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Analysis of Stage Difference Coordination of Protective Devices in Direct Current System

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Abstract. Stage difference coordination is an important part of DC system. Taking the GM series two-stage DC circuit breaker and the GMB series three-stage DC circuit breaker as examples, the protection characteristics of the DC circuit breaker are described. The 220kV substation is taken as an example to analyze the DC connection mode and protection analysis of the control loop and closing circuit. The analysis proves that the level difference plays an important role in the stability of the DC system. This paper provides a reliable basis for perfecting the stage difference coordination of the power system in DC systems.

1. Introduction

The DC operation power system is one of the indispensable secondary devices in power plants and substations, and its reliability directly affects the safe and reliable operation of power plants and substation equipment. The degree of automation of the power system is getting higher and higher with the automation of power dispatch and the development of relay protection equipment [1, 2]. Power plants and substations are gradually becoming unattended. In this case, the operation of all the switching devices and the operation of the relay protection device are controlled automatically or remotely through remote operations. If the DC system fails, it may cause a major accident, so the DC system becomes more and more important in each device.

The reason why stage difference coordination is important in DC systems is that if there is a short circuit or overload in the system, it may cause the circuit breaker to malfunction or refuse to act, if the differential mitigation does not achieve good selectivity [3, 4]. It has a serious impact on the entire DC system and may even make the entire related equipment related to the DC system unable to operate normally. Therefore, the correctness of stage difference coordination is directly related to whether the system's failure can be limited to the minimum range, which is essential to prevent system damage, accident expansion and serious damage to the main equipment [5, 6]. Therefore, strengthening the correctness of the selection and configuration of fuses and circuit breakers is of great significance for improving the safety and reliability of power system operation.

2. Analysis of Overload and Short Circuit Protection of GM Series DC Circuit Breaker

DC circuit breaker of GM series is currently the most widely used DC system protection appliance. The GM series molded case circuit breaker adopts the arc extinguishing technology CCV, quadruple acceleration and narrow slit breaking and dissociating arc extinguishing technology to realize zero arcing. It has higher breaking capacity (DC250V) 20kA, (DC440) 15kA, and Ics = 100% ICU. The
GM100 series has the load indicator, which eliminates the need for additional indicator lights on the panel to save space and simplify wiring in the screen.

The two-stage protection characteristics of the GM series DC circuit breakers are shown in Table 1.

Table 1. Two-stage protection features of GM series.

| model   | Overload | Short-circuit transient protection |
|---------|----------|------------------------------------|
|         | Inactivity time | Action time | Current setting multiple ±20% | Breaking time |
| GM100   | 1.05In time >2h  | 1.3In time <=2h | 10 In | 10 ms |
| GM225   |               |              | 15 ms |
| GM400   |               |              | 15 ms |
| GM800   |               |              | 20 ms |
| GM1250  |               |              |      |

The thermal overload (long delay) release consists of a heating element and a bimetal strip. When an overcurrent occurs, the heat generating element generates heat, causing the bimetallic strips of the same length and different materials to bend, triggering the actuator to separate the static and dynamic contacts of the circuit breaker. Overcurrent causes the heat generating element to generate heat Q=I²Rt. Therefore, the time required to transmit overload information to the actuator is inversely proportional to the square of the current. The overload tripping of the circuit breaker thus has inverse time characteristics.

The short-circuit (instantaneous) release consists of a core and electromagnetic coils. When the fault current is large enough (such as I_d>4KA), the electromagnetic coil core pulls in, and the actuator separates the dynamic and static contacts of the circuit breaker. The time required to transmit the information to the actuator is the solenoid coil pull-in time (usually several ms), so the momentary tripping of the circuit breaker is instantaneous.

The upper and lower levels of two-stage protection circuit breakers are matched by adjusting the current trip value of the instantaneous trip unit. The short-circuit current is not much different, when the upper and lower circuit breakers are installed close together. When the difference between the upper and lower levels is small, the two-stage protection circuit breaker is not easy to achieve selectivity.

3. Analysis of Short-time Delay Protection of GMB Series DC Circuit Breaker

GMB series DC circuit breakers are three-stage protection DC circuit breakers, rated operating voltage below DC660V, rated operating current below 1250A. Using the arc-extinguishing technology CCV, quadruple acceleration and narrow slit breaking and dissociating arc extinguishing technology, the breaking capacity is higher (DC250V) 20kA, (DC440) 15kA, and Ics=100%Icu. The upper and lower breakers only need to be selected according to the rated current level, so that fully selective three-stage protection can be realized. It is ensured that the fault current is cut off only by the circuit breaker closest to the fault point, in order to prevent the spread of the accident surface caused by step-over protection. Sometimes when the upper circuit breaker encounters a short-circuit current, after a short time delay (usually ms-level), the operation takes place. During a short delay, if the lower circuit breaker cuts the faulty circuit, the circuit breaker does not move. The upper circuit breaker operates to cut off the fault, if the lower circuit breaker fails and the protective action cannot be performed.

