Cooperation research between electrode line transversal differential protection and bridge differential protection in HVDC project

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Abstract. On July 14, 2017, the electrode line occurred ground fault near the ZhaoQing converter station of GaoZhao HVDC, the Delta Bridge Differential Protection (87CBD) of the valve area protection acted before the Electrode Line Transversal Differential Protection (60EL) of electrode area protection, which leads to the pole blocking. In view of the exposed problem between the 87CBD and the 60EL about the cooperation of the protection delays, the paper studies the feasibility of the delays adjustment. Overall considering from the aspects from the 87CBD delay, the 60EL export time, the 60EL measurement error, the cooperation of the 60EL and the restart blocking time, and so on, the optimization is proposed which improves the 60EL delay for 400ms, and improves the restart blocking time for 400ms. Simulation show that the proposed measures are feasible and effective, to ensure that when the electrode line fault occurred near the converter station, the pole blocking can avoid by the DC restart sequence of the 60EL.

1. Introduction

On July 14, 2017, 13:24:2.418, there are four valve no check back signals of Valve D4 in ZhaoQing converter station Pole 1 of the GaoZhao HVDC, exceeded the most redundant number, causing Pole 1 tripping and Pole 2 enter the metallic return mode, 34s after Pole 1 blocked, the Delta Bridge Differential Protection (87CBD) acted and lead to Pole 2 blocked, during the process of Pole 1 blocking, the Electrode Line Transversal Differential Protection (60EL) acted. It can be seen that the electrode line fault causes the valve area protection (87CBD) acts before the electrode line area protection, which does not meet the requirement of DC protection selectivity and quick action, indicating that there is optimal space for the coordination relationship between the 87CBD and 60EL.

Currently, the study of the 60EL optimization focuses on the protection logic, export, principle, and valve. the impact of the power flow after the electrode line fault on the valve side current of the converter transformer is not considered[1-8]. The paper [4] puts forward the improvement measures of 60EL protection from the protection logic, and uses the larger protection value if large load, otherwise uses the lower protection value. The paper [5-6] puts forward the improvement measures of 60EL protection export, and the 60EL protection export is changed into the restart sequence in monopolar ground return operation, which is favorable for eliminating the electrode line fault.

The paper [7] has proposed a way to protect the system based on the principle of longitudinal differential protection, which is to set the CT transformer to the both side of the electrode line. The longitudinal differential protection scheme and the protection criterion are presented, and the
protection export strategy is optimized. The paper [8] analyzes the necessity of adjusting the 60EL delay, which is not conducive to fault detection and do not play a significant role in reducing the DC blocking probability.

In this paper, the cooperation relationship between the 60EL and 87CBD protection are analyzed. The optimization measures of the 60EL delay and restart blocking time are put forward from the aspects of the protection export time, the measurement error, the restart blocking time, the fault feature, and the 87CBD action time, etc., which can avoid DC block by the 87CBD when electrode line fault.

2. Principle of related protection

2.1. Principle of the 87CBD

The 87CBD is mainly reflected in valve ground fault, short circuit fault and commutation failure. It can also reflect the AC system ground fault. The criterion of the 87CBD is $I_{ac}-I_{acD} > \Delta$, where:

$$I_{acY} = \left( |I_{L1Y}| + |I_{L2Y}| + |I_{L3Y}| \right) \times 1/2;$$

$$I_{acD} = \left( |I_{L1D}| + |I_{L2D}| + |I_{L3D}| \right) \times 1/2;$$

$$I_{ac} = \text{MAX}(I_{acY}, I_{acD}).$$

The integral principle of the 87CBD is implemented by the DISA module, which operates once every 1ms, as shown in Figure 1. When the difference between $\text{Max}(I_{acY}, I_{acD})$ and $I_{acD}$ exceeds $0.07 \times 33.3\% = 2.331\%$, the integrator is added by +20 per 1ms, otherwise subtracted by -1. When the integral is over the protection delay ($T=200\$ms$, the action time score is 4000), the 87CBD acts.

