https://doi.org/10.1186/s41601-023-00304-y

Protection and Control of Modern Power Systems

REVIEW **Open Access**

Circuit breakers in HVDC systems: state-of-the-art review and future trends

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Abstract

High voltage direct current (HVDC) systems are efficient solutions for the integration of large-scale renewable energy sources with the main power grids. The rapid development of the HVDC grid has resulted in a growing interest in DC circuit breakers (DCCBs). A fast and reliable circuit breaker is a necessary requirement in the development of large scale HVDC grids. This paper provides a comprehensive review and survey of the HVDC CBs and discusses potential research directions. Operational principles and the main features of various DCCBs are described and their merits and shortcomings are also highlighted.

Keywords DC circuit breakers (DCCBs), High voltage direct current (HVDC) system, Multi-terminal HVDC (MT-HVDC), Fault current isolation, Renewable energies, Voltage clamping

1 Introduction

HVDC technology is an attractive solution for transmitting large amounts of power via long-distance and asynchronous network interconnections. The demand for HVDC grids is continuously increasing because of large installations of renewable energy such as large-scale offshore wind farms and solar power [1–5]. In recent years, the number of HVDC projects in operation or under construction has seen significant growth and HVDC grids have been built in China [6, 7]. A basic point-to-point HVDC system comprises a converter station at each end, while a multi-terminal HVDC (MT-HVDC) system (HVDC grid) is formed when more than two substations are connected to the DC network. This can offer many benefits, e.g., loss and cost reduction, reliability and redundancy enhancement, etc. [5, 8].

HVDC systems are based on two distinct technologies, i.e., a line–commutated converter (LCC) using thyristors, and a self-commutated voltage source converter (VSC) using insulated gate bipolar transistors (IGBTs) [9, 10]. LCC-based HVDC systems consume a large amount of reactive power, which must be compensated by filters on the AC side. Moreover, the power reversal requires voltage polarity reversal of the system, which is problematic for an HVDC grid. However, this technology is mature, has low losses, and has high voltage and power ratings. VSC-based HVDC systems only produce high-frequency harmonics because of the use of the pulse wide modulation (PWM) technique, or even near sinusoidal output because of the use of advanced converter topology, and thus, only small AC filters (or even no filter) are required. VSC-HVDC systems provide independent control of active and reactive power that can be generated or consumed by the converters [11]. For power reversal, the voltage polarity will not be changed. However, it has higher losses than those of LCC technology. Table 1 lists the general characteristics of the LCC and VSC-based HVDC systems. Because of the VSC characteristics, VSC technology is suggested for using in MT-HVDC.

In contrast to the LCC, which is vulnerable to AC side faults but has a natural ability to withstand short circuits on the DC side, VSC is vulnerable to DC side faults, which can result in fast DC line voltage collapse and fault

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Table 1 Characteristics of LCC and VSC-based HVDC systems

Feature	LCC-based technology	VSC-based technology
Basic element	Thyristor-based technology	IGBT-based technology
Capability	Higher voltage and power capability—good overload capability	Lower voltage and power capability—weaker overload capability
Power flow reversal	Power reversal by changing voltage polarity	Power reversal by changing direction of current flow
Active/reactive power	Consumes large amount of reactive power	Independent control of active and reactive power
Overall cost	Lower station losses—Lower capital cost	Higher station losses—Higher capital cost
Harmonic related factors	Harmonic filters required—Large site area	Small/no filters required—Compact size area
AC network limits	Requires stronger AC systems	Possibility to connect to weak AC systems
Black start	Black start capability needs additional equipment	Black start capability
Form of storing energy	Store energy inductively	Store energy capacitive
Commutation issues	Possibility to commutation failures	Avoidance of commutation failure
Cables	Require use of MI cables	Ideal for use with XLPE cables
Fault related performance	Ability to withstand DC fault current—vulnerable to AC side faults	More vulnerable to DC side faults

current increase [9]. Generally, there are three main ways for interrupting the DC fault current in VSC-HVDC systems, i.e., conventional AC circuit breakers (ACCBs), DC circuit breakers (DCCBs), and specific fault-blocking converter stations. ACCBs have low interruption speed and require tens of milliseconds to interrupt the fault current. Owing to the lack of current zero crossing in DC systems, ACCB technology, which uses zero crossings of the fault current to achieve arcless interruption, cannot be used on the DC side for fault current interruption [12]. DCCB is one of the most promising solutions for isolating the faulty part of the DC network and improve the reliability of the grid. It is a key technology for MT-HVDC implementation [13–15].

A general comparison of the ACCBs and DCCBs in high voltage systems is presented in Table 2.

There are three main groups of DCCBs that have been developed to interrupt a DC fault current in HVDC grids. They are the mechanical circuit breaker (MCB), which relies on creation of a current-zero using a resonant circuit, the solid-state circuit breaker (SSCB), which uses power electronic components to perform the switching operation, and the hybrid circuit breaker (HCB), which is a combination of MCB and SSCB.

The aim of this paper is to present a comprehensive overview of the state-of-art of the DCCBs in HVDC systems, which are distinguished by MCB, SSCB, and HCB topologies. The ways of operation, advantages, and disadvantages of the different DCCB structures are described and recommendations for future research areas are also presented.

The rest of the paper is organized as follows: in Sect. 2, fault current in an HVDC system is discussed, and in Sect. 3, the main factors for circuit breaker design are presented. In Sect. 4, the general classification of DCCBs is discussed in detail, whereas Sect. 5 presents the commercialized HVDC circuit breakers, which have been implemented in real projects. Conclusions are given in Sect. 6.

2 HVDC fault current analysis

2.1 Fault current in HVAC/HVDC grids

Protection of HVAC/HVDC systems against faults is an urgent issue for secure and reliable operation of modern

Table 2 General comparison between ACCB and DCCB

	ACCB	DCCB
Interruption time	Tens of milliseconds (80–100 ms)	2–10 ms
Interruption mechanism	Utilizing natural zero crossing in fault current to extinguish the arc and interrupt the AC fault current	Utilizing additional branches to create a current zero crossing for the fault current interruption
Max. breaking current	40–60 kA	16–25 kA
Standardization	IEEE c37.06	No standards for DCCB
Development state	Commercially available	In research and development stage

power systems [16]. The fault current interruption in an HVDC system is more challenging than that of in an AC system. In contrast to the AC system, there is no natural zero crossing of current in a DC system. Moreover, due to the low line impedance of the DC system, the rate of rise of the fault current is very high. Therefore, the fault current needs to be interrupted very quickly and a large amount of energy stored in the DC system inductances must be dissipated [16–18].

