Analysis and Solution of Frequent Start-up of Incremental Differential Protection

Zhang Hongyue¹, Liu Zhiwen¹, Chen Hailong¹, Shen yanhua¹, Xiao Zhigang¹, Zhao ruidong¹, Xu Liming¹

¹XJ Electric Co., Ltd., Xuchang 461000, China

Abstract: In this paper, it is analyzed that the reason of frequent start-up of incremental differential protection is caused by double SC capacitor banks in a converter station. No abnormality was found in the secondary circuit of CT. In the process of inspection, it is found that the accuracy adjustment coefficient of 010A converter protection device 2 does not need to be adjusted, and the accuracy meets the error requirement. The accuracy adjustment coefficient of 010B converter protection device 2 can meet the error requirement only after individual adjustment. However, one year later, when the substation was out of service, it was found that the accuracy adjustment coefficient of the individual channels of 010B converter and rheological protection device 2 was quite different. Because the accuracy error of the external circuit meets the requirement, it is confirmed that the acquisition circuit of 010B converter protection device 2 is abnormal. Therefore, the acquisition circuit of 010B converter protection device 2 is replaced, including AC input circuit and sampling and holding circuit. After replacement, double SC capacitor banks were put into operation many times, and no start-up phenomenon occurred. In view of this incident, this paper also proposes two optimization schemes. One is to enhance the anti-interference measures of AC input plug-in of converter protection device. Secondly, dual redundancy is used in differential channel of single CPU plug-in.

1. Introduction
In UHV HVDC transmission system, converter transformer is one of the most important equipment. It is the core equipment of the converter and inverter in AC and DC transmission system. It realizes the electrical insulation and isolation of the AC and DC parts. At the same time, it provides the commutation voltage with the phase difference of 30 degrees for the commutation valve[1-2]. The converter transformer group is usually connected in parallel by a Y/Δ converter transformer and a Y/Y converter transformer[3-4]. The principle and configuration of the converter protection are related to the safe and stable operation of the converter. The dual configuration of protection is the mainstream at present, the two systems can not be completely duplex, which will affect the safe and stable operation of the converter and the daily operation and maintenance[5-6].

Starting from the specific events on the spot, this paper analyses the reasons for the frequent start-up of incremental differential protection, and puts forward not only the on-site solution, but also the follow-up optimization scheme.

2. Event description
On Dec.01, 2018, when the DC power of a converter station is increased and reactive power is
automatically put into the double SC capacitor bank, the master and slave systems all report "010B Incremental Differential Protection Action of Converter Lead and Converter", which protects the trip without exit, and the DC system runs normally.

On-site inspection of 010B converter protection device 2, converter protection device 2 tripping lights on, action message for "large difference incremental differential protection action", because the start element did not act, so converter protection device 2 did not exit. 010B converter protection device 1 operates normally without action alarm signal.

Protection sample value of 010B converter protective device 2 display normal at operating time.

3. Protection configuration
The converter station is equipped with two sets of redundant converter protection devices 010A and 010B. Each set of converter protection device is realized by two devices. The hardware of the two devices is identical. Among them, the converter protection device 1 realizes the functions of converter differential protection and backup protection. Converter protection device 2 realizes converter lead and converter differential protection, winding differential protection function. The configuration diagram of converter protection device 2 is shown in Figure 1.

![Configuration diagram of converter protection device 2](image1)

Both converter protection devices adopt "start + action" exit mode, as shown in Figure 2.

!["start + action" exit mode Schematic diagram](image2)

As shown in Figure 2, each device is equipped with two CPU plug-ins. CPU1 is used to realize the start-up discriminant logic of protection, CPU2 is used to realize the export discriminant logic of protection. Only two CPU plug-ins satisfy the operation conditions, the converter transformer protection device can allow to jump off the side circuit breaker and the middle circuit breaker of the converter transformer network side, and block the corresponding DC unit at the same time.

4. Incremental Differential Protection Principle of Converter Lead and Converter
In order to meet the requirements of relay protection in power system, the main protection of converter transformer consists of converter lead and converter differential protection, converter lead and converter incremental differential protection, converter lead and converter differential current over-limit, converter differential protection, converter incremental differential protection, converter differential current over-limit and winding differential protection. The main protection of converter transformer can reflect inter-phase short-circuit fault, single-phase grounding short-circuit fault and
Interturn short circuit fault in converter transformer.

