Researches on Two Kinds of Fault Restart Logic of Qishao ± 800 kV UHVDC Project

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Abstract: In order to improve the availability and operating efficiency of the DC system, Qishao ± 800 kV UHVDC transmission project pole layer control system is equipped with two kinds of fault restart logic, namely the instantaneous fault restart and the valve group fault restart. In this paper, the triggering mechanism, timing and opening conditions of these two fault restart logic are analyzed in detail, and the relationship between the instantaneous fault restart logic and other protections reacting transient faults in pole and bipolar zone is studied emphatically, DC system debugging scene recorded wave diagram is referred to illustrate the two restart logic of the action process and effect, with a view to provide some guidance and reference significance to the field operation and research work.

1. Introduction

UHVDC transmission has the advantages of large transmission capacity, long transmission distance, relatively low loss, et al, and is an effective way to solve China's energy-load reverse distribution, achieve energy clean alternatives and optimization configuration, and prevent air pollution. It has entered an all-round development and construction stage for UHVDC transmission in China [1]-[4]. The Qilian-Shao ±800 kV UHVDC transmission project begins in the Jiuquan region of Gansu Province in the northwest, passes through four provinces including Gansu, Shaanxi, Chongqing, and Hubei, and finally locates in Xiangtan, Hunan Province. Its total length is 2385.6 km. The operation of the project will help to make full use of Gansu's abundant wind energy and coal resources, and guide the rational development of the Jiuquan energy base in an orderly manner, while relieving the tension of electricity consumption in Hunan power grid and restraining the increasingly serious haze situation in Central China [5]-[7].

In order to improve the availability and efficiency of the UHVDC system, two kinds of fault restart functions are configured, namely, instantaneous fault restart and valve group fault restart. Among them, transient faults include transient grounding faults on the UHVDC transmission line, metal return line, and grounding electrode and bipolar neutral bus under monopolar operation. Valve group fault refers to the grounding fault in a single converter area. Depending on the rich and complete control capability of UHVDC systems, both fault restart logics can achieve fast and effective fault isolation, deionization, and system restart without relying on arc extinguishing capability of DC circuit breaker, which avoids the unnecessary monopolar outage of the system and improves the operation level of UHVDC projects. In this paper, the logic of ABB technology-based instantaneous fault restart and valve group fault restart in DC control and protection systems is studied in detail, and the two fault restart operation sequences are elaborated in detail in conjunction with the debug field recording of Qilian-Shao UHVDC transmission project, In order to provide guidance and reference for field operation and scientific research work.

2. Research on instantaneous fault restart logic
Instantaneous faults can be caused by lightning, branch discharge, line touch due to wind deflection, etc. Such faults do not have the ability to self-retain the fault circuit. If the fault is isolated for a short time, the power supply side will have a higher probability to achieve arc extinction and fault isolation and the system operation restore. Due to the low arc breaking ability of DC breakers at present, the transient faults in UHVDC projects must be extinguished by short-term blocking of the corresponding DC pole system. In other words, the execution subject of extinguishing the fault arc is the control system rather than the protection system. When a transient fault occurs, the control system can quickly adjust the trigger angle of the converter valve, instantaneously transform the rectifier side into an inverter property, and at the same time of interrupting the power output of the rectifier side, simultaneously release the energy of the fault point from the two stations, and the arc extinguishing effect is faster than the AC line reclosing.

Table 1 Protection types and principles for triggering transient fault restart logic

