Design of transformer protection scheme for DC system

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Abstract: Back-to-back flexible DC system can be used for interconnection of asynchronous power grids. In view of the different characteristics and operation modes of connected transformer equipment in back-to-back flexible DC system, this paper puts forward some special problems that need to be considered in the design of connected transformer protection, and puts forward a complete configuration scheme of connected transformer protection in view of its particularity. Finally, we establishes a real-time digital simulation model to verify the validity of the model using actual engineering parameters. The simulation results show that the theoretical analysis is correct and the proposed protection scheme can effectively guide the engineering application.

1. Introduction

A back-to-back flexible DC transmission project is the one with the highest voltage level and the largest transmission capacity in the world. For the first time in the world, the flexible DC transmission voltage is raised to ±420kv, and the power transmission capacity reaches 5 million kilowatts[1].

Reference[2-6] points out the advantages of flexible DC transmission, such as: weak source or passive system can be connected, reactive power can be generated, no communication between stations is required, short-circuit capacity of the system is not increased, harmonic distortion is reduced, switching times of devices are reduced, etc.

Coupling transformer is the key equipment between flexible DC converter and AC system. The reference[7-10] only points out some problems and solutions existing in the principle of converter transformer protection. Starting from the structure and characteristics of the coupling transformer, this paper puts forward some special problems that need to be considered in the design of the coupling transformer protection, gives a complete configuration scheme of the coupling transformer protection, and models on the real-time digital simulation system according to the actual parameters in the field to verify the correctness of the protection scheme.

2. Main wiring form of the system

The system mentioned in this paper adopts pseudo bipolar wiring, as shown in Figure 1. It can be seen from Figure 1 that the back-to-back flexible DC transmission system has no DC transmission line, no long-distance communication problem and low failure rate of DC system. The pseudo bipolar connection mode is adopted, and there is no ground point. When a single pole ground fault occurs, there will be no DC bias phenomenon.

In addition, the angle side winding is added as the balance winding to provide the channel for the third harmonic current and eliminate the third harmonic flux, so as to eliminate the third harmonic
component in the voltage and ensure that the phase electromotive force is close to the sinusoidal waveform, so as to avoid the influence of the waveform distortion of the phase electromotive force. One of the connection angle side is directly connected to the station transformer.

3. Characteristics of coupling transformer

coupling transformer is the link of energy exchange between converter station and AC system in flexible DC system. The difference between connection transformer and exchange transformer is as follows[11]:

(1) The harmonic content of the flexible HVDC system based on MMC is very low, but the harmonic content of the two-level or three-level DC transmission and distribution system is relatively large, so AC filter is usually required.

(2) Because VSC can work in four states of absorbing or emitting active and reactive power, the selection of the maximum operating voltage of the connection transformer needs to consider four operating states, the shift deviation of the tap changer and the design deviation of the system reactance.

(3) In the pseudo bipolar connection mode, the valve side of the coupling transformer not only bears the high frequency transient voltage during the commutation and disconnection of the converter valve, but also bears the DC voltage for a long time.

(4) In the back-to-back flexible DC transmission system, when there is a fault in the coupling transformer area, it is necessary to open the circuit breakers on both sides of the flexible DC system to completely isolate the fault point under the HVDC operation mode.

4. Protection zone

The coupling transformer protection, DC protection and valve body protection are used together to complete the protection of the whole flexible DC system. The protection of the whole flexible DC system can be divided into five areas: AC protection area, coupling transformer protection area, AC connection protection area, converter protection area and DC pole protection area. The schematic diagram of each protection zone is shown in Figure 2.
5. Special problems to be considered in connection transformer protection

5.1 Particularity of protection configuration

The configuration of converter protection for conventional DC transmission system is shown in Table 1.

| No | Pro.function | No | Pro.function |
|----|--------------|----|--------------|
| 1  | 87TC         | 2  | 87C          |
| 3  | 87T          | 4  | 87CN         |
| 5  | Net 87TW     | 6  | Valve 87TW   |
| 7  | 51           | 8  | 59T          |
| 9  | 24T          | 10 | 50CN         |
| 11 | Net 50T      | 12 | 21           |
| 13 | 50TN         | 14 |              |

Because the back-to-back flexible DC system has no single pole ground operation mode, and the coupling transformer angle side is connected with lead wire or station transformer, it is necessary to re-demonstrate the protection configuration of the coupling transformer according to the system characteristics and the coupling transformer characteristics.