As can be seen from Fig.1, the converter station adopts three-winding converter transformer. Converter lead and converter incremental differential protection are four-side differential protection, which is configured in converter protection device 2. The CT scans used are network side TA1 and TA2, valve Star side TA4 and valve angle side TA5.

4.1 Starting element
Converter lead and converter incremental differential protection, shares the startup elements of converter lead and converter differential protection. The operating conditions of the starting element are as follows:

The differential current is greater than 0.18 times the rated current, and the protective outlet power supply is opened after the starting element is operated.

\[ I_{op} > 0.18 I_e \]

Among: \( I_{op} = \left| \hat{I}_1 + \hat{I}_2 + \hat{I}_3 + \hat{I}_4 \right| \)

\( \hat{I}_1, \hat{I}_2, \hat{I}_3, \hat{I}_4 \) are the secondary currents of current transformers on each side of converter.

4.2 Converter lead and converter incremental differential protection
Incremental differential protection is not affected by normal operating load current and has higher sensitivity than ratio differential protection. Because the selection of braking current of ratio differential protection includes normal load current, when the converter transformer fails weakly, the ratio differential protection may delay operation or not because of the large braking current. Incremental differential protection mainly solves minor turn-to-turn fault and high resistance grounding fault of converter transformer.

Incremental differential action equation:

\[ I_{op} > 0.2 I_e \]

\[ I_{op} > 0.65 I_{res} \]

Among: \( I_{op} = \left| \Delta \hat{I}_1 + \Delta \hat{I}_2 + \Delta \hat{I}_3 + \Delta \hat{I}_4 \right| \)

\( \Delta \hat{I}_1, \Delta \hat{I}_2, \Delta \hat{I}_3, \Delta \hat{I}_4 \) are the increment of secondary current of current transformer on each side of converter transformer

\( \Delta I_{max} \) is the largest of four sides

\[ I_{res} = |\Delta I_{max}| \]

The operation characteristics and protection logic diagram of incremental differential protection are shown in Fig.3.
Fig. 3(a) Incremental differential protection operation characteristics

Fig. 3(b) Incremental differential protection logic diagram

5. Operation Analysis of 010B Converter Protection Device 2

5.1 Analysis of CPU2 action recording of 010B converter protection device 2

On Dec. 01, 2018, the CPU2 fault recording of 010B converter protection device 2 is shown in Fig. 4.

The data for large difference incremental differential action are shown in Table 1.

Table 1: The data for large difference incremental differential action

| No | Name       | Fundamental current (A) | Second harmonic current (%) |
|----|------------|-------------------------|----------------------------|

Fig. 4. Overall recording of CPU2 plug-in
As can be seen from Fig. 4 and Table 1, it can be seen that at fault time, phase A of converter lead and converter differential protection is judged as regional fault, phase A incremental relay of converter lead and converter differential protection starts component acts, phase A incremental relay of converter lead and converter differential protection satisfies operation exit condition. Because protective starting element of CPU1 is not activated and the protective outlet 24V positive power supply is not opened, the protective device of the device has not tripped out. This incident also shows that it is absolutely necessary for converter protection device to adopt the "start + action" exit mode.

5.2 Recording Analysis of External Recording Device
Due to December 01, 2018, 010B converter protection device 1 did not start, only 010B converter protection device 2 CPU2 acts. The external fault recorder is connected with 010A converter protection device 1 and 2, but not with 010B converter protection device 1 and 2, so it can not be accurately analyzed.

5.3 Analysis of protection effect of double SC capacitor bank input on converter transformer
Double SC capacitor banks share a switch by two groups of SC capacitor banks, whose capacity is twice that of the general SC capacitor banks. Double SC capacitor banks are the last group of input and the first to exit in the sequence of filter switching. When a double SC capacitor bank is put into operation, the impact is larger than that of a single filter bank. When the DC power is close to the rated power, the impact is greater.

6. Unstarted analysis of 010B converter protection device 1
Incremental differential protection of converter transformer is three-side differential protection, which is arranged in converter transformer protection device 1. The TA images used are net side TA3, Star side TA4 and angle side TA5, as shown in Figure 1.

The impact of double SC capacitor banks at the time of operation only affects TA (TA1 and TA2) in the network side. Therefore, 010B Converter Protection Device 1 is not started.

7. Unstarted analysis of 010A converter protection device 2
Redundant configuration of 010A converter protection device 2 for 010B converter protection device 2. The hardware structure of the two devices is the same and the program is the same. Therefore, there is no problem with the procedure of converter protection device 2.

