection strategy of Inter-pole fault

When proper smoothing reactors are installed at two terminals of line, it can achieve faulty line selection by single terminal travelling wave protection.

2) Fault isolation

When faults occur, the detection and line selection philosophy acts as described above and the action is to trip line DC breaker that is near the fault point and trip line DC breaker of another side simultaneously through inter-station communication channel. The fault is isolated by tripping of DC breakers and healthy parts of VSC-HVDC link keeps in operation.

The failure protection of DC breaker is configured to prevent failure to operate which may cause failure of fault isolation and shutdown of whole HVDC link. The action of failure protection is that tripping all DC breakers on the bus that connects to fault line and the valves connect to same bus should be blocked and their AC breaker should trip too. In figure 7, when DCB1 is failure to operate, the failure protection will issue command to trip DCB2 that connects to same bus, simultaneously block valve and trip AC breaker, the valve and transmission lines are shut down and the healthy parts keep in operation.

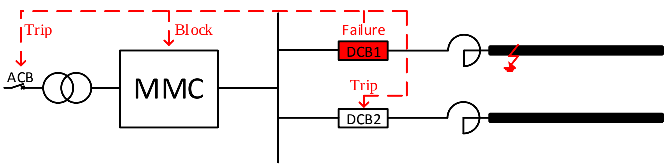


Figure 7 Action of failure protection

3) Reclosure of DC breaker

When overhead line is installed in HVDC link, it has more possibility of suffering transient fault, like lightning strike. The HVDC link can recover to normal operation after the clearance of transient fault. In this case, the DC breaker should have the capability of reclosure. It is effective way to distinguish transient fault and permanent fault.

When DC breaker receives reclosure command, it triggers IGBT of breaker branch, the bus charges DC line through DC breaker. If it is transient fault, the DC voltage of line increases and charging current is relatively small. If it is permanent fault, DC voltage sustains in low level and charging current increases. The type of fault can be distinguished by characteristics of DC voltage and current. In case of permanent fault, the DC breaker re-trip by stopping to trigger the IGBT of breaker branch. For transient fault, the reclosure procedure will continue: close S1 and trigger Q1 in load branch; then block IGBT Q2.

In the circumstances cable is applied, the DC breaker is generally not reclosed due to the cable fault is always permanent one, reclosure may aggravate damage of cable.

4. Simulation

A simulation model based on Zhoushan 5-terminal VSC-HVDC is applied to verify the efficiency of fault clearance strategy by DC breaker, this model is developed in PSCAD/EMTDC application.

The SLD of Zhoushan project is shown as figure 8, symmetrical monopole topology, DC voltage ±200kV and capacities are 400MW/300MW/100MW /100MW/100MW respectively. Two sets of DC breakers are installed at two terminals of cable. DB1-DB7 represents two sets of DC breakers installed on positive and negative cables in single converter station.

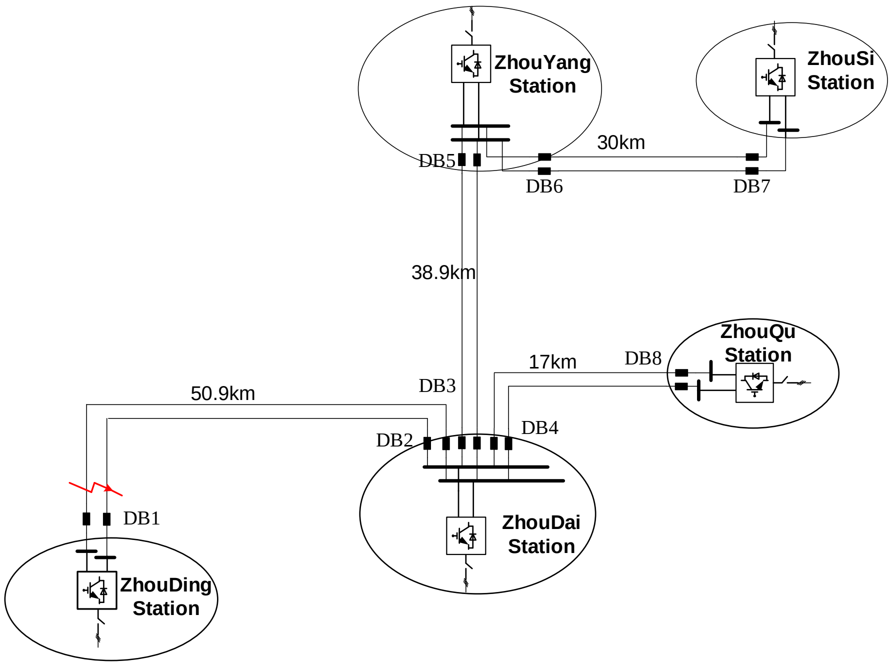


Figure 8 SLD of ZhouShan 5-Terminal VSC-HVDC

In the simulation, the Zhouding station is DC voltage control mode and other 4 terminals are active power control modes, each of these 4 terminals provides 100MW to AC grid respectively. The fault is simulated in Zhouding-Zhoudai line, fault types are single pole earthing fault and inter-pole fault.