![Figure 1. Logic of 87CBD.](image)

| Table 1. Principle of 60EL |
|---------------------------|
| **Criterion of action**   | **value** | **Delay** | **Export** |
| Bipolar: $|I_{dee1}-I_{dee2}| > \Delta$ & $\text{max}(I_{dee1}, I_{dee2}) > 550A$ | 120A | 1s | Pole balance |
|                          | 120A     | 9s        | Pole blocked |
| Bipolar: $|I_{dee1H}-I_{dee2H}| > \Delta$ & $\text{max}(I_{dee1}, I_{dee2}) < 550A$ | 22.5A | 1s | Pole balance |
|                          | 22.5A    | 9s        | Pole blocked |
| Single pole: $|I_{dee1}-I_{dee2}| > \Delta$ & $\text{max}(I_{dee1}, I_{dee2}) > 550A$ | 120A | Rectifier:500ms Inverter:1s | Recovery logic |
|                          | 120A     | 9s        | Pole blocked |
| Single pole: $|I_{dee1H}-I_{dee2H}| > \Delta$ & $\text{max}(I_{dee1}, I_{dee2}) < 550A$ | 22.5A | Rectifier:500ms Inverter:1s | Recovery logic |
|                          | 22.5A    | 9s        | Pole blocked |

2.2. Principle of the 60EL

The 60EL reflects the ground fault or broken line of any electrode line, and the protection criterion is $|I_{dee1}-I_{dee2}| > \Delta$, which is shown in Table 1[9]. As well as the 87CBD, the 60EL also uses the DISA module.

3. Action analysis of the 87CBD

Using the Guiguang HVDC PSCAD/EMTDC model, a DC power of 1500MW in monopolar earth return mode is simulated. The ground fault point is set near the inverter station, and the fault moment is at 3.58s, the failure duration is 2s.

As shown in Figure 2, the neutral point of the YY and YD transformer are both flowing through the current, among the YY transformer has a small current flow, and YD transformer has a larger one. As shown in Figure 3, the valve side current of the YY transformer is unchanged, and the YD converter
valve side current is negatively biased, causing the current transformer(CT) saturation, which causes the distortion of the valve side current after the CT. As shown in Figure 4, the valve side current(IacY) of the YY transformer is unchanged and the IacD is less than IacY. After the 87CBD action, Idee1 and Idee2 are rapidly reduced to zero, the delay of the 60EL is not met, so the 60EL is not active.

The above simulation results are basically consistent with the change of IacY and IacD in Pole 2. It is indicate that that reason of the blocking of Pole 2 is that, the ground fault occurs near the outside of the converter station, and the large current flows into the neutral point of the YD transformer, causing the valve side current to be negatively biased, and causing the CT to be saturated, thus lead to the distortion of IacD, and finally reaching the protection value of the 87CBD.

![Figure 2. Neutral point current of YY and YD transformer.](image)

![Figure 3. Valve-side current of YY and YD transformer before and after CT.](image)

![Figure 4. Simulation wave of IacY and IacD.](image)

4. Optimization study of the 60EL
It can be seen from the procedure of pole 2 blocking, the protection (87CBD) of the valve area acts before the protection (60EL) of the electrode area under the electrode line fault outside the station, which has violated the selectivity and speed requirement of the DC protection. Therefore it needs further evaluation on the cooperation relationship between the 60EL and the 87CBD.

The 87CBD protection value mainly considers the short-circuit failure of the valve in the low power mode, and the optimal margin of the protection value is not large.

The valve group differential protection (87CG) mainly reflects the short-circuit failure of the valve zone and the commutation failure, of which the principle is Min (IdH, IdN) -Max (IacY, IacD) >Δ, the IacD decrease does not result in the action of the 87CG, and therefore there is no impact on the 87CG.
For this incident, if the 60EL acts before the 87CBD when electrode line fault occurs, it perform a DC line fault restart to avoid the DC trip[10-12]. Considering the higher the 60EL value is, the larger the dead zone will be, so it is not recommended to adjust the protection value. For the 60EL delay, there is different among the HVDC projects, some projects are only 400ms, indicating that the possibility of optimization of the 60EL delay. In the following, the feasibility of the 60EL delay can be comprehensively analyzed in terms of the protection output time, 87CBD action delay, restart blocking time, measurement error, etc., and the optimization scheme is proposed.