8. First Improvement Program
After checking, it is found that the sampling of CPU1 plug-in of 010B converter protection device 2 is normal, and there are several abnormal sampling values of CPU2 plug-in, as shown in Table 2.

| No | CPU2 | Before adjustment (A) | After adjustment (A) |
|----|------|-----------------------|----------------------|
| 1  | Ia2  | 0.082                 | 5.829%               |
| 2  | Ib2  | 0.132                 | 14.1%                |
| 3  | Ic2  | 0.148                 | 21.85%               |
| 4  | Id1a | 0.070                 | 10.66%               |
| 5  | Id1b | 0.012                 | 17.04%               |
| 6  | Idc1 | 0.008                 | 791.7%               |
|   |   |   |
|---|---|---|
| 3 | 1c2 | 0.954 | 0.999 |
| 4 | IVYa1 | 1.000 | 1.000 |
| 5 | IVYb1 | 0.964 | 1.000 |
| 6 | IVYc1 | 1.000 | 1.000 |
| 7 | IVDa1 | 1.000 | 1.000 |
| 8 | IVDb1 | 1.000 | 1.000 |
| 9 | IVDc1 | 0.946 | 1.000 |
| 10 | IACDa1 | 1.000 | 0.999 |
| 11 | IACDb1 | 1.000 | 1.000 |
| 12 | IACDc1 | 0.976 | 1.000 |

Notes:
Ia2: Phase A of Medium Switch TA on Grid Side
IVYa1: Phase A of Y/Y Transformer winding head TA on valve Side
IVDa1: Phase A of Y/ΔTransformer winding head TA on valve Side
IACDa1: Phase A of Transformer winding head TA on Grid Side
Among, medium switch on network side TA, valve angle head side TA and valve star head side TA are all the TA used in the differential protection discrimination are TA used in differential protection discrimination.

This data can provide a preliminary explanation for the events of December 01, 2018. That is to say, the sampling value of CPU1 is normal and not started, while the sampling value of CPU2 channel is small, which satisfies the incremental differential logic discrimination. Because CPU1 does not open 24V positive power supply, the device has not been exported.

At the same time, the relevant TA secondary circuit was inspected on site, no abnormalities were found, and the TA secondary circuit insulation test was qualified.

After adjusting the channel coefficient, the sampling values of CPU1 and CPU2 plug-ins are basically the same when 010B converter protection device 2 is running normally.

9. Follow up development
During 010B converter protection device 2 is put into normal operation, the start-up phenomenon will still occur when the double SC capacitor bank is put into operation. At this time, DC power increases from 2100 MW to 3000 MW.

The starting waveform of converter protection device 2 is shown in Fig.5.
Fig. 5 Start-up waveform of converter protection device 2

The analog curve information is shown in Table 3.

| No | Name  | Fundamental amplitude (A) | Fundamental phase |
|----|-------|---------------------------|-------------------|
| 1  | IVDa  | 0.637                     | -43.516           |
| 2  | Ia1   | 0.156                     | 126.965           |
| 3  | Ia2   | 0.169                     | 170.872           |
| 4  | IVYa  | 0.548                     | -43.153           |
| 5  | Ida1  | 0.075                     | -112.085          |

A phase differential current of converter lead and converter differential protection at the time indicated by the red line is 0.075A. According to the fixed value list, the rated current secondary value of converter is 0.329A. The starting current is fixed at 0.18 times the rated current. Namely, 0.18*0.329=0.059A. Because 0.075A is greater than 0.059A, start component acts. After the starting element operates, the protective outlet power supply is opened.

Since the converter protection device 2 of 010A has never been started, it is necessary to compare the acquisition circuits of 010A converter protection device 2 and 010B converter protection device 2. The acquisition loops that need to be compared include AC input plug-ins of external TA, cables, protection devices and acquisition and maintenance plug-ins.

10. Second Improvement Program
The pretreatment scheme is as follows:

(1) The accuracy of 010A converter protection device 2 and 010B converter protection device 2 is compared.

(2) Field staff is cooperated with to measure the accuracy error of external circuit.

(3) Adjust the recording position of the external circuit and connect it to 010B converter protection cabinet.

