HVDC Circuit Breaker Development and Applications in VSC-HVDC Transmission Project

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Abstract. High voltage direct current (HVDC), especially voltage source based HVDC (VSC-HVDC), transmission technology has been expanding in recent decades. HVDC circuit breaker therefore attracts significant interest due to its abilities of current interruption and fault isolation. This paper aims to present the technical development, specifically the topology, control and protection technology and test technology, of HVDC circuit breaker and its applications in VSC-HVDC transmission project. The project background, system configurations, and circuit breaker topology are described for each project. Based on current circuit breaker development and applications, the challenges and associated future development are also presented.

Keywords: VSC-HVDC transmission; HVDC circuit breaker; current interruption.

1. Introduction
Since the first high voltage direct current (HVDC) transmission project was put into operation in Sweden in 1954, HVDC transmission technology has been expanding with the development of power electronics technology, optical fibre technology, computer science, etc. [1]. In recent decades HVDC transmission technology based on voltage source converter, namely, VSC-HVDC, has developed rapidly and played an important role in such areas as urban distribution network, island power supply and renewable energy grid integration due to its abilities of independent power regulation and flexible operation [2, 3].

However, one of the major challenges that hinder the development of VSC-HVDC is the lack of HVDC circuit breaker (CB) since the DC fault current has no zero-crossing and is difficult to interrupt. Therefore, economical and reliable HVDC CB capable of fast current interruption is urgently needed for VSC-HVDC power transmission. This paper aims to investigate the HVDC CB technical development and its engineering applications, specifically the project background, system configurations and topology of the HVDC CB adopted.

2. Key Technology Development

2.1. Topology Development

Mechanical HVDC CB Topology. In 1980s, a mechanical HVDC CB topology was developed by Brown Boveri Corporation (BBC), with its prototype tested in the field on the Pacific Intertie [3, 4]. This technique utilises arc voltage of AC CB and resonance of capacitor and inductor to create zero-crossing. The topology is shown in Fig. 1 [3]. During switching process, the current is first
transferred from the CB circuit to the L-C series resonant circuit, and then flows through the energy absorber (MOV) circuit for energy dissipation, thus achieving current interruption [4].

![Figure 1. Topology of Mechanical HVDC CB [3].](image)

The topology of mechanical HVDC CB is simple and has the advantages of high operating stability, large load capacity and low conducting loss, etc. In order for high-voltage and rapid-interruption applications, many studies on topology optimisation have been carried out. In 2016, Huazhong University of Science and Technology, China, proposed a coupling mechanical HVDC CB topology, in which the CB structure is divided into high-voltage side and low-voltage side through coupling reactors, such that the voltage level of trigger unit and difficulty of capacitor charging can be effectively reduced. The HVDC CB based on such topology is successfully applied in Nan’ao 3-terminal VSC-HVDC project, detail of which is shown in Section 3.1 [5, 6].

**Solid-state HVDC CB Topology.** The solid-state HVDC CB employs power electronic device to achieve current control. From 1980s to 1990s, the solid-state HVDC CB has developed rapidly due to the advancement of power electronic devices including gate turn-off thyristor (GTO), insulated gate bipolar transistor (IGBT), integrated gate commutated thyristor (IGCT), etc. A simple topology of solid-state HVDC CB is given in Fig. 2 [7]. The current flows through the solid-state switch in normal operation. When fault occurs, however, the power electronic device will turn off rapidly. Then the CB voltage will rise until it reaches the action threshold of surge arrester, and the system energy will be absorbed by the energy absorption branch [8].

![Figure 2. Topology of Solid-state HVDC CB [7].](image)

Compared with mechanical CB, the biggest advantage of solid-state HVDC CB is fast interruption speed due to power electronic devices. By far, the research of solid-state HVDC CB mainly focuses on current interruption at low voltage level and its application is therefore limited [7]. Therefore, in order to meet current engineering requirements, the performance of solid-state HVDC CB, especially voltage level, conducting loss, product cost, etc., needs to be further developed.

**Hybrid HVDC CB Topology.** The hybrid HVDC CB is obtained by a reasonable combination of mechanical switches and power electronic devices. Fig. 3 gives a basic hybrid HVDC CB structure, in which the mechanical switch and power electronic device are connected in parallel directly [8].
Figure 3. Basic Structure of Hybrid Circuit Breaker [8].

Under normal operating condition, the current mainly passes through the main branch, which contains mechanical switches. When DC fault occurs, the fault current will be transferred to the power electronic switch branch for a short period of time when the mechanical switch is open. The fault current will finally be driven to zero in the energy absorption branch [8].