4.1. Export time of the 60EL

The DC protection device output time of the 60EL is about 67ms. The time for reducing DC current to zero is about 39ms during the restart sequence, as shown in Figure 5. Therefore, the total time from the 60EL action to reducing the current is about 67+39ms=106ms.

![Figure 5. The time of the current decline to zero during the restart sequence.](image1)

![Figure 6. wave of IacD after fault.](image2)
4.2. The 87CBD action time in the electrode line fault
As shown in Figure 6, the time from the electrode line fault occurring to the 87CBD action is 855ms, and the time T1 of the IacY and IacD differential current increases from zero to the first time to meet the protection value is 347ms, and the time T2 from the first time of the current difference satisfying the 87CBD value to the output time of the protection device is 508ms.

The fault features of the current distortion of the valve side are basically unchanged under the current change of the neutral point of the YD transformer. That is to say, the characteristics of the current fluctuation are almost the same with the similar fault, and the state of the current saturation will sustain a certain time. In this case, the fault occurs in the near area of the converter station under the full DC power, which is basically the most serious condition in the class. Therefore, it can be considered that the T1 and T2 values of the same kind fault will not be significantly reduced.

Consider a certain margin, take T1=200ms, T2=350ms, when the ground current flow through the neutral point of the YD transformer, the action time of the 87CBD is not less than 550 ms.

4.3. Coordination relationship between the 60EL and the restart blocking time
In case of DC line fault, the station may send a restart signal to the other station. Similarly, if the other station detects a line fault, it will also send the restart signal to the station. There is a time difference between the two stations to start the DC restart signal in the same DC line fault, which may cause the repeated counting of the DC restart times. Therefore, the Gaozhao HVDC has set 1s to the restart blocking time, that is, when the station detects the DC line fault to send the DC restart signal, and if the restart signal is received less than 1s, the restart signal of the other station will be blocked, and the restart times is still counted as one time. While the DC restart signal received by the station is not restricted by the restart blocking time.

Notably, the two stations detect DC line fault at almost the same time, the restart blocking time is considered mainly by the station communication delay, and the station communication delay is not more than 20ms. Therefore, it can be seen that the restart blocking time still has a great optimizing space.

The 60EL delay needs to be considered in coordination with the restart blocking time, assuming that the deionization time T3 is 400 ms, the restart blocking time is 1s. When the rectifier station performs a restart order, and the electrode line fault is occurred in the inverter station, in order to avoid the blocking of the restart order from the inverter station, the 60EL delay shall not be less than 600ms. At present, the 60EL delay is set to 1s, satisfying the matching requirements with the restart blocking time.

Therefore, if the 60EL delay T4 is shortened, the restart blocking time T5 shall be reduced accordingly, and T5<T3+T4 shall be ensured.

4.4. Analysis of the 60EL measurement error
In the case of monopole ground return mode, due to the measurement errors in Idee1 and Idee2, it is possible that there is a certain difference between Idee1 and Idee2 at the steady-state conditions, so that the 60EL delay needs to avoid the measurement error. In order to guarantee the high sensitivity under different DC load, the different accuracy of sensors is adopted(Idee1H/Idee2H for high precision, Idee1/Idee2 for low precision). When the current is large (Max (Idee1, Idee2)>550A), the low precision is adopted, otherwise(Max (Idee1, Idee2)>550A), the high precision is adopted. Based on the actual recorded wave, the relationship of the 60EL measurement error and the 60EL delay is analyzed.