It should be noted that, the behavior of the converters during the DC fault presents a challenging issue in the protection of MT-HVDC systems and must be considered [5, 9]. This is due to the fact that power converters based on IGBTs are vulnerable to over-current. Therefore, a fast and reliable fault current interrupter is required to isolate the faulty part of the system and minimize its impact on the healthy part of the grid. Owing to the limited breaking capability of DCCBs and the sensitivity of power electronic devices, the permissible fault clearing time in HVDC systems lies in a range of 5–10 ms.

2.2 Types of fault current in an HVDC system

As previously mentioned, in contrast to an LCC-HVDC system, a VSC-HVDC system is vulnerable to DC side faults. Different types of faults can occur on the DC side, including pole-to-ground fault, pole-to-pole fault, and double pole-to-ground fault. The type of fault and the grounding of the HVDC system play vital roles in the response of the system and the voltage insulation requirement of a DCCB [19–21]. In general, the short-circuit fault current on a VSC-HVDC system is characterized by two responses: one is the DC-link capacitor discharging, and the other is grid current feeding. The fault current transient progress during the pole-to-ground fault is depicted in Fig. 1 [18]. This type of fault current is largely dependent on the fault resistance. After the fault occurrence, the DC capacitor discharges instantaneously, which causes the DC voltage to decrease. In the second stage, the freewheeling diodes in the VSC are forward-biased and the grid starts feeding fault current. The detailed analysis of fault currents resulting from different sources such as DC-link capacitor and AC side is presented in [22–24].

3 Objectives in HVDC circuit breaker design

Owing to the demanding requirements on DCCBs in HVDC systems, the concept and operation of DCCBs are quite different from that of the ACCBs. The predominant goal in designing a DCCB is to interrupt the fault current reliably within a timeframe of milliseconds. Generally, DCCBs have to meet the following requirements:

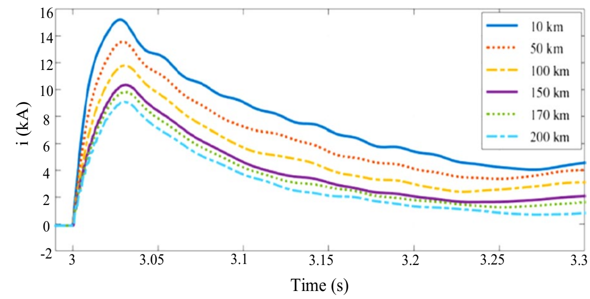

Fig. 1 DC fault current response of VSC-HVDC system under pole-to-ground fault [18]

- Creation of a current-zero to interrupt the fault current reliably.
- Fast fault current breaking to quickly isolate the faulty parts of the system (under 10 ms).
- Low conduction losses during normal operation of the breaker.
- Overvoltage suppression after fault current interruption.
- Dissipating a large amount of energy trapped in the DC system. This is achieved by using metal oxide varistors (MOVs) [25].
- The maximum fault current breaking capability must be high enough to safely and reliably interrupt fault current without being damaged.
- The total cost and dimension should be kept low.

4 HVDC circuit breaker configurations

In general, the focal point of this study is to review DCCB topologies that have been reported in the literature. In HVDC applications, fault current breaking is realized based on different concepts. For the protection of LCC-HVDC systems, traditional mechanical CBs can be used [26]. However, these CBs are slow and thus not an effective solution for VSC-HVDC grid protection. Hence, it is essential to develop fast DCCBs to protect VSC-based HVDC grids. The general classification of DCCBs is presented in Fig. 2 and will be explained in the following section.

4.1 Mechanical circuit breaker (MCB)

The principle of DC fault current interruption using mechanical DCCBs is to create an artificial zero crossing in the fault current. It can be generated by active or passive commutation of direct current [27–29]. Generally, an MCB is built using a mechanical interrupter (usually SF6 or vacuum interrupter), supplemented with a commutation branch, and an energy dissipation branch which limits the breaker voltage and dissipates the energy

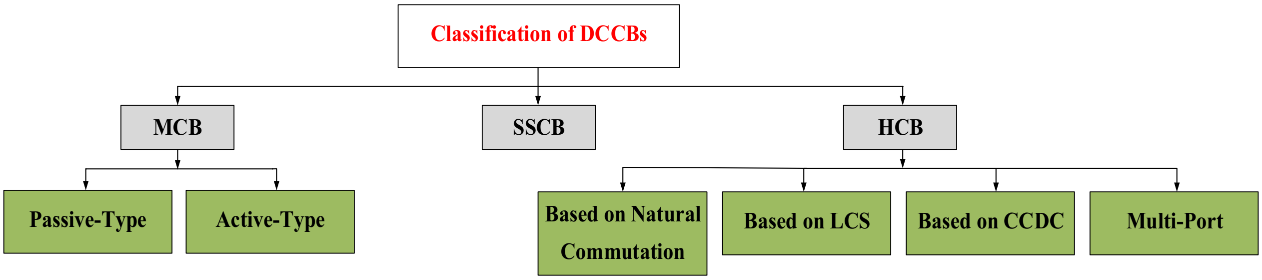

Fig. 2 Classification of different types of DCCBs

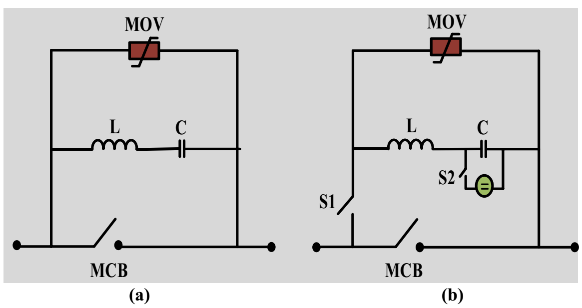

Fig. 3 The schematic of **a** passive MCB and **b** active MCB

of the system. In the passive scheme as illustrated in Fig. 3a, the commutation circuit is composed of a capacitor and inductor. These are connected across the main interrupter. Opening the main breaker results in an electric arc, which excites the tuned L-C circuit into current oscillation. The counter-current is injected into the main interrupter circuit and artificial zero crossings are created to facilitate the circuit isolation. However, although the passive resonant MCB has a simple structure and high breaking reliability, its operational speed is very slow (several tens of milliseconds) and the arcing time of the mechanical switch is approximately tens of milliseconds [30]. Long-term arc burning results in deterioration of the performance of the CB and limits its application in HVDC systems [31, 32]. With the help of power electronics technology, a new passive MCB is proposed in [33], which can generate a large number of zero crossings in a short time to enhance the breaking speed.