According to the main wiring characteristics shown in Figure 1, no DC current flows into the grounding point in normal operation no matter which operation mode is adopted. Therefore, it is unnecessary to consider the problem of DC bias and configure DC saturation protection.

Different from the general 330kV transformer, the star side of the coupling transformer valve is directly connected with the valve body rather than the bus. If impedance protection is configured, its protection range will overlap with that of the AC connection protection zone, converter protection zone and DC pole protection zone, and the setting value is not easy to set. Therefore, it is recommended to cancel the impedance protection.

If the angle side TA of large differential protection adopts the conventional angle side bushing TA, the connecting angle changing side lead is not protected. There is a scheme, which is equipped with two sections of angle side overcurrent protection, one quick acting section, as the main protection of angle side lead, and one delay section, which is used together with station transformer protection. However, the overcurrent protection of quick acting section has no directionality and is not recommended. Therefore, the actual scheme adopted is to modify the wide differential protection range, the angle TA is modified to the angle switch TA, and the protection range is increased from the original only including the coupling transformer and the grid side lead to also including the angle side lead. In this way, the main protection of the lead wire at the angle changing side is differential protection, and the backup protection is overcurrent protection at the angle side. In addition, due to the single-phase ground fault at the angle changing side of the connection, the fault current is very small and the current protection does not act, but the single-phase ground fault will cause the voltage to rise, so it is necessary to configure the zero sequence voltage alarm function at the angle side to remind the operators to deal with it.

5.2 Particularity of inrush current of coupling transformer

The coupling transformer is still a transformer in essence, so the differential protection based on flux balance is still selected as its main protection. For the differential protection based on flux balance, the magnetic saturation characteristic and inrush current of transformer must be considered. As the same as the conventional transformer, the winding voltage is generally reduced in case of various faults inside and outside the zone, and there is no serious magnetic saturation. Compared with the short-circuit current, the excitation current in case of short-circuit can generally be ignored. Therefore, the conventional inrush current criterion can be used. On the other hand, because the charging resistance at the valve side is not put into use and the characteristics of the inrush current at the air charging are not the converter transformer, the conventional transformer is obvious.
5.3 Particularity of fault removal method
If the back-to-back conventional DC system fault occurs in the valve area, because it is a public area, the protection on both sides will react, and the AC circuit breaker of two stations will be opened. If it occurs in the converter area, only the AC breaker on the fault side needs to be opened. In general practical engineering, in order to ensure reliability, the back-to-back conventional DC system is generally equipped with AC side circuit breakers that trip two stations.

The converter valve in the back-to-back flexible DC system can be charged after the AC circuit breaker on either side is closed. Therefore, even if there is a fault in the coupling transformer area, theoretically, it is necessary to open the two station AC circuit breaker to reliably isolate the fault point. However, when the flexible DC system operates in STATCOM mode, when the fault occurs in the coupling transformer area on the opposite side, it is not expected that the AC circuit breaker of STATCOM station will also jump off.

Therefore, it is necessary to distinguish the operation mode of the flexible DC system to determine whether the opposite switch needs to be tripped when the breaker of the opposite station is tripped. However, the coupling transformer protection cannot realize this function. Therefore, for the back-to-back flexible DC system, the coupling transformer protection only trips the circuit breaker of the station. After the operation mode of the circuit breaker of the station is determined by the pole control, then choose whether to follow the trip or not.

6. Protection scheme of coupling transformer
The operation mode of the coupling transformer is different from that of the converter, so the acquisition position of the analog quantity is also different.

6.1 Protection configuration scheme
In this paper, TV1, TV2 and TV3 are network side voltage transformer, angle side voltage transformer and valve Star side voltage transformer respectively; TA1 and TA2 are network side TA, TA3.1 and TA3.2 are network side head end bushing TA, TA3’ is network side tail end bushing TA, TA6 is network side neutral point TA, TA4 and TA4’ are network side neutral point TA, respectively. The head end and tail end casings TA, TA5 and TA5’ on the star side are respectively the head end and tail end casings TA on the angle side, TA6 is the neutral point TA on the grid side, and TA7 is the head end switch TA on the angle side.