| Protection object | Protection type | Protection principle | Protection fault features |
|-------------------|-----------------|----------------------|--------------------------|
| DC line           | Travel wave protection | \( \frac{dP}{dt} > \Delta_1, \frac{dP}{P} > \Delta_2, P > \Delta_3 \) \( P = Z(I_a - I_{a}) \) \( G = Z_0(I_{DEL} + I_{CN1} + I_{CN2}) \times 0.5 - (U_{d1} + U_{d2}) \times 0.5 \) | When a ground fault occurs on the DC line, fault waves travel to both ends of the line, causing rapid changes in pole and ground waves. |
|                   | Voltage sudden changing protection | \( U_{d1} < \Delta_1, \frac{dU_{d1}}{dt} > \Delta_2 \) | Detect bolted ground faults on the DC line. When the DC line has a ground fault, the DC voltage on both sides will drop rapidly. |
|                   | Low voltage protection | \( U_{d1} < \Delta \) | Detect bolted ground faults and high-resistance ground faults on the DC line. |
|                   | Longitudinal differential protection | \( |I_{d1} - I_{d1,os}| > B + K \times I_{d1} \) | When there is a ground fault on the DC line, the DC currents of the two stations are inconsistent, resulting in a differential current. |
| Metal return line | metal return line ground protection | \( |U_{DGND} + I_{DDEL} + I_{DEEL}| > B + K \times I_{DNE} \) | In normal operation, there is no DC current flow at the ground point on the inverter side; if there is a ground fault in the DC system, the fault current in the ground will flow through the ground electrode. |
| Grounding electrode lead | metal return line longitudinal differential protection | \( |I_{DEE} + I_{DME,os}| > B + K \times (I_{DME} - I_{DME,os}) \) | If there is a ground fault in the metal return line, the fault point and the grounding pole on the inverter side form a loop. This loop is connected in parallel with the faulty point on the metal return line on the inverter side, which causes the differential current to appear. |
|                   | Ground lead unbalance protection | \( |I_{DEL1} - I_{DEL2}| > I_{set} \) | Ground fault detection. The grounding wire will be disconnected. The grounding lead is erected on the same rod with double return. |
|                   | Earthing pole differential | \( |I_{DEE} - I_{DEE}| > B + K \times I_{DEL} \) | When a ground fault occurs in one of the grounding pole lines, the current
### Bipolar Neutral Bus Differential Protection

| Protection          | Formula                                                                 | Notes                                                                 |
|---------------------|-------------------------------------------------------------------------|----------------------------------------------------------------------|
| Bipolar Neutral Bus | $I_{	ext{diff}} > B + K \times |I_{\text{DME}} - I_{\text{DME,OP}}|$ | Detect ground fault on bipolar neutral bus. When the bipolar neutral bus is grounded, the grounding point diverts the grounded pole and forms a differential current. |
| Differential Protection | $I_{	ext{diff}} = |I_{\text{DME}} - I_{\text{DME,OP}} - I_{\text{DME}}| – |I_{\text{DGND}} - I_{\text{DEL,1}} - I_{\text{DEL,2}}|$ | at both ends of the grounding pole line will be inconsistent and a differential current will be formed. |

**Notes:** Among the above formulaties, $P$ is a polar wave, $G$ is ground wave; $Z_s$ is the pole wave impedance; $I_{dl}$ is the DC line current, $Z_0$ is ground wave impedance; $U_{dl}$ is the DC line voltage. Subscripts 1 and 2 indicate pole 1 and pole 2; $I_{\text{DME}}$ is combined current of ground lead; $I_{\text{CN}}$ is a very neutral bus capacitor current; $\Delta$ is fixed, $i=1,2,\ldots$; $I_{\text{DME,OP}}$ is the DC current of the other station, $B$ is the starting current, $K$ is the proportional coefficient. $I_{\text{DGND}}$ is the grounding current in the station. $I_{\text{DME}}$ is the pole-neutral bus ground current. $I_{\text{DME,OS}}$ is metal return line current, $I_{\text{DME,OS}}$ is metal return live current of the other station.

#### 2.1. Triggering of instantaneous fault restart logic

The fault restart logic is triggered by the corresponding protection action signal, which is controlled by the master pole. The QiShao DC project is configured with instantaneous fault restarts for DC line, metal return line, grounding electrode circuit and bipolar neutral bus bar, as shown in Table 1.

#### 2.2. Related issues description of Restart logic

Faults in different parts of the DC system may have similar fault characteristics. In order to ensure the selectivity and reliability of the restart logic, the coordination relationship between logic and related protection under similar fault characteristics must be carefully restarted.

#### 2.2.1. The distinction between pole bus grounding and DC line grounding fault

The characteristics of the pole bus grounding fault is that the DC voltage reduces, the DC current on the rectifier side increases, and the DC current on the inverter side reduces, which is similar to the DC line grounding. However, because the pole bus fault is more serious and generally permanent, the DC line protection should not be activated to avoid unnecessary secondary shocks on the DC system.