In an active scheme, the commutation circuit consists of a pre-charged capacitor, an inductance, and a switch. Figure 3b shows the traditional schematic diagram of an active resonance MCB. In this scheme, the artificial zero crossings in the main interrupter circuit are produced by using the current injection from the pre-charged capacitor into the commutation circuit [34, 35]. This improves the speed and reliability of the system. The counter-current magnitude depends on the voltage of the capacitor and the surge impedance of the commutation path. The traditional schematic diagram of an active resonance CB is depicted in Fig. 3b. Optimal selection of the commutation branch parameters can improve the performance of the MCB [36]. The effect of commutation circuit components including capacitor, inductor, and resistance on the breaker performance is tested in [37]. Reference [38] introduces a MCB based on a vacuum interrupter (VI) unit and active commutation circuit and a prototype was used to validate its feasibility through a current interruption test. The results demonstrated that the interruption current was 5.8 kA and the transient recovery voltage (TRV) after the interruption was approximately 4.4 kV. The time taken from triggering the mechanical switch open to current interruption was only 2 ms. The effect of the saturable reactor on the performance of the MCB with an active commutation circuit is analyzed in [39]. It claims that by applying saturable reactors to the DCCB, it is possible to reduce the size of the capacitor and inductor in the commutation branch and thus decrease the size and cost of the whole DCCB.

The MCB proposed in [40] uses cross-field interrupters in a sequential switching mode. It shows that by using a sequential switching concept, reliable current interruption can be achieved. A new MCB based on the active commutation branch is proposed in [41], one which does not require a continuous external voltage source to charge the commutation capacitor. A large commutation capacitor is not required either, since the interruption time is decreased. Consequently, the electrode surface erosion can be reduced. It also assesses the impact of *di/dt* and *dv/dt* and interruption current level on the successful interruption of the proposed DCCB. Reference [42] proposes an active resonant MCB that can interrupt DC current up to 16 kA within a few milliseconds. Moreover, the effect of the cell capacitance of the VSC converter and the effect of various inductance values at each converter station on the performance of the DCCB are also investigated.

In [43], the performance of the VI and MOV in fault current interruption is analyzed. It finds that the arc duration, interruption current magnitude, *di/dt* near current zero crossing, and the rate of rising and duration of the transient interruption voltage (TIV) determine the interruption performance of a VI. SF6 and VI are two promising candidates for HVDC circuit breaker applications [44, 45]. The performance of VI and gas interrupter in terms of the transient recovery voltage is assessed in [34], and it claims that it is best to use a series connected VI and gas interrupter.

Reference [46] introduces a bidirectional design for a DCCB based on the active resonant circuit that can interrupt the current in either direction, while [47] presents a novel bidirectional MCB, which uses IGCTs to enhance the breaking capability at low cost. The 10 kV/20kA prototype was built with a fault current interruption time of 2.5 ms. A DCCB using nonlinear resistors and two commutation switches in a parallel path is introduced in [48], while two HVDC CBs are presented in [49]. The proposed MCBs are composed of a current limiting inductor, a current control inductor, two mechanical switches, and a multilevel converter with phase-shifted carrier PWM. In [34] a DC current interruption system that uses a pulse transformer to facilitate the CB operation is introduced. In the proposed scheme, a trigger gap is used to inject a high-frequency oscillating current into the mechanical switch through the pulse transformer and pre-charged capacitor in order to interrupt the fault current. Reference [50] proposes two types of MCB. The first topology is based on the pre-charged capacitor that uses a bridge-type commutation branch. This can realize bidirectional interruption and provides freewheeling time for VI. For the second one, it is an improved bidirectional topology based on the magnetic induction current commutation module (MICCM), which uses a low pre-charged voltage capacitor on the primary side to realize current commutation on the secondary side. This topology has a shorter commutation time than the first topology. As the pre-charged capacitor at the primary side is completely isolated from the high-voltage circuit at the secondary side, it has better breaking reliability. The simulation results show that both topologies can break fault current up to 23 kA within 3 ms. Reference [51] introduces an improved current injection DCCB integrating current commutation and energy dissipation as shown in Fig. 4. This eliminates the need for the commutation capacitor. The combination of current commutation and energy dissipation process realizes one-time current commutation and fast breaking at low cost. Reference [52] proposes a bidirectional DCCB based on artificial current zero. Its main breaker is comprised of modularized vacuum switches in series. Each module is formed by three branches in parallel, including a low voltage vacuum CB (VCB), a MOV, and a RC snubber. The number of modules is determined by the system voltage level. In this scheme, a triggered sphere gap (TSG) is employed as the commutation switch in order to obtain bidirectional breaking. Compared with using a single high voltage vacuum breaker, the VCB in the proposed scheme has a higher opening speed because of its smaller axial dimension. The parameter design method for a modularized MCB is developed in [53], in which an optimal combination of the parameters is used for the interruption characteristics simulation. Reference [54] develops a new active MCB based on the multiple series gap (MSG) with a voltage dividing network and self-charging trigger component. This consists of several VCBs in series with energy absorber and RC snubber branches in parallel. The MSG with its voltage dividing network is used in order to control the turn on and off of the oscillating circuit. A novel active MCB is presented in [55]. This can interrupt fault current consecutively. As depicted in Fig. 5, the commutation path is formed by a pre-charged capacitor, a stray resistor, an oscillation inductor, and four spark gap switches (SGSs). In this scheme, two pairs of SGSs are alternately triggered to break the fault current. To reduce the electrical insulation requirements for the capacitor

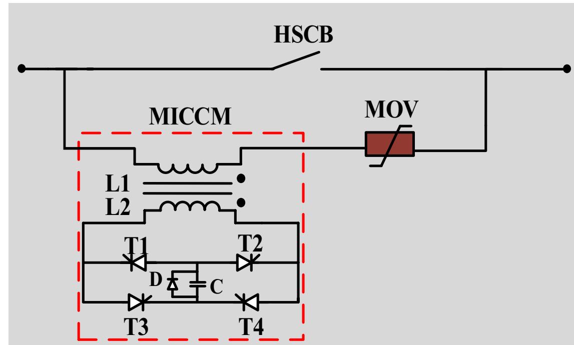

Fig. 4 The topology of MCB with MICCM [51]

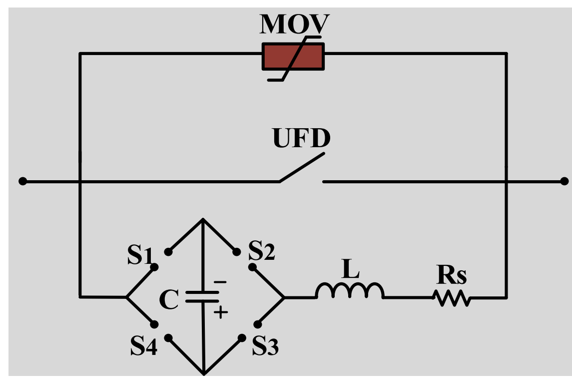

Fig. 5 Topology of a MCB with four spark gap switches [55]

and its charging system in the commutation path, a new MCB based on negative voltage source is proposed in [56]. Based on the transient operating voltage, a new reclosing strategy is developed for the proposed MCB. The adaptive reclosing strategy for an MCB is developed in [57], and the results show that the proposed strategy can identify the temporary and permanent faults reliably.