(4) If the accuracy error of the outer circuit meets the requirement, replace the acquisition circuit of the device, including the AC input plug-in and the sampling and holding plug-in.
10.1 Accuracy comparison between 010A converter protection device 2 and 010B converter protection device 2
The 010A converter protection device 2 and 010B converter protection device 2 are connected in series to observe the accuracy of the two devices. During debugging, it was found that: The accuracy adjustment coefficient of 010A converter protection device 2 does not need to be adjusted, and the accuracy meets the error requirement. The accuracy adjustment coefficient of 010B converter protection device 2 needs to be adjusted individually. After adjustment, the accuracy of 010B converter protection device 2 meets the error requirements. The channels for adjustment are shown in Table 4.

| No | Channel name | 010B | 010B | 010A | 010A |
|----|--------------|------|------|------|------|
| 1  | IVDc1        | 0.966| 1.05 | 0.959| 0.959|
| 2  | Ia2         | 0.996| 1.028| 0.958| 0.958|
| 3  | IACDc2      | 1.024| 1.025| 0.957| 0.957|
| 4  | Ic2         | 0.984| 1.018| 0.959| 0.960|
| 5  | IVYb1       | 1.030| 1.021| 0.959| 0.958|

Notes:
IVDc1 : Phase C of Y/ΔTransformer winding head TA on valve Side
Ia2 : Phase A of Medium Switch TA on Grid Side
IACDc2: Phase C of Transformer winding end TA on Grid Side
IVYb1 : Phase B of Y/Y Transformer winding head TA on valve Side
Table 4 shows that the acquisition circuit of 010A converter protection device 2 is normal, and that of 010B converter protection device 2 is abnormal.

10.2 Measurement of Outer Loop Accuracy
The accuracy of the side and middle switches of the grid side has been tested by the staff of the high-voltage shift on the spot. the measurement accuracy of the side and middle switches of the grid side meets the error requirements.

10.3 Adjusting Recording Position of Outer Circuit
Adjust the recording position of the external circuit and connect it to 010B converter protection cabinet.

10.4 Hardware replacement
Because the accuracy error of external circuit meets the requirement, and the acquisition circuit of 010B converter protection device 2 is abnormal, the acquisition circuit of 010B converter protection device 2 is replaced, including AC input plug-in and sampling and holding plug-in. After replacement, zero drift adjustment, accuracy verification and external circuit test are carried out to ensure the stable operation of 010B converter protection device 2.

11. Optimization plan
In response to this incident, we proposed two optimization schemes.
(1) Enhance the anti-interference measures of AC input plug-in of 010B converter protection device. The main error in the acquisition part of the device is mutual inductance between current converters on AC input plug-ins. A metal shield layer is added to each current converter on the AC input plug-in. The shielding layer can effectively reduce the mutual inductance current between current transformers.
Dual redundancy is used for calculating differential protection channels on single CPU plug-ins. The alarm threshold of channel acquisition (less than 0.95 In, greater than 1.05 In) is only set for single channel, and the error superposition of several channels for differential protection is not considered. Therefore, the error threshold for channel redundancy is less than 2.5% In.

12. Conclusion
The phenomenon of frequent start-up of incremental differential protection has been corrected twice on site, and now it is in normal operation. Double SC capacitor banks have been put into operation for many times. No start-up of 010B converter protection device 2 has occurred.

About the author:
zhanghongyue(1971—), female, Henan, Xuchang, China, professor of Engineering, The main research direction is the research and Simulation of UHV DC transmission and power system relay protection (E-mail: 13839029912@163.com); telephone: 13839029912

Reference
[1] DAI Xi-jie. DC transmission Foundation[M]. Beijing: Hydraulic power press, 1990. ZHAO Wan-jun. HVDC transmission engineering technology [M]. Beijing: China Electric Power Press, 2004.
[2] YAN Nai-chen, Zhao Qiang. Inconsistent analysis of Converter Transformer Tap in HVDC transmission project[J]. power electronics
[3] TAN Tao-Liang, Zhang Yao etc. Limit induced bifurcation due to converter transformer and the DC limit[J]. Journal of Physics, 2012, 02(61)
[4] ZHANG Zhi-chao, LIU Tao etc. Research on switching control of converter transformer tap changer in Yun-Guang UHVDC project[J]. Power system protection and control, 2010, 20(38).
[5] WU Hong-bo, SONG Shu-bo etc. Introduction of Converter Transformer Tap Changer Control in Zhaoqing Converter Station[J]. High voltage technology, 2006, 9(32)
[6] HONG Le-zhou, MAO Hai-peng etc. Function comparison and operation suggestions of Converter Transformer Tap Changer Control in yunguang DC and tianguang DC[J]. Electrical technology