The coupling transformer adopts yn-yn-d-11 wiring mode. The coupling transformer protection mainly includes large differential protection, variable differential protection, small differential protection, lead differential protection, grid side winding differential protection, valve Star side winding differential protection, angle side winding differential protection, zero sequence differential protection, lead overcurrent protection, zero sequence current protection, overexcitation protection, overvoltage protection, overload, angle side overcurrent protection Protection, angle side zero voltage protection, etc. The protection configuration is shown in Figure 3.

The protection range of lead differential protection and small differential protection is similar to that of conventional commutation, respectively protecting the lead wire and the coupling transformer at the coupling transformer network side, reflecting various faults on the coupling transformer body and the lead wire at the network side.

The protection range of large differential protection and variable differential protection is slightly different from that of conventional commutation. In addition to the protection of coupling transformer network side lead and coupling transformer, it is also necessary to protect connecting transformer angle side lead, reflecting various faults on coupling transformer body, network side lead and angle side lead.

The over-voltage protection reflects the over-voltage capacity of the coupling transformer. Lead over-current protection mainly reflects the overload capacity of the coupling transformer. The angle side zero sequence voltage alarm is used to reflect the angle side single-phase ground fault, and the
angle side over-current protection is used as the backup protection of the triangle winding outgoing line to reflect other faults except the single-phase ground fault.

Fig. 3 measuring point configuration diagram of connecting transformer

6.2 Trip mode and cooperation
For the back-to-back flexible DC system mentioned in this paper, when the fault occurs in the area, the fault isolation can be realized only when the four circuit breakers on this side and the four circuit breakers on the opposite side of the coupling transformer electrical quantity protection are opened. When the electric quantity protection of the coupling transformer trips, it also needs to start the failure and blocking valve (ESOF); the other functions of the outlet of the non electric quantity protection of the coupling transformer are the same as those of the electric quantity protection except that the failure is not started.

Because the coupling transformer protection cannot realize the discrimination of the operation mode of the flexible DC system, therefore, the coupling transformer protection is only responsible for tripping four circuit breakers on its own side, and the four circuit breakers on the opposite side are tripped by the pole control. The coupling transformer protection device and the pole control are connected by optical fiber. After different protection elements act, the outlet mode can be adjusted by various trip matrix to adapt to different trip requirements.

7. Simulation test verification
In this paper, the real parameters are used to verify by RTDS simulation.

7.1 Model main wiring and parameters
The fault point setting of the coupling transformer is shown in Figure 4.

Fig. 4 Electrical wiring diagram of connection transformer

Representative meaning of fault point: outside the grid side area of K1 connecting transformer, K2 is in the lead area, K3 is in the grid side casing area, K4 is in the valve Star side casing area, K5 is in the angle side casing area, K6 is outside the valve Star side casing area, K7 is in the angle side switch area, and K8 is in the high voltage side area of station transformer. The protection settings are shown: 87TC is 6Ie, 87T is 0.4Ie, 87TW is 0.3Ie, 87C is 0.6A.
here are two kinds of simulation tests: ① single unit protection test; ② double unit protection test. There are three simulation conditions: ① DC start; ② HVDC mode; ③ STATCOM mode. Power flow control: ① power forward; ② power reverse. Fault types include: single-phase ground fault, two-phase short-circuit fault, two-phase short-circuit ground fault and three-phase short-circuit fault.

During the simulation test, more than 400 different faults are simulated under different combination conditions. When the protection device has no fault or out of zone fault, it is reliable and can not act. When there is fault in the zone, it can act quickly, which proves the rationality and reliability of the scheme.

8. Conclusion
Starting from the structure and characteristics of the coupling transformer, this paper focuses on the analysis of the particularity of the coupling transformer protection design, and gives a complete configuration scheme and setting principle of the coupling transformer protection. The correctness of protection configuration and criterion is verified by RTDS simulation. The following conclusions are obtained through simulation analysis:

(1) There is no DC transmission line in back-to-back flexible DC transmission system, and the failure rate of DC system is low. When a single pole ground fault occurs, the DC bias phenomenon will not occur. The angle side winding is added to the coupling transformer. In this paper, a special coupling transformer protection configuration scheme is proposed and verified by simulation.

(2) In the back-to-back flexible DC system, the protection action of the connection transformer only trips the circuit breaker of the station. After judging the operation mode of the circuit breaker of the station by the pole control, choose whether to follow the trip or not.

At present, the protection device using this scheme has been put into operation successfully and is in good condition. This paper also provides a reference for the protection design of other connected transformers in the power system.

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