The traveling wave protection and the voltage abrupt change protection are based on the direction discrimination of the DC line current change rate $dI_{dl}/dt$, and when the pole bus ground fault occurs, the main line protection will not operate reliably. The longitudinal differential protection has natural selectivity and will not act on the outside fault. DC line low voltage protection has no directionality, and mismatch can occur if the protection is not compatible with other polar grounding protection.

#### 2.2.2. Comparison of Grounding Fault between Bipolar Neutral Bus and Metal Loop

In the condition of metal return line operation, only the inverter-side grounding electrode is used to clamp the zero potential, so the grounding of the inverter-side bipolar neutral bus bar area will not have obvious fault characteristics. If the rectifier side bipolar neutral busbar is grounded, the connection place constitutes the temporary grounding electrode in the station, which is connected with the reverse side grounding pole, and the fault current can simultaneously promote the bipolar neutral bus differential protection and the reverse side metal return protection, which may lead to the situation that the metal loop ground protection acts first. However, under the condition of monopole metal loop operation, the bipolar neutral bus differential protection also triggers the restart logic, that is, the metal loop operation and the bipolar neutral bus differential protection have the same action effect, and the misoperation causes no additional adverse effects will be produced.

#### 2.3. Instantaneous fault restart operation timing
Transient fault restart can only be performed by rectifier station, because rectifier station is the power side. The protection action signals listed in Table 1 are transmitted directly or indirectly to the station’s pole control system, and then triggered by the logic diagram shown in Fig. 2. In the figure, INIT DOWN and ORD DOWN have the same definition, both are deionization signal and restart logic trigger signal, but the former is applicable to the DC line protection action signal, the latter is applicable to the metal return line, the grounding lead and the bipolar Neutral bus protection action signal. On the rectifier side, INIT DOWN and ORD DOWN directly trigger the restart logic via the OR gate; On the inverter side, the INIT DOWN and ORD DOWN signals are transmitted to the rectifier station via the inter-station communication, and are then triggered at the rectifier station via an OR gate. When the communication between the stations is interrupted, the above protection action signal on the inverter side cannot be transmitted to the rectifier side, and no restart will be triggered. The corresponding fault will be directly acted on the trip by other protection of the inverter station or the above-mentioned protection delay section. In addition, if the above protection of the rectifier station and the inverter station operates simultaneously, the rectifier station will shield the protection action signal sent from the inverter station.

The time sequence of transient fault restart operation can be summarized as three phases: phase shifting, deionization and restart. Instantaneous fault restart in sequence includes the full voltage restart, the reduction voltage restart.. Among them, the full voltage restart is to restart the DC voltage to the level before the fault, the reduction voltage restart is to restart the DC voltage to the reduced operation level. The control system specifies the number of restarts under various operating conditions. For example, under bipolar full-voltage operation conditions, if the failure is more stubborn, the system will perform two full voltage restarts and one reduction voltage restart.

2.4. System debug record waveform analysis
Fig. 2 and Fig. 3 show the recorded waveforms of the high-side valve group control host of the rectifier side and the inverter side pole 1 during the test of the DC line ground faults on the side of the Shaoshan HVDC system. In the figure, UDL_IN is the pole I pole bus to ground voltage, the unit is kV; IDCP and IDCN are respectively the high-side current and the low-side current of the high-end valve group of pole I, and IDNC and IDNE are the currents of the pole-neutral bus near the valve side.
and near the grounding pole, and the unit is A; ALPHA_MEAS and ALPHA_ORD are the measured value and the command value of the trigger angle, and GAMMA_CFC is the measured value of the extinguish angle. RETARD is the phase-shift signal, BLOCK is the valve block lock signal, DEBLOCK is the valve block unlock signal, BPPO is the input bypass signal, ACTIVE is the main signal of the valve bank control host, BPS_CLOSE_IND is the valve bypass switch co-position signal, ORD_ALPHA90_OUT is input the ALPHA90 signal, TRIP_ACCB is the AC switch signal.