The two-stage protection characteristics of GMB series DC circuit breakers are shown in Table 2.
Table 2. Three-stage protection characteristics of GMB series.

| model   | Overload | Short circuit short delay protection | Short-circuit transient protection |
|---------|----------|--------------------------------------|-----------------------------------|
|         | Inactivity time | Action time | Current value | Time setting value /ms | Arcing time /ms | Breaking time /ms | Release action current | Breaking time /ms |
| GMB100  | 1.05In   | Inactivity time >2h | 10In | 10, 30, 60 | 5 | t+5 | 6kA | 10 |
| GMB225  | 1.3In    | Inactivity time <=2h | 10In | 10, 30, 60 | 5 | t+5 | 8kA | 15 |
| GMB400  |          |           | 10In | 30, 60 | 5 | t+5 | 15kA | 20 |
| GMB800  |          |           | 5In  | 30, 60 | 6 | t+6 | 20kA | 20 |
| GMB1250 |          |           | 5In  | 30, 60 | 6 | t+6 | 20kA | 20 |

GMB series circuit breakers also have a short-circuit short-time release, in addition to the thermal overload release and short-circuit release.

Short-circuit short-delay release action principle: The delay electronics are turned on when the fault current exceeds a certain threshold (eg, 10 In). The delay circuit turns on a shunt trip device with its own power supply inside the breaker, if the fault current still exists after a fixed delay time. The "fault occurred" message is transmitted to the actuator in the form of "separation of the split coil core." The actuator separates the contacts of the circuit breaker. The delay circuit is disconnected and reset, if the fault current has been eliminated.

The time required to deliver information to the actuator is a fixed electronic delay time. The time delay of the circuit breaker is a definite time characteristic. In the event of a fault current of very large size, the short-circuit short-delay release and the overload release are excited. The circuit breaker exhibits instantaneous tripping characteristics, when the fault current is large.

The upper and lower matching of the three-stage protection circuit breaker is achieved by selecting short circuit short time delay. Theoretically reliable selectivity can be achieved.

4. Middle-level Differential Analysis of Engineering Design

Taking a 220kV substation as an example. There are 2 main transformers, 5 outlets of 220kV, 10 outletsof 110 kV, 6 groups of 10kV capacitors, 220kV and 110kV double wiring, and 10kV single or double sectional wiring. The DC power supply is 200Ah lead-acid valve-regulated sealed battery, 2V single unit, 103 units, and cabinet type assembly. The charger is a high frequency switch module. The battery-to-line switch distance is 3 meters, the total switch-to-feed line switch distance is 2 meters, and the feeder switch-to-load switch counts according to the actual position.

(1) Control Loop

Load circuit breakers are selected based on the load current. According to the actual power consumption of the microcomputer protection and monitoring device, and taking into account the appropriate margin, the rated current of the load circuit breaker is 3A.

Feeder circuit breakers are selected based on load current and selectivity differential requirements. The maximum load circuit is considered as 220kV/110kV/main transformer unit, and the optional differential level is set as 3 to 4 levels. The rated current of the feeder circuit breaker is 16A or more, select 20A.

The battery outlet circuit breaker is selectively selected based on the battery discharge rate and protection actions. According to in ≥ I1h = 5.5 × 20 = 110A, considering the selective differential cooperation, 160A ~ 200A should be taken and 160A selected.

Determine the short-circuit point and calculate the short-circuit current: main bus (point M), feeder breaker (point T), feeder end (point F), load breaker (point R).

M: IscM=1986A=12.4Imn, Imn=160A;
T: IscT=1815A=91Ifn =11.34Imn;
F: IscF=1048A=52.4Ifn=6.55Imn, Ifn=20A;
R: \( \text{IscR} = 397 \text{A, Irn} = 3 \text{A} \).

\( \text{IscM} \) — Short circuit current at point M installation; \( \text{Irm} \) — M point breaker; Short circuit current at \( \text{IscT} \) — T point installation point; Short circuit current at \( \text{IscF} \) — F point installation point; Short circuit current; \( \text{Irn} \) — R point circuit breaker rated current.