Each terminal of cable installs a 100mH reactor to restrain fault current within 10kA to ensure the fault current doesn't exceed the breaking capability of DC breaker.

a) Single pole earthing fault

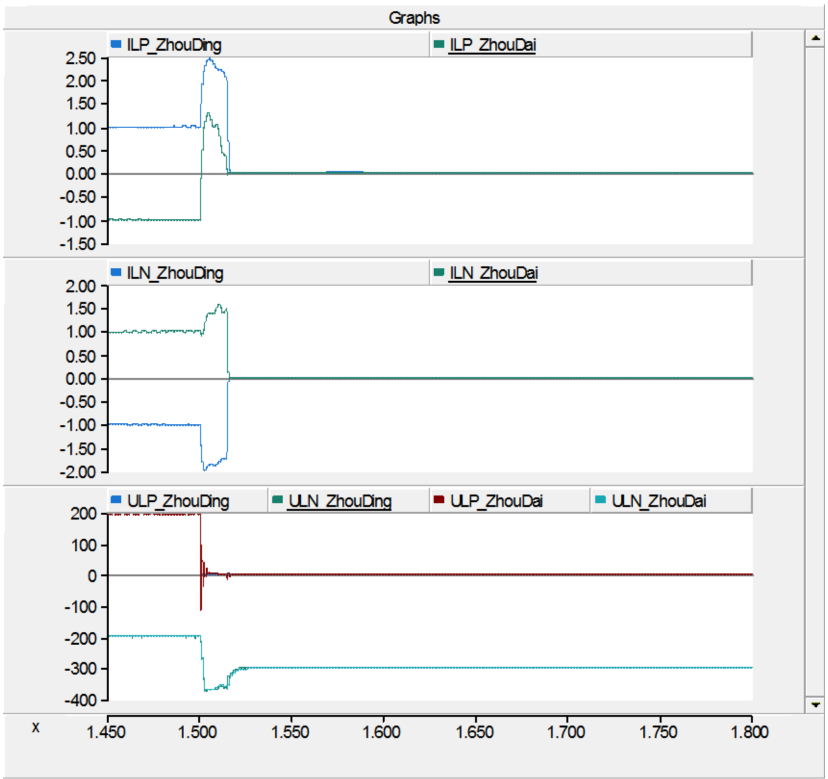
A positive pole earthing fault occurs at 1.5s in Zhouding-Zhoudai line near Zhouding station, it is shown as figure 9.

In figure 9 (a), the top figure shows two terminal currents of Zhouding-Zhoudai positive line; the middle figure shows two terminal currents of Zhouding-Zhoudai negative line; the below one shows two terminal voltage of fault line. The forward direction is defined as from busbar to line.

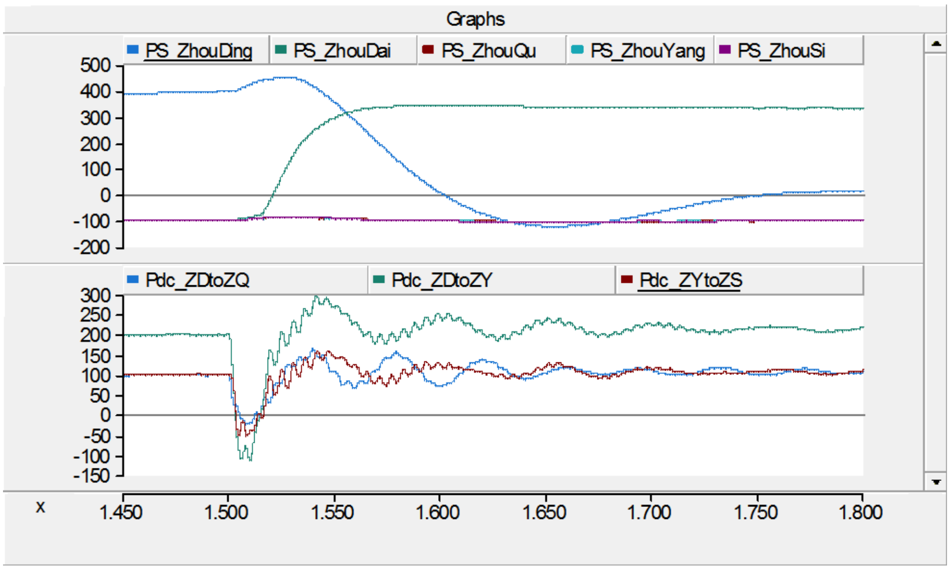
In figure 9 (b), the upper figure illustrates powers of other 3 healthy lines. The lower one shows AC active powers of other 4 converter stations.