From Fig. 2 and Fig. 3, it can be seen that there have been two restarts during the grounding test of the DC line on the Shaoshan side, that is, two RETARD signals have occurred. After the grounding fault, the DC voltage at the rectifier side drops and the DC current increases sharply. At the same time, the DC voltage and DC current at the inverter side disappear at the same time, causing the main protection action of the line. The first restart is triggered. The response is kept for the first RETARD signal for 150ms in the oscillogram. Then the system restarts trying to recover the DC voltage, that is, the RETARD signal disappears and the rectifier side falls back the firing angle, but because the fault is not eliminated, the rectifier side cannot establish a normal DC voltage after restart and is accompanied by a large fault DC current, but at this time the line main protection can’t be operated due to the increase of the DC voltage change trend. The low-voltage protection delay is 80ms to trigger the secondary restart. The response is the second RETARD signal held in the oscillogram for 200ms. Then the system restarts, that is, RETARD disappears for the second time. At this time, the grounding copper wire is still not fully burned, so the instantaneous rectifier side cannot still establish a normal DC voltage after the second restart, and the DC current increases sharply. The copper is grounded after about 20ms. The line is completely burned, the fault disappears, the fault point returns to normal voltage level, and the DC current also falls back. In the oscillogram, a small arch appears in the DC current waveform after the second RETARD signal disappears; after the fault disappears, the rectifier side rapidly establishes a normal voltage, and the low-voltage protection returns and the system restarts successfully.

3. Valve group fault restart logic research

3.1. Characteristics of grounding fault in converter area

The converter fault restart logic means that under the condition that the two poles are all operated in the bipolar power control mode and the communication between the stations is normal, the ground fault in the single inverter area of the station causes the differential protection of the inverter to act on blocking both poles. Then the control system automatically inputs non-fault valve groups to quickly restore bipolar balancing operation. Figure 4 shows the fault current path when Shaoshan station pole 1 low-voltage converter zone high-pressure wall bushing fault occurs. The C12 valve group was
short-circuited, that is, the DC voltage on the inverter side was reduced by about 400 kV, so the DC current will increase significantly when the fault occurs. At the same time, the fault current flows through the IDC2P without flowing through the IDC2N, so the differential protection of the low-side converter with IDC2P and IDC2N as differentials will operate. For ungrounded faults in the converter area, the control system after the relevant protection action can quickly isolate the fault by the by-pass function generated by the bypass switch; But for the grounding fault in the converter area, such as the fault point F, the bypass function fails after closing the BPS2, because the fault point can still form the loop through the earth and the rectifier station, and the circuit is less impedance because it does not pass through the smoothing reactor on the very neutral bus. Since the anode/cathode switch of the valve group does not have the capability of arc breaking, the ground fault in the single converter must be blocked by blocking the same-pole dual valve group, and short-term interruption of the DC current to achieve rapid arc extinction at the fault point.

![Diagram](image)

**Figure 4** the fault current path when Shaoshan station pole 1 low-voltage converter zone high-pressure wall bushing fault occurs

**Figure 5** the fault current path when the rectifier side pole 1 low-voltage converter zone high-pressure wall bushing fault occurs

Notes: C11 and C12 are respectively the high-end and low-end valve group of Pole I; Z1 is the Pole 1 DC Filter; R1 and R2 are smoothing reactors; A11 and A12 are anode switch; C11 and C12 are cathode switch; BPS1 and BPS are bypass breaker; BPI1 and BPI2 are bypass switch; F is fault point; IDC1P and IDC1N are respectively the high-voltage and low-voltage side current of the Pole 1 high-end valve group; IDC2P and IDC2N are respectively the high-voltage and low-voltage side current of the Pole 1 low-end valve group.

Figure 4 shows a relatively special grounding fault in the converter area. When the fault point moves down and approaches the common-cathode point of the low-voltage six-pulse bridge, the fault circuit is also present, but the fault current must flow through the valve side windings of the converter first, and the fault loop impedance will increase while the fault current reduce. It is worth noting that at this time, the low-end valve group has been blocked. Due to the semi-controllability of the converter valve, the bridge arm that is open before the lock-out will continue to conduct, and will not be re-commutated. The flow through the valve side windings of the converter transformer will be direct current instead of alternating current. So even if the low-side valve group is open-circuited on the network side of the converter, the fault current can still form a loop through its valve-side winding.

