Research on Magnetic Field Characteristics in DC Yard of Dinghai Converter Station Under Monopolar Grounding Fault

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Abstract. In Dinghai converter station of Zhoushan VSC-HVDC transmission project, 200 kV hybrid DC circuit breaker is used for the first time to realize DC side fault isolation. When DC side short circuit occurs, its fault current characteristics are different from those of AC substation and HVDC converter station, and the magnetic field interference to secondary equipment in DC yard is still unknown. In this paper, taking the single pole grounding short circuit fault with high probability in flexible DC power grid as an example, the electromagnetic transient simulation model of fault current in Dinghai converter station is established, and the time-domain current waveform is obtained. Then, the magnetic field calculation model of DC circuit breaker and other key electrical equipment is established, and the magnetic field of secondary equipment in DC yard is calculated based on Biot-Savart Law. The results show that the maximum magnetic field strength at the secondary equipment is 59 A/m, the waveform is ms level, and it is aperiodic. The distribution of magnetic field in DC yard varies between 3 and 346 A/m.

1. Introduction
When DC side short circuit occurs in flexible DC power grid, the short-circuit current rises rapidly [1,2]. With the development of high-power power electronic devices, it is possible to use hybrid DC circuit breaker to realize fast fault isolation at DC side in voltage source converter based high voltage direct current (VSC-HVDC) transmission project [3,4].

Global Energy Interconnection Research Institute and other units completed the development of 200 kV hybrid DC circuit breaker prototype in 2014, which can break 15 kA short-circuit current in 3 ms, and was put into operation in Zhoushan five-terminal VSC-HVDC transmission project in late 2016 [2], which is the first project application of high-voltage hybrid DC circuit breaker. In 2017, several companies completed the development of 535 kV hybrid DC circuit breaker, which can break the short-circuit current with peak value of 25 kA within 3 ms [1], and has been put into operation in Zhangbei 500 kV four-terminal VSC-HVDC transmission project.

With the continuous improvement of the voltage level, when the hybrid DC circuit breaker breaks the higher fault current, the electromagnetic interference to the surrounding secondary equipment will reach what value, and whether it will cause misoperation, all need field measurement. The existing literature mostly discusses the topological structure of hybrid DC circuit breaker [5-6]. The research on the space field around the hybrid DC circuit breaker mainly focuses on the electric field. In [7], the spatial electric field of 535 kV hybrid DC circuit breaker was solved by finite element method, and the electric field distribution was studied. In [8], a three-dimensional model of 535 kV hybrid DC circuit breaker was established to study the electric field distribution of each component under the breaking
condition. The calculation of the magnetic field of flexible DC converter station mainly focuses on the electromagnetic disturbance caused by the normal operation of converter valve. In [9-10], the radiation model of converter valve is established and the radiated electromagnetic disturbance produced by converter valve in normal operation is studied. There is no literature analysis on the magnetic field generated around hybrid DC circuit breaker when breaking, and the magnetic field is difficult to shield. The extensive assessment standard adopted in the project, that is, using the highest standard to assess the immunity of secondary equipment, often has excessive margin and high cost.

Current is the source of magnetic field, but it is difficult to obtain the measured current, so the simulation model is usually built in electromagnetic transient software. At present, PSCAD/EMTDC and other electromagnetic transient software can meet the modelling requirements of modular multilevel converter (MMC), hybrid DC circuit breaker, cable and other electrical equipment, and the model is relatively perfect [11-14]. There are many kinds of electrical equipment in DC yard (discharge of DC equipment) and the structure of electrical equipment is complex. It is difficult to directly establish the whole three dimensional model for electromagnetic field analysis, so it is necessary to simplify the electrical equipment. A lot of research has been done on the magnetic field calculation model of electrical equipment such as bus bar and smoothing reactor [15-16], and the calculation method is relatively mature.