A thyristor-based HVDC circuit breaker is presented in [58]. This is comprised of a pulse generator, damping branches, and vacuum switches. The pulse generator is formed by a pre-charged capacitor, a thyristor stack, an inductor, and an MOV. In the proposed CB, creation of an artificial zero current crossing is the main function of the pulse generator. Modular structure of components and the scalability up to high voltage are the main advantages of the proposed CB. A new active type DCCB based on MICCM is introduced in [59]. MICCM is used to generate the injection current and current-zero in VI is obtained by electromagnetic induction between the primary and secondary windings of the MICCM. The effects of the main component parameters on the commutation performance are also assessed.

A VSC assisted resonant current (VARC) circuit breaker is a new active type MCB that is proposed in [45, 60]. According to Fig. 6 ,the main current path is formed by a VI, current limiting reactor, and a residual circuit breaker (RCB). The current injection branch is composed of a not pre-charged capacitor, an inductor, a resistor, and a full-bridge VSC. In the proposed DCCB, the amplitude of the oscillating current can be gradually increased by changing the output voltage polarity of the VSC in the same direction as the oscillating current. The details on the design of the main parameters of the VARC circuit breaker components are given in [61].

In the active type MCBs, the capacitor charging speed and the operational stability of the charging component are highly demanding owing to the limited arcing time of the mechanical switch. However, in comparison with the passive type, they have faster interruption speed and more stable interruption capability. Generally, although the MCBs offer low conduction losses, they have relatively slow operational speed because of the arc extinguishment between contactors. Moreover, to obtain a large current commutation capability under the fault current interruption, the commutation capacitor must be designed carefully.

4.2 Solid-state circuit breaker (SSCB)

With the rapid development of semiconductor devices, solid-state circuit breakers (SSCBs) have drawn more attentions. SSCBs take a shorter time to isolate the fault current compared to that of the resonant type DCCBs [62–64]. A typical SSCB is comprised of a number of semiconductor components in series in its main current path. An insulated gate bipolar transistor (IGBT), integrated gate commutated thyristor (IGCT), and gate turns off (GTO) thyristor are possible semiconductor switches to be used. A comparison between the different types of semiconductor devices is presented in [65]. Figure 7 depicts the simplest scheme of the SSCB, which can interrupt current in both directions. During normal operation, the current flows through the solid-state devices. In the fault condition, the semiconductor switches are switched off, resulting in a fast increase of voltage, which is clamped by the MOV [63]. The number of devices in series and parallel connection are determined by the voltage and current ratings of the CB, respectively [66, 67]. A comprehensive review of SSCB technologies is presented in [68]. Reference [69] studies the voltage unbalancing factors of the series-connected IGBTs in SSCBs and an active gate drive is developed to minimize the voltage peak difference of the IGBTs.

The SSCB presented in [70], employed thyristors in its structure. It is economical and has relatively low on-state losses. The proposed CB interrupts the fault

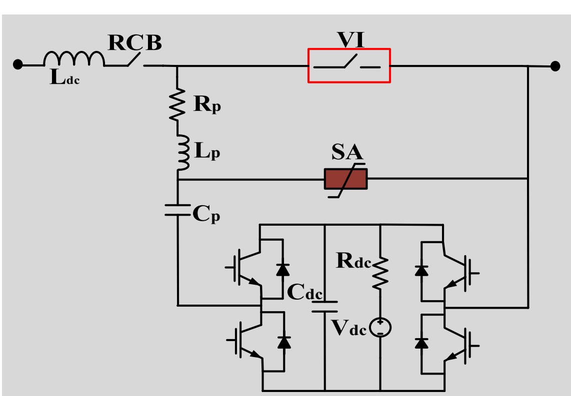

Fig.6 The topology of the VARC circuit breaker [45]

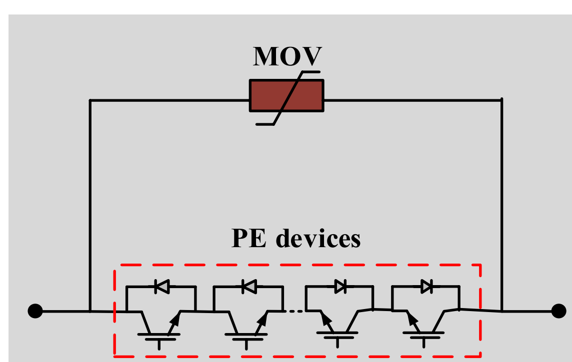

Fig. 7 The simple scheme of SSCB

current using L-C resonant current, while the capacitor is charged to a voltage required for the current interruption. Similar topology is developed in [71]. However, in contrast to the previous topology, it can perform natural charging and the switching operation of thyristors for charging the capacitor is eliminated. It also performs with fewer elements than the previous CB. Therefore, the proposed CB is faster and more economic than the previous one. Reference [72] presents a new DCCB based on thyristors that combines the circuit breaker design and fault current limiter. Because it uses thyristors, this SSCB has low cost and on-state losses. In [73] a SSCB based on IGBT series connection with snubber circuit is proposed, whereas [74] proposes an innovative SSCB, one which can decrease the surge voltage arising from the current interruption by employing the freewheeling diodes to bypass the fault current. The proposed CB realizes high blocking voltage by connecting many semiconductor switches in series with a snubber circuits in parallel to maintain voltage balancing among the devices. Reference [75] studies the diode recovery characteristics and analyzes the cooperation of the standard recovery diodes with the fast switching action of fully controlled semiconductor switches such as IGBTs. A trigonometric exponential model is proposed in [76] to describe the reverse recovery process of thyristors in a CB with an L-C resonance circuit. Reference [77] designs a SSCB using a series-connected SiC MOSFET which uses a single isolated gate driver to control the series-connected devices.