Under monopole ground return mode, the difference between Idee1 and Idee2 is much less than the 60EL value. During transient state of the DC restart, the difference current of Idee1 and Idee2 with the high precision is greater than the protection value 22.5 A, and the longest duration is 41.4 ms, but still far less than the protection delay, as shown in Figure 7. The difference current of Idee1 and Idee2 with the low precision is less than the protection value 120A, as shown in Figure 8. It can be seen that considering the measurement error, there is still a significant decrease space for the 60EL delay.
4.5. Optimization scheme of the 60EL

In view of the above, to ensure that the 60EL acts in advance of the 87CBD in case of the electrode line fault. Considering the 60EL export time, the 87CBD action time, the restart blocking time, and the measurement error, the operation time of the 60EL shall not exceed 550-106ms = 444ms, which the 60EL delay of 400ms in Niucong and Jingzhong HVDC. The optimization scheme is proposed as follows:

1) the 60EL delay of the rectifier side and inverter side under monopole ground return mode are optimized to 400ms.
2) according to the coordination relationship between the 60EL delay and the restarting blocking time, the restarting blocking time will be changed from 1s to 400ms.

5. Simulation test

In order to verify the effectiveness and correctness of the 60EL protection optimization scheme, the simulation test is carried out to analyze the impact of the DC line and electrode line fault, the restart blocking function, the power level, the conversion of the ground and metal return and other operating conditions or factors to the protection of 60EL, and a total of 10 kinds of test items are developed. The experimental purposes are shown in table 2. Setting the DC line fault restarting times is 3 times, 60EL protection delay is 400ms, and the restart blocking time is 400ms.

| No | Test Item | Test Purpose |
|----|-----------|--------------|
| 1  | the electrode line fault near the Converter station (to reproduce the scene). | Verify 60EL acts before 87CBD, DC restart successfully. |
| 2  | Coordination relationship between the 60EL and the restart blocking time. | Verify that the electrode line fault of inverter station is correctly implemented. |
| 3  | Pole 1 ground return, electrode line fault for once. | Verify that the DC line restart sequence is correctly implemented by 60EL. |
| 4  | Pole 1 ground return, electrode line fault for 3 times. | Verify that the DC line restart sequences are correctly implemented by 60EL. |
| 5  | Pole 1 ground return, The rectifier side and the inverter side occur electrode line fault successively. | Verify that the DC line restart sequences are successively implemented by 60EL at both side. |
| 6  | Pole 1 ground return, DC line and electrode line fault at the same time. | Verify that the DC line restart sequences are correctly implemented by DC line protection and 60EL. |
| 7  | Pole 1 ground return, DC line and electrode line fault successively. | Verify that the DC line restart sequences are correctly implemented by DC line protection and 60EL. |
| 8  | Bipole ground return, two pole occur DC line and electrode line fault respectively. | Verify that one pole is blocked by the DC line protection and DC line restart sequences of the other pole is correctly implemented by 60EL. |
| 9  | Pole 1 ground return, low power, electrode line fault. | Verify that the DC line restart sequences are correctly implemented by 60EL with low power. |
| 10 | Pole 1 ground and metal conversion test | Verify that during the ground and metal conversion process, 60EL is reliably acted. |

Table 2. Test item and test purpose.
5.1. 60EL protection delay 400ms, IdeE1 ground fault near the station
The DC power is 1500MW, the electrode line fault is triggered at 4.08s, and the failure duration is 500ms. The simulation waveform is shown in Figure 9- Figure 10. The TRPBDCP is the action signal of the 87CBD, and the TRP_ECB is the action signal of the 60EL. It can be seen from Figure 10 that, the time from the fault occurring to the difference flow of the 87CBD significantly increased is about 300ms. The 60EL delay is shortened from 1s to 400ms and acts before 87CBD, which restores the DC system by the DC restart.

5.2. The problem of DC voltage and current decline caused by blocking the restart signal
The DC line fault duration is 0~0.2s, and the fault duration of the electrode line at the inverter side is 0.45~0.9s, and the deionization time of restart is 400ms. If the restart blocking time T is greater than or equal to 1.1s, and the DC line fault and the electrode line fault of the inverter side occur successively, after the DC restart sequence of the rectifier side is performed, the 60EL of the inverter side sends DC restart order to rectifier side, and the rectifier side will block the order, which causes DC voltage and current decline, as shown in Figure 11- Figure 12.