At present, two 200 kV hybrid DC circuit breakers are installed in Dinghai converter station of Zhoushan VSC-HVDC transmission project to realize fast switching on and off of single station. In [17], the artificial short circuit test scheme of hybrid DC circuit breaker for Zhoushan VSC-HVDC transmission project is proposed. In this paper, based on the action logic of the artificial short-circuit test, the electromagnetic transient simulation model of single station fault current in Dinghai converter station is built, and the time-domain current waveform is obtained. Based on Biot-Savart Law, the magnetic field generated by current source is calculated in time domain. On this basis, the magnetic field characteristics of secondary equipment around hybrid DC circuit breaker are studied.

2. Simulation of fault current under short circuit condition

2.1. Topological structure and parameters
In [17], the artificial short circuit test was carried out at Dinghai converter station of Zhoushan flexible DC transmission project. The main wiring diagram of Dinghai converter station is shown in Figure 1. The converter station adopts MMC based on half bridge structure. Two 200 kV hybrid DC circuit breakers are installed on the positive and negative DC lines to achieve DC side fault isolation. The DC circuit breaker can break the fault current with peak value no more than 15 kA within 3ms, realizing fast fault isolation and flexible switching of single station [17].

![Figure 1. Main wiring diagram of Dinghai converter station](image)

![Figure 2. Simulation results of main circuit current in single pole short circuit test](image)

According to the main parameters of Dinghai converter station shown in Table 1, topology structure shown in Figure 1 and actual control strategy, the fault current electromagnetic transient simulation model of Dinghai converter station is built based on PSCAD platform, and the converter of
Dinghai converter station works in constant DC voltage control mode. The transformer adopts Y/Δ connection, MMC adopts Thevenin equivalent model with high simulation accuracy, with a total of 6 bridge arms [11]. Each bridge arm is composed of a number of sub modules, 1 inductor and 1 resistor [12]. The sub modules of hybrid DC circuit breaker adopts IGBT full bridge structure [13]. The voltage and current data of arrester model are read by I-V curve. The phase domain model of frequency dependent model is used for the cable [14]. According to the cable parameters shown in Table 2, the cable model is created in the simulation software.

| Table 1. Main parameters of Dinghai converter station |
|------------------------------------------------------|
| Transformer | Converter Valve | Inductance value of smoothing reactor(mH) |
| Rated Rapacity (MVA) | Short Circuit Impedance (pu) | Rated voltage of grid side (kV) |Rated voltage of valve side (kV)| Bridge arm reactance (mH)| Sub module capacitance value (mF)| |
| 450 | 0.15 | 230 | 205.13 | 90 | 8 | 20 |

| Table 2. Cable parameters |
|---------------------------|
| Cable structure | Resistivity (Ω·m) | Relative permittivity | Relative permeability |
|------------------|-----------------|------------------|------------------|
| Conductor | 1.7*10⁻⁸ | - | 1 |
| Insulator 1 | - | 2.3 | 1 |
| Insulator 2 | 2.2*10⁻⁷ | - | 1 |
| Armor | - | 2.3 | 1 |
| Insulator 3 | 1.8*10⁻⁷ | - | 400 |

2.2. Fault current simulation results

Figure 2 shows the simulation results of main circuit current when single pole grounding short circuit occurs. The action sequence set in the artificial short circuit test is marked in [14]. In case of single pole grounding short circuit fault, DC circuit breaker can isolate fault in time and converter valve is not locked.

3. Modelling of magnetic field

When the DC side short circuit occurs, the current flowing through the line changes rapidly. On the one hand, the current with high amplitude and fast changing speed will produce high overvoltage on the line through conduction coupling, on the other hand, it will generate electromagnetic disturbance in space through current carrying conductors such as bus, DC circuit breaker and cable. The magnetic field source in the DC yard is mainly the current carrying conductor and electrical equipment, including hybrid DC circuit breaker and smoothing reactor.