In [78] a SSCB is presented which employs a mutual inductance, a capacitor, and a resistor to perform the task of absorbing energy. It claimed that the requirement for fault energy absorption is eliminated, as the energy stored in the inductance of the system is suppressed by the mutual inductance plus capacitor and resistor. The SSCB presented in [79] splits the overvoltage protection and energy absorption between two separate varistors. A fast SSCB is designed in [80]. In normal condition, current flows through IGBTs and capacitor charges through the thyristors to the nominal voltage level. Upon detection of fault current, the IGBTs are switched off and at the same time the pre-charged capacitor starts feeding fault current through an inductor and a resistor. When the IGBTs are turned off, the stored energy in the capacitor and system inductance is dissipated by the resistor.

Generally, SSCBs provide fast arcless breaking, high reliability, and long life. However, the on-state voltage drop is high. Consequently, the losses are significant and the requirement for the heat dissipation devices is high. To achieve high blocking voltage level and decrease power losses, wide band gap (WBG) power components can be utilized. In many studies, these emerging power semiconductor devices have been applied to SSCBs [81, 82]. The performance of a 22 kV SiC ETO thyristor for high voltage applications such as SSCBs is assessed in [83], while10 kV and 15 kV SiC MOSFETs, 15 kV SiC GTO, and 15 kV SiC IGBT have been studied in [84] and [85]. A SSCB developed in [86] is based on the parallel operation of 15 kV ETO thyristors. The test results show that the SiC ETO has very low voltage drop and has large turn-off current capability. A self-powered bidirectional SSCB with two back-to-back connected SiC JFETs is introduced in [82].

4.3 Hybrid circuit breaker (HCB)

Hybrid circuit breakers (HCBs) are combinations of MCBs and SSCBs that attempt to have low losses during normal operation and fast interruption performance [87–91]. In contrast to MCBs, in which the fault current interruption is carried out inside the mechanical breaker unit, in HCBs, the current interruption is performed in the auxiliary branch paralleled with the main current conduction path. Similar to SSCBs, power electronic devices are the core components in HCBs. The voltage and current stresses, on-state voltage drop, failure characteristics, series voltage equalization effect, and parallel current sharing impact of power electronic devices, have significant impact on the performance of HCBs. In [92], the main characteristics of IGBT, IGCT, and IEGT are assessed in terms of the maximum current breaking capability, on-state power losses, current conduction ability, and robustness. It is found that IGBT and IEGT are more suitable for high current interruption. However, because of the low on-state voltage and high surge current conduction ability of an IGCT, it is a better choice to be used in low voltage high current HCBs. Based on the principles of commutation, HCBs can be classified into four main categories: (1) HCBs based on natural commutation, which uses the arc voltage of a mechanical switch to obtain current commutation; (2) HCBs based on LCS; (3) Multi-port HCBs; and (4) HCBs based on CCDC, which uses auxiliary commutation components to achieve current commutation.

4.3.1 HCB based on natural commutation

A hybrid DCCB prototype based on the mechanical switch and static DCCB is developed in [93] (see Fig. 8). The static DCCB branch is composed of two IGCTs connected in parallel, and four diodes in a rectifier scheme, which allows the CB to be used for both current directions in a DC system, and an MOV element. In normal condition, the load current is carried by the mechanical switch. In the case of a short-circuit, the mechanical switch is commanded to open and at the same time turn on signals for the IGCTs are produced. As the arc voltage generated by the contacts separation of the mechanical

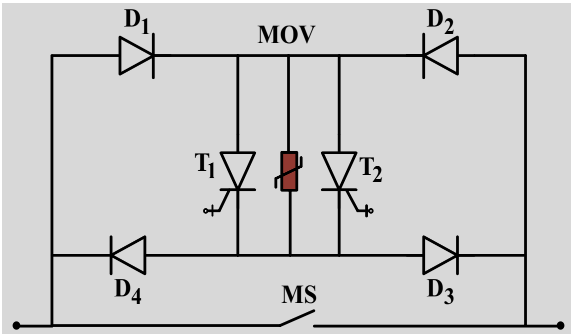

Fig. 8 An HCB based on static D CCB [93]

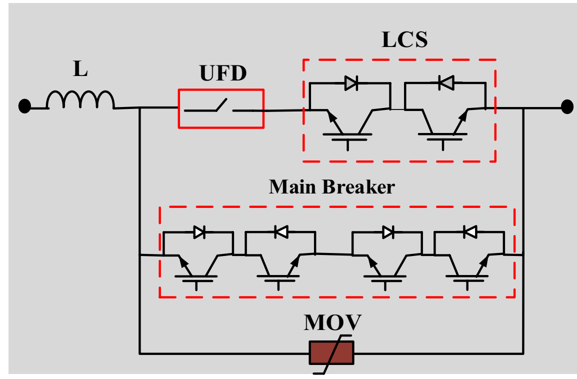

Fig. 9 Basic schematic of an HCB with LCS

switch is higher than the voltage drop of the static DCCB, the current will naturally redirect from the mechanical switch to the static DCCB. When the mechanical switch can tolerate the TRV, the static DCCB is turned off and fault current is interrupted. Finally the energy remaining in the circuit is dissipated by the MOV. Based on similar topology, reference [94] proposes an HCB with a rated current of 10 kA and recovery voltage of 10 kV for superconducting magnet protection.

Arcless commutation in an HCB composed of vacuum connector, SiC- MOSFETs, and a varistor is presented in [95]. The test results show that 100% arcless commutation is obtained at 74A with two SiC-MOSFET devices connected in parallel. However, at higher circuit currents, owing to the increase in turn-on voltages of SiC-MOSFETs and the voltage drop across the stray inductance, the probability of arcless commutation is decreased. In [96], a 4 kV/3.4kA HCB is developed. SF6 is used as the mechanical switch, because it has larger arc voltage than that of the vacuum switch. It is found that although the arc voltage of an SF6 switch is large enough for commutation of the current in the proposed HCB, the operating time is too long for MTDC grids. Generally, a successful current commutation in an HCB needs the arc voltage appearing at the mechanical switch terminals when it starts opening, be higher than the on-state voltage of the main breaker branch [97]. With increase of the rated voltage of the circuit breaker, the voltage drop of the breaker branch rises hundreds of volts. However, the arc voltage of the mechanical switch cannot rise to that high within several milliseconds, which results in commutation failure. To overcome this problem, hybrid CBs with a load commutation switch (LCS) and a current commutation drive circuit (CCDC) are used.

4.3.2 HCB based on LCS

The essential components of these types of HCBs are an ultra-fast disconnector (UFD), load commutation switch (LCS), main breaker, and a stack of MOVs. In general, such an HCB has a low loss branch in which the UFD and LCS are placed in series (see Fig. 9). This branch is the current path in the normal status. Turning off the LCS results in commutation of the current to the main breaker branch, which is composed of large stacks of semiconductor devices. When the current commutation is finished, the UFD opens in zero current. When the distance between the mechanical switch contacts is sufficient to withstand the overvoltage (it takes around 2 ms), the main breaker is allowed to be switched off. At the end of the process, the fault energy will be dissipated by the MOVs.