When single pole earthing fault occurs, DC voltage of positive line drops steeply, simultaneously voltage of negative line increases fast and causes action of surge arrester. Fault current is pumped into fault point from two terminals of fault line. Protection acts in 10ms and issues trip order to DC breaker. The 4 DC breakers at two terminals of positive and negative lines are tripped. Based on performance of NR's DC breaker, the breaking time of DC breaker is 3ms. So the DC line fault is isolated successfully in 13ms. When DC breakers of Zhoudai station side trip, control mode of Zhoudai station switch from active power control to DC voltage control, it transmits power to other 3 terminals. The power of DC line can recover promptly after fault isolation and control mode switch. The short interruption of DC line has tiny impact on AC grid due to the capacitors of converter valve have storage of energy.

According to simulation result, when fault occurs, healthy pole suffers transient over voltage, the maximum level is up to -372kV. The fault is isolated in less than 20ms by DC breakers and powers of healthy lines recover to same level before fault in 40ms. The interruption has tiny impact on power of AC grid.



(a)



(b)

Figure 9 Waveform of single pole earthing fault

b) Inter-pole fault

A inter-pole fault occurs at 1.5s in Zhouding-Zhoudai line near Zhouding station, it is shown as figure 10. the first figure shows two terminal currents of Zhouding-Zhoudai positive line; the second figure shows two terminal currents of Zhouding-Zhoudai negative line; the third one shows two terminal voltage of fault lines. The fourth figure shows powers of healthy lines. The forward direction is defined as from busbar to line.

When inter-pole fault happens, the voltages of two DC poles drop steeply and fault current increases simultaneously. DC line protection acts in 3ms and DC breakers finish breaking in 6ms, the DC line fault is isolated successfully. The breaking current of DC breakers in Zhouding side is up to 8.5kA and Zhoudai side is 5.6kA. When DC breakers of Zhoudai station side trip, control mode of Zhoudai station switch from active power control to DC voltage control, it transmits power to other 3 terminals.

The breaking current of DC breakers in Zhoudai side is shown as figure 11. The upper figure is currents of DC breaker's main load branch and breaker branch; the lower one shows voltages of DC breaker's converter side and line side.

When DC breaker receives trip order, it blocks Q1 and triggers Q2 to transfer fault current from main load branch to breaker branch. After the open of mechanical switch S1, block breaking model Q2. The fault current goes through MOV branch and dissipated. During the current dissipation period, an over voltage around 300kV will arise.

According to simulation, the action of DC breaker prevents further increase of fault current and isolates the fault without tripping AC breakers, the powers of healthy lines recover to same level before fault in 40ms.

Figure 10 Waveform of inter-pole fault

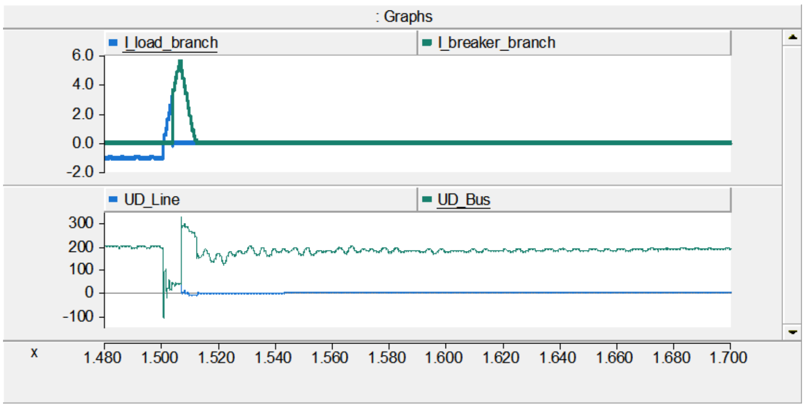


Figure 11 Breaking current of DC breaker

5. Conclusion

This paper introduces principle and topology of DC breaker and presents the fast fault clearance strategy of VSC-HVDC system by DC breaker. Base on features of DC breaker, a detailed strategy of fault detection, fault line selection, fault isolation and reclosure of DC breaker is introduced.

The strategy is verified and simulated in PSCAD/EMTDC application according to Zhousan 5-terminal VSC-HVDC project. According to the simulation results, the DC breaker is effective and high performance for isolating fault and keeping healthy parts in operation. It is proven that DC breaker is good solution for multi terminal VSC-HVDC and DC grid.

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