In order to study the magnetic field distribution in the DC yard of flexible DC converter station, it is necessary to calculate the magnetic field generated by each magnetic field source quantitatively. Dinghai converter station is 42 metres long, 21 metres wide and 12 metres high, the breaking process of hybrid DC circuit breaker is completed in about 3 ms [5], and the fastest internal commutation process is 10 μs, where the corresponding wavelength of equivalent frequency band in this process is larger than that of converter station. Therefore, the calculation of magnetic field in DC yard during hybrid DC circuit breaker breaking can be reduced to Near-Field (kr<<1). Due to the irregular shape of hybrid DC circuit breaker and smoothing reactor, if the three-dimensional model of converter station is established, the structure is complex and the actual structure is difficult to obtain, and the secondary equipment is located outside electrical equipment, so the magnetic field source can be reasonably simplified and an equivalent model for calculating the DC yard magnetic field of converter station can be found.
The topology structure of 200 kV hybrid DC circuit breaker is shown in Figure 3, which is composed of main branch, transfer branch and energy consumption branch. The main branch is composed of mechanical switch and a small number of power electronic modules. The transfer branch is composed of several power electronic modules. The power electronic module adopts IGBT with full bridge structure, and the energy consumption branch is composed of arrester. When the system operates normally, the current flows through the main branch. When a short circuit fault occurs on the DC side, the fault current increases. When the main branch IGBTs action threshold is reached, the main branch IGBTs are turned off, and the transfer branch IGBTs is on, and the current is transferred to the transfer branch. When the main branch current reaches 0 A, the mechanical switch can realize non arcing open. When the mechanical switch reaches a certain opening distance, the transfer branch IGBTs are turned off and the current charges the capacitor of the transfer branch sub modules. When the charging voltage reaches the action voltage of arrester, the arrester will act and the fault current will be cleared.

The hybrid DC circuit breaker has commutation process when breaking, and the current flow path changes. Therefore, the magnetic field generated by hybrid DC circuit breaker needs to be modelled separately for main branch, transfer branch and energy consumption branch. The actual structure of hybrid DC circuit breaker is shown in Figure 4 [18]. Since the magnetic field at the secondary equipment outside the DC circuit breaker is studied in this paper, the main branch, transfer branch and energy consumption branch are equivalent to linear straight conductor according to the actual current flow path. The influence of other components such as supporting insulator can be ignored.

\[ dH = \frac{I dl \times r}{4\pi r^2} \]  \hspace{1cm} (1)

Where \( r \) is distance between current element.

Figure 5 shows the smoothing reactor used in Dinghai converter station. It is a dry hollow structure, which is composed of aluminum star frame and concentric cylinder in parallel. The inductance is 20 mH, the height is 2.5 m, and the height of the support insulator is 3.6 m. In [16], the air core reactor can be equivalent to the single encapsulation model, and then calculated by the magnetic field calculation formula of the air core cylindrical coil. The calculation formula of magnetic field is described in reference [16].

The DC yard of Dinghai converter station adopts cable for power transmission. Since the cable shielding layer adopts the double terminal grounding mode, when the fault current flows through the
cable core, the current will be induced in the cable shielding layer, and the current in the cable shielding layer will counteract the external magnetic field. Therefore, during the modeling, the cable is simulated according to the actual parameters, and two small resistances are used to simulate the grounding resistance, as shown in Figure 6. The core current and shield current obtained by simulation are substituted into Biot-Savart Law.

In addition, there are tube buses, incoming lines, outgoing lines and conductors connected between equipment in DC yard. These current carrying conductors are suitable for linear straight conductor model and calculated by Biot-Savart Law. According to the size and connection mode of the actual layout in the DC yard of Dinghai converter station, the model of each equipment in the DC yard is established. Figure 7 shows the DC yard modeling diagram of Dinghai converter station.