The general description of such hybrid DCCBs is presented in [98] and [87] and their operating principles are analyzed, including the key design elements of the hybrid DCCB during commutation, the effect of commutation current, DC side inductance, snubber capacitance, parasitic inductance, and DC voltage level on the LCS peak voltage and commutation time. An accurate model of an HCB is presented in [99] to facilitate DC grid protection and transience studies. To decrease the cost of the main breaker branch, a new HCB is proposed in [100], one which integrates high capacity IGCTs and high turn-off ability IGBTs. In [101], two innovative bidirectional HCB are introduced with the goal of minimizing semiconductor devices, as well as size and weight. The first topology includes the UFD and bidirectional LCS in its main current path, a main valve that is composed of IGBT switches and MOVs, and two double throw UFDs in the main breaker branch. The bidirectional breaking capability is obtained using double throw UFDs to route the current in the positive direction through the main valve regardless of the direction of line. In this topology, based on the initial orientation of the double throw UFDs with respect to the current direction, the interruption time is either 2 ms or 4 ms. For the second topology, the main breaker branch consists of four UFDs, four diodes, and a main valve. In this scheme, the total breaking time is 2 ms.

Reference [102] designs a thyristor full-bridge-based HCB. The main breaker is comprised of a diode rectifier, a thyristor full-bridge, and an L-C branch, which is in parallel connection with the energy dissipation branches. It is found that the proposed breaker has advantages of pre-activation, fast reclosing, and fast breaking of large and small currents. In [103] a novel HCB based on fast thyristors is proposed, which has a voltage rating of 120 kV and current rating of 10 kA. The results indicate that with the fast thyristors, the proposed HCB can isolate the fault current in 2.5 ms. For HCB cost reduction, reference [104] introduces an HCB with the main breaker branch provided by hybrid connection of thyristors and IGBT half-bridge modules. In this scheme, thyristors withstand the majority of the turn off surge voltage while the IGBT half-bridge modules realize negative voltage across thyristors to turn them off. As a result, the required number of IGBT modules reduces significantly, and this decreases the total cost of the HCB. A hybrid bridge-type HVDC breaker is presented in [105], in which the fault current is limited in two stages by a bypassing reactor and resistive fault current limiter to reduce the main breaker dissipated energy. In [106], a design methodology based on discreet MOVs of an HCB with series-connected power electronic devices is proposed, whereas [107] studies the snubber and MOV optimization design of an IGCT for overvoltage suppression. Cost performance improvement of 8.5% is achieved based on the study. Reference [108] designs a new HCB with self-powered gate drive. The switches in the main breaking branch are gated using energy stored in low voltage capacitors, thus eliminating the need for external gate power supplies for this branch. In [109] a hybrid CB is proposed, which utilizes the voltage clamping and current limiting function of pre-charged capacitors for isolating DC faults. In this scheme, the fault interruption and energy dissipation processes are decoupled, such that they can be conducted separately.

A novel DCCB topology is a combination of a liquid metal load commutation switch (LMLCS) and a two stages commutation circuit, and it is implemented in [110]. The main conduction branch is composed of LMLCS, which has low on-state losses and realizes arcless opening of mechanical switch and UFD. The bridge-type branch, which acts as the main breaker branch, comprises a pre-charged capacitor, thyristors, and inductances. The fault current is controlled to communicate to the capacitor in two stages. It reduces the rate of rise of overvoltage during the interruption and improves breaking reliability. The results show that the proposed CB can break fault current up to 14.5 kA and 17.5 kA in 200 kV and 500 kV applications, respectively.

4.4 Multi-port HCB

The application of integrated an HCB can be technically and economically attractive. In multi-port HCB topologies, the overall construction cost and power losses can be reduced, owing to the sharing of the main breaker part [111–113]. Reference [114] presents a novel multi-port HCB for offshore multi-terminal HVDC applications. The core concept of the proposed DCCB is similar to that presented in [87]. This CB has n-port, each of which interrupts the fault current independent of other ports and also irrespective of the direction of fault current. In comparison with typical HCBs, it requires fewer IGBTs in the main breaker unit and LCS. Moreover, the size of surge arresters can be significantly reduced owing to the smaller discharge current and energy absorption in its arrester. Consequently, its cost is lower than other HCBs. An economical multiport HCB for DC grids is presented in [115], which shows that the introduced multiport CB can break different types of fault current and can be a promising fault handling solution for future grids. In [116], two innovative bridge-type integrated HCBs are developed to reduce the controllable semiconductor devices, while protecting HVDC grids from faults in various conditions. In both topologies, one shared bridge-type main breaker associated with several bypass branches is used. An extra merit of the proposed topologies is that the currents are transmitted through the nodes even during a DC bus fault event. A new multi-port HCB with soft reclosing capability is developed in [117]. This can reduce the fault interruption time and the capacities of arresters. A fast multi-port CB is presented in [118], in which, the LCSs, the main breaker, and the surge arrester are shared among the DC lines. Large volume and lack of backup protection are the limitations of the proposed HCB.

4.4.1 HCB based on CCDC

Similar to LCS, a current commutation drive circuit (CCDC) based on a coupled-inductor can be used as an auxiliary commutation device in HCBs. The CCDC is an important device to guarantee successful commutation in a high voltage HCB [119–121]. Reference [94] presents a new DCCB, one which uses the CCDC instead of LCS in series with the mechanical switch (see Fig. 10). In the proposed HCB, the CCDC is used to commutate the current quickly and reliably. In steady-state, the thyristor and the static DCCB are in the off state and current is only carried by the vacuum switch and L2. In a fault condition, the turn on signal is sent to the static DCCB