As demonstrated in [9], a cascaded full-bridge hybrid HVDC CB that employs IGBT H-bridge modules is developed and applied in Zhoushan 5-terminal VSC-HVDC project, details of which is given in Section 3.2. The hybrid HVDC CB combines the advantages of both mechanical switch and power electronic device, and has short interruption time and low conducting loss. However, its cost is relatively high due to large numbers of IGBTs. Therefore, a novel commutation module based on diode full-bridge is proposed in order to reduce the number of IGBTs and planned to be applied in Zhangbei 4-terminal VSC-HVDC project, as described in Section 3.3 [3, 5].

2.2. Control and Protection Technology

The control and protection (C&P) system of HVDC CB is mainly used for coordinated control and fault treatment of primary equipment. In order to ensure safety and reliable operation of the CB, the C&P system with functions of rapid fault detection and effective reclosing is required [10].

Fast fault detection is a key technology relating to interruption time, which is crucial for design and cost of the HVDC CB. Wei et al. proposed a rapid fault detection method in [11]. The approach analyses the amplitude and change rate of current to improve response speed and sets over-current amplitude according to current variations, such that the fault detection delay, the mechanical switch action time and therefore the fault current peak can be effectively reduced [11].

The reclosing function is another critical technology. The HVDC CBs with reclosing functions should be able to recover the system after transient fault or mistrip, while interrupt fault current when permanent fault occurs. In [10], a synchronous reclosing strategy based on commutation branch current detection, and a step-by-step reclosing strategy based on energy absorption branch current detection, is compared, showing that the former is suitable for single-terminal reclosing and thus dependent on inter-station communication, while the later allows double-terminal reclosing and is suitable for DC grid that adopts overhead lines.

By far, the most commonly used C&P system is based on a hardware platform composed of high-performance DSP, FPGA and other chips, and adopts high-speed optical fibre and data bus for high-speed data transmission.

2.3. Test Technology

Before commercial operation of the HVDC CB, different types of tests will be carried out. The tests ensure a comprehensive check of the design, assembly, function and performance of HVDC CB and its C&P system.

The HVDC CB test is the assessment of the electrical design, complete functionality and high-voltage withstand ability of the equipment. The test items mainly include insulation test, such as DC voltage withstand and partial discharge test, switching impulse test, and lightning impulse test; operation test, such as rated current breaking test, short-circuit current breaking test, reclosing test and electromagnetic compatibility (EMC) test. However, relevant standards and specifications need to be developed for reference [12].
The C&P test is mainly to test the functions and performance of C&P and the coordination between C&P and the primary system. Dynamic simulation test, type test (such as high/low temperature test, EMC test), operation test and other tests are typically carried out, such that the performance of products can be verified and meet the engineering requirements.

3. Typical Application Projects

3.1. Nan’ao 3-terminal VSC-HVDC Project

Project Background and System Configuration. The Nan’ao islands located in Guangdong Province of China is an area in possession of wind power resources and has a wide distribution of wind farms. At the end of 2013, the Nan’ao 3-terminal VSC-HVDC project, as the world's first multi-terminal VSC-HVDC project, was commercialised. There are three converter stations configured for the project: Sucheng station (200 MW), Jinniu station (100 MW) and Qing’ao station (50 MW), allowing the scattered wind energy in Nan’ao islands to be gathered through Qing’ao station and Jinniu station, and sent out through Sucheng station, as shown in Fig. 4 [13, 14].

![Figure 4. Primary Structure of Nan’ao VSC-HVDC Project [14].](image)

On December 20, 2017, the world's first mechanical HVDC CB was successfully put into operation for the project, thereby achieving rapid fault current interruption function and therefore improving the flexibility and reliability of the project.

Topology of the HVDC CB. Nan’ao VSC-HVDC project adopts mechanical HVDC CB based on coupling reactors, topology of which is mainly divided into two parts: high-voltage side and low-voltage side, as shown in Fig. 5 [14]. Specifically, the high-voltage side is composed of four cascaded mechanical switch modules, commutation branch (L2-C2) and energy absorption branch (MOV). The low-voltage side is composed of pre-charging capacitor C1, coupling reactor primary side L1, and thyristor SCR module [14]. Normally the load current mainly passes through the mechanical switches. During current interruption, the switches disconnect and SCR conducts, the low-voltage side energy is then transferred to high-voltage side. The increasing voltage of CB will finally trigger the action of arrester for energy dissipation [13, 14].

By installing the HVDC CBs, one converter station can be switched on/off due to failure or maintenance, during which time the continuous operation of the other two converter stations will not be affected. The HVDC CB is capable of interrupting current greater than 9 kA with an interruption time less than 5 ms [13].
3.2. Zhoushan 5-terminal VSC-HVDC Project

Project Background and System Configuration. The Zhoushan islands is a rapidly developing area located in Zhejiang Province of China. The interconnection between these islands, however, is weak, making the grid system very unreliable. On the other hand, the Zhoushan islands are rich in resources, especially new energy resources such as wind energy and tidal energy [15, 16]. Therefore, the Zhoushan 5-terminal VSC-HVDC project was designed, and officially put into operation in July 2014, thus achieving flexible conversion and allocation of electric energy between Zhoushan islands.