The breaker tripper range is determined based on each short circuit current. M point: According to the circuit breaker rated current multiple: \( \text{Idz} \geq 10 \times 160 = 1600 \text{A} \), press circuit breaker short circuit. Instantaneous protection current with the setting: \( \text{Idz} \geq 4 \times 20 \times 10 = 800 \text{A} \), take 1600A.

\[ \text{Figure 1. DC circuit short circuit diagram of the control loop.} \]

Short-circuit verification of the circuit, from the power line breaker to the load circuit breaker, can reliably act when a short-circuit fault occurs within the corresponding protection range. However, when a short-circuit fault occurs on the near-end load side of the incoming line breaker and the feeder circuit breaker, it will be non-selectively mis-operated, and the requirement of selective cooperation cannot be achieved.

Selecting the circuit breaker with short delay provides effective support for the implementation of the DC loop selectivity scheme. With a circuit breaker with a short delay, it is possible to eliminate the possibility of non-selective misoperation and perform only a short-circuit behavior test. The feeder circuit breaker (20A) selects a short delay of 10ms, the incoming line breaker (160A) selects a short delay of 30ms, and the short-circuit setting of the circuit breakers at all levels remains unchanged, as shown in Figure 2.

\[ \text{Figure 2. DC link diagram of the control loop after retrofit.} \]

(2) Closing Circuit

According to the load current, 220kV breaker is selected as the hydraulic or spring mechanism. The closing motor current is generally 7A, so the breaker is selected to be 10A. Feeder circuit breakers are selected based on load current and selectivity differential requirements. The maximum load circuit is considered in the 220kV switch energy storage circuit, and the optional differential level is set in the 3 to 4 settings. Feeder circuit breaker rated current is taken as 32A.

The battery is selectively selected based on the battery discharge rate and protection action. The outlet circuit breaker shall be \( \text{In} \geq 11h = 5.5 \times 20 = 110 \text{A} \). Considering selective differential cooperation, 160A ~ 200A should be taken and 160A selected.

Determine the short-circuit current: main bus (M point), feeder circuit breaker (T point), first branch feeder end (F1 point), load breaker (R1 point), nth branch feeder end (Fn point), load Circuit Breaker (Rn point).

M: \( \text{IM} = 1986 \text{A, Imn} = 160 \text{A} \);

T: \( \text{IT} = 1899 \text{A, Ih} = 11.87 \text{Imn} \);
F1: IF1=535A=16.7Ifn=3.34Imn, Ifn=32A;
R1: IR1=448A=44.8Irn =14 Ifn, Irn=10A;
Fn: IF=293A=9.16Ifn=1.83 Imn, Ifn=32A;
Rn: IR=265A=26.5Irn=8.28 Ifn, Irn=10A.

IM-M point installation short-circuit current; Imn-M point breaker rated current; IT-T point installation short-circuit current; IF1-F1 point installation short-circuit current; Ifn-F point breaker rated current; IR1— Short-circuit current at R1 point of installation; Irn-R point circuit breaker rated current; IFn-Fn point short-circuit current at the installation point; IRn-Rn point installation short-circuit current.

According to each short-circuit current to determine the setting range of the circuit breaker trip, verify the sensitivity and correctness of the action. M point: According to the circuit breaker rated current multiple setting: \( \text{Idz} \geq 10 \times 160 = 1600 \text{A} \). Press the circuit breaker short-circuit transient protection current with the setting: \( \text{Idz} \geq 4 \times 20 \times 10 = 800 \text{A} \), take 1600A.

![Figure 3. DC circuit short circuit of the closing circuit.](image)

In order to avoid the non-selective malfunction of feeder circuit breakers or feeder circuit breakers caused by short-circuit faults in load feeders, short-circuit short-delay release units are required for the incoming line breakers and feeder circuit breakers, and their short delays are 30 ms to 10 ms. The circuit breaker configuration after the change is shown in Figure 4.

![Figure 4. DC connection diagram of the closing circuit after retrofit.](image)

5. Conclusion
The degree of automation of the power system is getting higher and higher with the automation of power dispatch and the development of relay protection equipment. Power plants and substations are gradually becoming unattended. In this case, the operation of all switching devices and relay protection devices are controlled automatically or remotely through remote control. If the DC system fails, it may cause a major accident, so the DC system becomes more and more important in each device. Customers place higher demands on the reliability, high intelligence, and maintenance-free performance of power supplies. This has also become an inevitable trend in the development of power products.
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