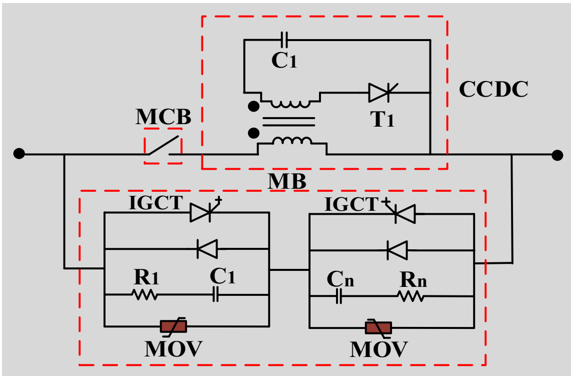

Fig. 10 HCB topology with CCDC [94]

and opening command to the MVS. Thus, the arc voltage is produced and part of the fault current commutates to the static DCCB. After that, the thyristor is turned on and a voltage is induced on L2. This induced voltage results in further current commutation to the static DCCB. Thus, the current through the MVS decreases to zero. The static DCCB is turned off when the dielectric strength of the MVS can withstand the TRV. Finally, the current commutates from the IGCT branch into the MOV branch. The experimental results show that the proposed CB can interrupt fault current of 3.4 kA within 2 ms. It is found that in comparison with LCS, the CCDC has lower cost and lower operating losses. Reference [119] uses a GA algorithm for the design of DCCB parameters. The optimization results show that the cost of the CCDC with a certain current commutation capability is decreased. To realize large current interrupting capability and low conducting loss, Reference [122] presents an HCB which integrates current commutation and damping. The bridge-type solid-state switch in combination with the current damping module is used to achieve a cost effective solution for fault current interruption. In [123] a 500 kV HCB based on CCDC is designed for current commutation from VI to the breaker branch. The test results show that the proposed breaker has the ability to break 25 kA in 2.7 ms with 800 kV overvoltage.

The general comparison between the high voltage DCCBs is given in Table 3 with more information from [124, 125]. Moreover, the main features of different types of HCBs are listed in Table 4.

4.5 Other types of high voltage DC circuit breakers

A hybrid DCCB with commutation booster is proposed and patented in [97] and [126]. It uses a coupled-inductor connected in parallel branches for automatic current commutation. To reduce the constraints in designing the coupled-inductor, an HCB with coupled-inductor connected in series is developed in [127], in which, the

Table 3 Comparative study on different types of DCCBs

Types of CB	Fault clearing speed	Conduction losses	Arcing hazard	Voltage blocking capability	Current interrupting capability	Complexity	Cost
MCB	Low	Very low	Yes	High	Moderate	Low	Low
SSCB	Very high	Very high	No	High	High	High	High
HCB	High	Moderate	No	High	High	Very high	Very high

Table 4 The comparison between different types of HCBs

Method	Main advantages	Main disadvantages	Refs.
HCB based on natural commutation	Lower conduction losses Simple and low complexity Low cost Mature technology	Not suitable for high voltages Arcing hazard Commutation failure in higher voltages	[8, 96]
HCB based on LCS	Arcless commutation Suitable for high voltages applications High reliability Fast in reclosing	High equipment cost, especially in bidirectional scheme Higher conduction losses Liquid cooling system is required High system complexity Full-controlled semiconductor devices is required	[87, 98, 100, 138]
HCB based on CCDC	Low cost Low operation losses Free maintenance Suitable for higher voltages Low pre-charged voltage of capacitor	Arcing hazard Weak in reclosing action Has high constraints in designing the auxiliary circuit Difficulty in breaking low currents	[96, 119, 123]

coupled-inductor is used to force the fault current to commutate automatically from the normal current path to the main breaker branch. An innovative hybrid DCCB is presented in [128], in which the pre-charged capacitor is employed as a commutation element to commutate the fault current from the mechanical switch to the breaker branch.

Superconducting hybrid DCCBs have the potential for quick fault current interruption with low power losses [129]. Reference [130] proposes a superconducting hybrid CB in which the superconducting coil is utilized as a current commutation device, and the automatic quench of the coil results in transferring the fault current from the normal current path to the main breaker branch. To validate the performance of the proposed superconductive breaker, a low voltage prototype was built and tested. In [131], a proactive hybrid circuit breaker in combination with a superconductive fault current limiter (SFCL) is proposed. Simulation results show that utilizing the SFCL located in the main current path of the hybrid DCCB can significantly reduce the fault current interruption stress for the CB components. The feasibility analyses and the application of the proposed hybrid DCCB are investigated in [132]. Another superconductive current limiting type DCCB is proposed in [129], in which the impact of the quench resistance on the fault current interruption performance is investigated.

5 Commercialized HVDC circuit breakers

Different types of DCCBs have been implemented in recent HVDC grid projects. However, their number is limited. In 2017, a 160 kV/9 kA active type MCB was installed in the Nan'ao multi-terminal HVDC system in China [133], while in 2019, Mitsubishi Electric successfully tested the 160 kV/16 kA MCB [134]. The 500 kV/25 kA forced commutated HCB based on a CCDC was built in the Zhangbei Flexible DC Grid [7, 123]. In the proposed breaker (Fig. 11), the CCDC is utilized to force the fault current to commutate from the mechanical switch to the breaker branch, and the CB can break 25 kA DC fault current in 2.7 ms with 800 kV overvoltage. The Zhoushan 200 kV hybrid DCCB is presented in [135], in which the IGBT full-bridge module is its basic unit. In 2016, a 200 kV/15.6 kA HVDC CB was successfully tested and manufactured by GEIRI and CEPRI [136]. An 80 kV/15 kA HVDC circuit breaker based on the VARC concept have been designed and implemented by SciBreak in 2020 [137].

Three well-known companies, namely, ABB group, Alstom Grid, and Siemens have presented commercialized high voltage DCCBs. All are embedded in the HCB concept based on LCS.

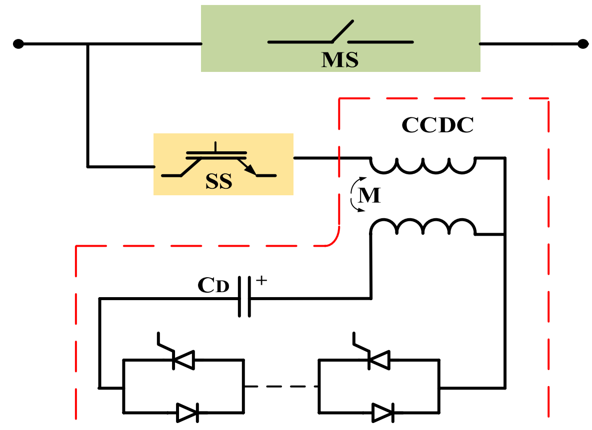

Fig. 11 The schematic diagram of Zhangbei circuit breaker [123]

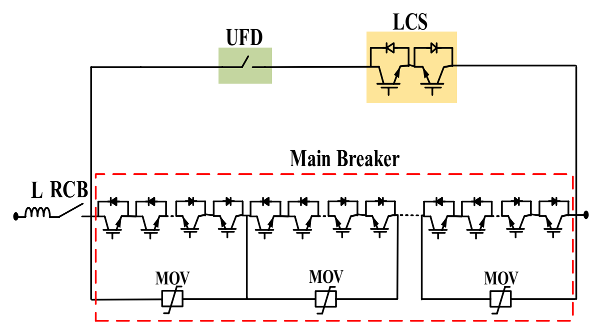

Fig. 12 The schematic diagram of ABB circuit breaker

The ABB hybrid DCCB with 320 kV rated voltage and 9 kA current breaking capability is proposed in [138]. As shown in Fig. 12, it consists of a full solid-state DC breaker branch, which acts as the main DC breaker, and an additional branch, comprised of the auxiliary semiconductor-based breaker in series with a mechanical switch. The main components of the main breaker branch are IGBTs. An inductor is used in series with the breaker for current limiting. In normal conditions, the load current flows through the bypass branch, and the current in the main breaker branch is nearly zero. During fault conditions, the LCS commutates the current to the main breaker branch. When the commutation is accomplished the UFD opens at zero current with low voltage stress. The main DC breaker will be commutated in the off state once the UFD is fully opened. Finally, the current flows through the arrester bank. After the fault clearance, the RCB will be opened.