Five converter stations are configured for the project: Zhouding station (400 MW), Zhoudai station (300 MW), Zhouqu station (100 MW), Zhousi station (100 MW), and Zhouyang station (100 MW); four ±200 kV DC transmission lines were constructed with a total length of 280.8 km, including submarine cables of 258 km and land cables of 22.8 km, as shown in Fig. 6 [16, 17, 18].

There are 10 locations where HVDC CB can be installed (CB1-CB10), but the HVDC CB is finally decided to be installed in Zhouding station, due to its large area of DC field, and ease and low cost of construction [17]. On December 29, 2016, the 200kV HVDC CB, as the world’s first HVDC CB used for engineering application, was successfully commercialised in Zhoushan five-terminal VSC-HVDC transmission project.

Topology of the HVDC CB. The Zhoushan VSC-HVDC project adopts the cascaded full-bridge
hybrid HVDC CB, which is mainly composed of three parallel branches, namely main branch, commutation branch and energy absorption branch, as shown in Fig. 7 [17]. The main branch is used to conduct the load current and is composed of high-speed switches and several full-bridge modules. The commutation branch is used to interrupt the short-circuit fault current and is composed of cascaded full-bridge modules. The energy absorption branch is used to absorb the short-circuit current of the system and is composed of arrester groups [17].

Figure 7. Topology of the HVDC CB Used in Zhoushan VSC-HVDC Project.

Under steady-state operating condition, the load current mainly passes through the main branch due to its lower conducting resistance. When DC short-circuit fault occurs, the IGBTs of full-bridge modules in the main branch will turn off, then the current is transferred to the commutation branch and drops rapidly to 0, and meanwhile the high-speed switches are open. When the CB voltage reaches the protection threshold of the arrester, the current will be transferred to the energy absorption branch until it drops to 0, achieving current interruption and fault isolation [9, 17].

The interruption current of the HVDC CB ranges from 0 to 15 kA, with an interruption time of 3 ms. The main branch has high overload capacity, and is able to conduct rated current of 6 kA and overload current of 8 kA. The HVDC CB is able to withstand current of 15 kA for 5s, and current of 40 kA for 5 ms [18].

3.3. Zhangbei 4-terminal VSC-HVDC Project

Zhangbei area is located in Hebei Province of China and is rich in renewable resources. With the development of wind power, photovoltaic energy and other resources, the VSC-HVDC grid is planned to construct in Zhangbei in order for safe grid connection, flexible energy collection, and ease of power transmission [19]. Based on power distribution and grid development, a four-terminal VSC-HVDC grid is designed, the primary structure of which is shown in Fig. 8 [19].
Figure 8. Primary Structure of Zhangbei VSC-HVDC Project [19].

The project includes four converter stations with voltage level of ±500 kV constructed in Kangbao County, Zhangbei County, Fengning County and Beijing City respectively, among which Zhangbei station and Kangbao station gather local wind energy, Fengning station is connected to local pumped storage power station, and Beijing station provides stable and clean power to Beijing area [19, 20]. Based on system scheme, four HVDC CBs are expected to be installed in each converter station. Theoretically, the rated voltage of the HVDC CB is 535 kV and the rated current is 3 kA. The CB is required to interrupt current not less than 25 kA within 3 ms. Mechanical and hybrid HVDC CBs are currently developed and tested by the project partners. The successful operation of HVDC CB in Zhangbei project will promote the development of HVDC technology and bring a great breakthrough in the development and manufacturing of HVDC equipment [3].

4. Challenges and Future Directions

Though HVDC circuit breaker has been developed rapidly and successfully applied in several HVDC transmission projects, there are still some problems that need to be solved [17, 21]. The drawbacks and future directions mainly include: (1) the expense of the HVDC CB is high due to its structure and power electronic devices, especially for hybrid circuit breaker. Optimal topology and low-cost components are needed; (2) current commutation technology mainly includes passive commutation, active commutation and integrated commutation. However, the parameter design of some commutation circuits lacks systematic principles, and some commutation techniques cannot meet practical engineering requirements and withstand the increasing voltage level. Future commutation technology will focus on small-current interruption, bi-directional commutation, commutation mode switching and system reliability research; (3) rapid detection and location of DC fault technology should be further developed in order for effective and efficient equipment protection; (4) there is a lack of relevant standards and specifications for HVDC CB, especially for testing techniques. Such normative references need to be developed.

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