![Figure 5. Smoothing reactor](Image)

![Figure 6. Double terminal grounding diagram of cable shield](Image)

4. Research on magnetic field characteristics of DC yard

4.1. Calculation of magnetic field at sensitive position

Next, according to the single pole grounding short circuit fault, the magnetic field strength of the secondary equipment in the DC yard is calculated. Field point 1 and point 2 are disconnector control cabinets, field point 3 and point 4 are DC circuit breaker control cabinets. The calculation area is DC yard 42 m along x-axis and 21 m along y-axis. The plane layout of secondary equipment of DC yard is shown in Figure 8. Figure 9 shows the magnetic field strength of field point 1 and 4 in case of single pole grounding short circuit fault. The secondary peak strength of the device is listed in Table 3.

It can be seen from Figure 9 that the magnetic field intensity at field point 1 and point 3 is higher than that at field point 2 and point 4. This is because in case of negative grounding short circuit fault, the current flowing through the negative line is higher than that of the positive line, and the magnetic field strength near the fault pole DC circuit breaker is higher than that of the non fault pole. The magnetic field intensity waveforms of field point 3 are basically consistent with the main circuit current waveform, and the time when the magnetic field intensity reaches the peak value is the time when the current reaches the peak value. The peak value of magnetic field intensity at field point 1, point 2 and point 4 appears at the time of commutation from main branch to transfer branch, and the waveform of magnetic field intensity is related to the commutation process of DC circuit breaker. It can be seen from Table 3 that the peak value of magnetic field intensity at the secondary equipment is 59 A/m. The magnetic field waveform is ms level and aperiodic. The results can be used as a reference for the immunity assessment of secondary equipment in DC yard.

4.2. The distribution of magnetic field

In order to clearly display the magnetic field distribution in the DC yard, taking the moment when the current reaches the peak value, the magnetic field distribution at 1 m away from the ground in the DC
yard is calculated when the single pole grounding fault occurs in the DC side. Since this paper mainly focuses on the secondary equipment outside the DC circuit breaker, the calculation is only for the external DC circuit breaker. The calculation results are shown in the equivalent color block diagram, as shown in Figure 10.

It can be seen from Figure 10 that when single pole grounding short circuit occurs at DC side, the distribution of magnetic field in DC yard varies between 3 and 346 A/m. The maximum magnetic field intensity appears near the smoothing reactor and DC bus, and the magnetic field decays rapidly with the increase of distance. The magnetic field around the negative line is greater than that around the positive line, then the magnetic field strength near the negative DC circuit breaker is higher, and the magnetic field strength near the fault pole DC circuit breaker is higher than that of the non fault pole.

![Figure 7. Overall modeling diagram of DC yard of Dinghai converter station](image)

![Figure 8. The plane layout of secondary equipment of DC yard](image)

![Figure 9. Magnetic field strength of each field point in case of single pole-to-ground fault](image)

![Figure 10. The distribution of magnetic field at 1m from ground in DC yard under single pole earth fault](image)

|      | Point 1 | Point 2 | Point 3 | Point 4 |
|------|---------|---------|---------|---------|
| H(A·m⁻¹) | 42 A/m | 17 A/m | 59 A/m | 21 A/m |

5. Conclusions
In this paper, for Dinghai converter station with hybrid DC circuit breaker, the magnetic field around the hybrid DC circuit breaker is calculated and the distribution of magnetic field is studied. The specific conclusions are as follows:

(1) The fault current electromagnetic transient simulation model and the magnetic field calculation model of DC yard of Dinghai converter station are established. The magnetic field of secondary equipment in DC yard is calculated by Biot-Savart Law.
(2) When the single pole grounding short circuit fault occurs at the DC side, the maximum magnetic field intensity at the secondary equipment in the DC yard of Dinghai converter station is 59 A/m, and the duration of magnetic field waveform is ms level, and it is non periodic waveform.

(3) when the single pole grounding short circuit fault occurs at the DC side, the distribution of magnetic field in DC yard varies between 3 and 346 A/m.

The calculation model of DC yard and magnetic field established in this paper can provide reference for the calculation of magnetic field in Zhangbei ±500 kV four-terminal VSC-HVDC transmission project with the same installation of hybrid DC circuit breaker.

6. References
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