When the high-end valve group faults, the situation is slightly different. If a ground fault occurs in the high-side converter area, the fault current flows directly from the fault point back to the ground pole of the Qilian station, causing the fault point to be short-circuited to the common cathode point of the low-voltage six-pulse bridge of the low-side converter. The DC voltage of the inverter side is larger and the fault current is larger. At this time, although the low-end valve group does not supply power to the fault point, it still needs to close the same-pole dual valve group to stop power supply to the fault point. In addition, the ground fault in the rectifier-side converter area is different from the inverter side, as shown in Figure 5. It can be seen from the figure that after a ground fault occurs at the high-voltage wall bushing in the low-side converter area of the rectifier side pole 1, the fault point and the ground electrode on the rectifier side constitute a loop, and the low-side converter forms a large forward.
voltage drop to the fault point resulting in a larger fault current. At the same time, the low-end converter is short circuited by the fault point resulting in interruption of the DC line current.

3.2. Valve group fault restart action sequence
The timing sequence of the valve group failure restarts is as follows: ①the valve control host blocks the fault valve group and transmits the differential protection action signal to the pole control host by real time control LAN net after receiving the converter differential protection action signal; ②the pole control host sends a command to block the non-fault valve group and perform pole isolation and discriminates fault valve group and trigger valve group fault restart logic after receiving the converter differential protection action signal; ③After the valve group fault restart logic is triggered, the pole control host sends a valve group isolation instruction to the fault valve group and sends a non-fault valve group number and a restart command to the same-pole dual valve group; ④After the non-fault valve group receives the pole control command, if it is judged that its own number is consistent with the number issued, the restart command takes effect, and after receiving the fault valve group isolation indication (that is, the fault valve group BPI is closed, AI, and CI are in open), the logic of entering a valve group is automatically restarted, and the fault valve group is locked due to the inconsistency between its own number and the number issued by the pole control host.

3.3. System debug record waveform analysis
Fig. 6 and Fig. 7 are the recorded waveforms of group block process and valve group restart process of ShaoShan Railway Station non fault valve group (high-voltage valve group) automatic restart test. According to the time scale in the figure, the interval between the two is about 2 minutes. The variables in the figure are the same as in Figure 2. The test is done through the program configuration number. From Fig. 6 and Fig. 7, it can be seen that the high-end valve group and the low-end valve group performs blocking after the failure. Inverter side pole 2 dual valve group is bypassed and the voltage drop to zero, resulting in a drastic increase in DC current. But after the rectifier side receives the protection action signal from the station, the blocking pole is closed so that the DC current is interrupted and the fault point is extinguished. After the pole isolation, low-end valve block isolation and pole connection automatic sequence operation, that is, after about 2 minutes, the low-end valve group automatically restarts and the DC current is successfully restored.

![Waveform analysis](Image)

Figure 6: Valve group block process of ShaoShan Railway Station non fault valve group (high-voltage valve group) automatic restart test

Figure 7: Valve group restart process of ShaoShan Railway Station non fault valve group (high-voltage valve group) automatic restart test

4. Conclusion
UHVDC transmission has become a reality due to the existence of strict logic and perfect control system. In this paper, instantaneous fault restart logic and valve group fault restart logic in polar layer control system of Qi-Shao UHVDC project are thoroughly studied, and the trigger mechanism, action sequence and open conditions of the two restart logics is analyzed, the relationship between
instantaneous fault restart logic and other instantaneous fault protection is studied. According to the Qi-Shao UHVDC system debugging field oscillogram, the implementation of two restart logics was analyzed. Instantaneous fault restart can effectively improve the availability of the DC system, and in the meanwhile the valve group fault restart logic is beneficial to optimize the operation level of the DC system. Some other special and complex control logics of Qi-Shao UHVDC project will be studied in our future researches, and it is hoped that our studies can help on-site operation and abnormal analysis.

5. Reference

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