Alstom Grid has built and tested a 120 kV HCB with current breaking capability of 7.5 kA (see Fig. 13) [139]. This breaker consists of main, auxiliary, and extinguishing branches. The main branch is composed of a UFD in series with a low voltage IGBT valve, while the auxiliary

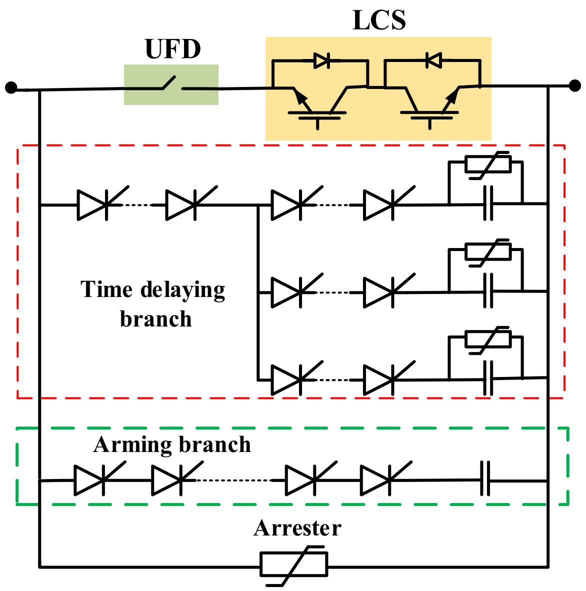

Fig. 13 The schematic diagram of Alstom circuit breaker

branch is composed of several parallel branches of thyristors, each with its own capacitor bank. Therefore it can withstand a high fault current. In normal conditions, the current flows through the low impedance branch, whereas in the fault condition, IGBTs in the main branch are switched off and the thyristor stack of the first time–delaying branch is switched on simultaneously. Thus, all the current starts to commutate into the first time-delaying branch of the auxiliary branch and the capacitor bank starts to charge up. During the contact separation of UFD, thyristors in the second time-delaying branch are triggered, and then the current commutates to the second time delaying branch. Depending on the requirements, a third time-delaying branch can be added. Finally, when the current is transferred from the arming-branches into the main surge arrester, the fault current is interrupted.

The topology of the Siemens HVDC CB is presented in [140]. Similar to other two CBs, it is based on a hybrid scheme (see Fig. 14). It utilizes a mechanical switch and an auxiliary electronic DCCB. The power electronic switching devices in the main breaker branch are replaced by a not pre-charged capacitor for isolating fault current in the case of short circuit. In this scheme, arresters and damping resistors are also included.

It has a discharge circuit to provide fast reclosing. The comparisons among the three mentioned CBs are given in Table 5.

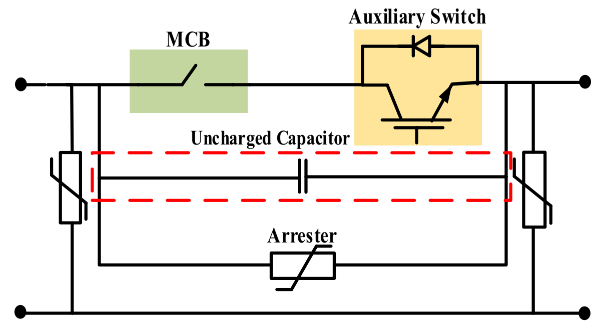

Fig. 14 The schematic diagram of Siemens circuit breaker

6 Conclusions

This review on DCCB architectures has discussed the concept and operational principle of various DCCB topologies in the open literature and highlighted their strengths and weaknesses. This study does not recommend any DCCBs for HVDC grids. Rather it advocates research and development in technical areas to enhance the DCCB technology. These areas are as follows:

- Optimization of DCCB elements such as capacitors, inductors, varistors, and charging units is required, to improve the interruption speed and reduce the size and total cost.
- Further research is needed to improve the high speed mechanical switch with high recovery voltage withstand capability and being low on state losses. Further improvements in terms of the reaction time, opening speed, and also life cycle are also required.
- The utilization of fault current limiters in combination with DCCBs in HVDC systems in order to

Table 5 Comparison between ABB, Alstom, and Siemens CBs

Types of CB	Description
ABB	With 320 kV rated voltage and 9 kA current breaking capability Uses series connection of IGBTs in the auxiliary branch Fast switching capability Cannot tolerate the high peak current during DC faults
Alstom	Water cooling system is needed for LCS With 160 kV rated voltage and 7.5 kA current breaking capability Uses thyristor stacks in series with a capacitor Can withstand a high fault current Turning the thyristors off is the main challenge
Siemens	Uses an uncharged capacitor instead of power electronic switches in the auxiliary branches Possible use of one or more varistors in combination with CB High impedance fault current breaking is the main challenge

decrease the CB cost and improve the breaker reliability.

- Utilization of low on-state loss semiconductor switches with no additional heat such as new wide band gap power semiconductors in HVDC CBs.
- Modeling and optimization of the switching arcs in HVDC CBs with detailed assessment of arc properties under various conditions.
- Designing the DCCBs with a comprehensive experimental platform.
- Standardization for HVDC systems is an essential requirement, especially for high voltage DCCBs and their coordination with protection systems.

Acknowledgements
Not applicable.

Author contributions
This paper presents a comprehensive overview of HVDC circuit breakers, considering different topologies have been presented in the literature so far. This paper broadly categorizes high voltage DCCB topologies into three main categories and describes the concepts, the operation principles, merits, and possible shortcomings of the different DCCB topologies. Recommendations for the improvement of the high voltage DCCBs are also discussed.

Funding
Not applicable.

Availability of data and materials
Not applicable.

Declarations

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Received: 31 December 2022 Accepted: 19 June 2023
Published online: 08 August 2023

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