Figure 9. Wave of voltage and current after modification.
Figure 10. Wave of 60EL acting after modification.

Figure 11. Wave of restart sequence in rectifier side.
The reason for DC voltage and current decline is: when the rectifier side detects the DC line fault, the DC restart signal will be maintained in the pole control system with 1.1s. During this period, the restart order from the inverter side is blocked. In the inverter side, the pole control system performs a DC restart sequence, and the inverter side is controlled by from the voltage control to the extinction angle control, which increases the firing angle to 95 degrees, while the rectifier side does not perform a forced retard, causing DC voltage and current decline.

5.3. Test results
1) The 60EL delay of Gaozhao HVDC underground return mode is optimized for 400 ms. According to the simulation results in Table 2, the 60EL acts correctly in both rectifier and inverter side.

2) When the DC line fault and the electrode line fault of the inverter side are successively occurred, if the restart blocking time is less than or equal to 1s, the DC restart sequence is performed correctly and the restart order from the inverter side will not be blocked. Therefore, if the restart blocking time is optimized for 400ms, the DC restart sequence can be implemented correctly by the 60EL of the inverter side.

3) When the DC line fault and the electrode line fault of the inverter side are successively occurred, if the restart blocking time is longer than or equal to 1s, the rectifier side will block the restart order from the inverter side, which causing DC voltage and current decline.

6. Conclusions
In the case of the electrode line fault near the ZhaoQin station of the Gaozhao HVDC, which lead to pole 2 blocking on "7.14", this paper study the features of the valve current of the 87CBD in this fault case, considering the 60EL export time, the 87CBD action time, the restart blocking time, the measurement error, the optimization is proposed which improves 60EL delay for 400ms, and improves the restart blocking time for 400ms. The simulation results show that the optimization measures are feasible and effective, to ensure that when the electrode line fault occurs, the 60EL will act before the 87CBD, reducing the risk of a DC tripping.

For the failure condition discussed in this paper, the 60EL optimization scheme mentioned in this paper also applies to other HVDC projects.

References
[1] YU Yang, WEI Chen 2010 ZHU Lin Impact of HVDC ground electrode current on transformers with different structures[J]. Power System Protection and Control 38(24) 71-76
[2] JI Guang 2010 ZHU Tao-xi Abnormality of converter transformers in Guangzhou inverter station and its treatments [J]. Power System Protection and Control 38(1) 115-120
[3] CHEN Dan 2012 [J] Power System Protection and Control 40(14) 92-96
[4] YU Jiang, ZHOU Hong-yang, et al 2008 Discussion on Issues of Electrode Line Unbalance Protection [J]. Southern Power System Technology 2(3) 26-29
[5] YU Jiang, ZHOU Hong-yang, WANG Bin 2009 [J] Southern Power System Technology 3 62-66
[6] ZHU Tao-xi, HE Fang, HE Ye-yong, et al 2009 Discussion on operation results of electrode current unbalanced protection used in HVDC transmission system in CSG [J]. Power System Protection and Control 37(15) 112-116
[7] ZENG Xiang-jun, ZHANG Xi, YANG Tao, et al 2014 [J] Power System Protection and Control 42(24) 132-137
[8] OU Kai-jian, HAN Wei-qiang, HUANG Li-bin 2008 [J] Southern Power System Technology 2(4) 98-100
[9] SIEMENS DC Protection Coordination Study Report (GG1) [Z] Erlangen SIEMENS, 2003
[10] WANG Hai-jun, LI Peng-fei, ZENG Nan-chao, et al 2006 [J] Power System Technology 30(23) 32-35
[11] ZHAO Jun, CAO Sen, LIU Tao, et al 2010 Research and optimization on DC line fault recovery strategy used in Gui-Guang HVDC project [J]. Power System Protection and Control 38(23) 127-132
[12] GAO Xi-ming, ZHANG Peng, HE Zhi 2005 Analyse of performance of HVDC line protection [J]. Automation of Electric Power Systems 29(14) 96-99