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# Protection Schemes used in HVDC Transmission Lines: A Review

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**Abstract:** The continuously increasing demand for electric power and the economic access to remote renewable energy sources such as off-shore wind power or solar thermal generation in deserts have revived the interest in High-Voltage Direct Current (HVDC) Multiterminal Systems (networks). A lot of work was done in this area, especially in the 1980s, but only two three-terminal systems were realized. Since then, HVDC technology has advanced considerably and, despite numerous technical challenges, the realization of large-scale HVDC networks is now seriously discussed and considered. For the acceptance and reliability of these networks, the availability of HVDC Circuit Breakers (CBs) will be critical, making them one of the key enabling technologies. Numerous ideas for HVDC breaker schemes have been published and patented, but no acceptable solution has been found to interrupt HVDC short-circuit currents. This paper aims to summarize the literature, especially that of the last two decades, on technology areas that are relevant to HVDC breakers. Additionally, different technologies based on derived information from literatures are compared. Finally, recommendations for improvement of circuit breakers are presented.

**Keywords:** HVDC, HVDC fault current, Solid-state DC circuit breaker, Hybrid circuit breaker, Power-conditioning units; dc/dc converters; dc/ac inverters, Distributed generation; Renewable energy sources; Fuel cell systems.

## I. INTRODUCTION

In recent years, the development of HVDC based on voltage source converters has been rapidly developed, making it possible to form a multi-terminal HVDC network. Compared with high-voltage AC transmission, HVDC has a relatively low active power loss, while zero reactive loss. However, the impedance in a HVDC system is relatively low, when the fault occurs in a DC system it will spread faster and wider. Therefore, fast and reliable DC circuit breakers are required to isolate faults and to minimize interference during commutation, especially when faulty lines and cables are not connected to the converter station, the fault should be cleared in milliseconds. At present, the DC circuit breaker can be divided into two main categories of mechanical circuit breakers and solid state circuit breakers. Existing HVDC circuit breakers (mechanical type) can turn off the circuit in tens of milliseconds, but for the HVDC transmission system, the existing HVDC circuit breakers can't meet the requirements. In addition, mechanical DC circuit breakers need to add reactive components to. There are significant differences between the requirements of ac and dc CBs, mainly due to the absence of a natural current zero crossing in dc systems. DC breakers have to interrupt short-circuit currents very quickly and need to dissipate the large amount of energy which is stored in the inductances in the system. Today, dc CBs are only widely available for the low- and medium-voltage range. For HVDC applications, only transfer and load current switches are in use. Breakers interrupting HVDC short-circuit currents are not commonly available and have very limited ratings. Numerous proposals for breaker designs have been presented in articles and patent applications [1], [2]. All comprise different series and parallel connections of classical ac interrupters, resonance circuits with inductors and capacitors, semiconductors, charging units, and resistors. Each of the numerous concepts has certain advantages and drawbacks. Most of the publications address only a few, or even only a single aspect of the many requirements, but no contribution has tried to give an overall picture. The main aim of this paper is to give an overview of HVDC CBs, to identify areas where research and development are needed, and, by this, to review the discussion on this subject. Obviously, this paper cannot discuss each of these identified needs in detail. But by citing relevant literature, it should serve as a reference point for others working in this area.

## II. CIRCUIT TOPOLOGY AND WORKING PRINCIPLE

In today's point-to-point HVDC transmission systems, dc interrupters are used for several different switching duties. A neutral bus switch (NBS), neutral bus ground switch (NBGS), metal return transfer breaker (MRTB), ground return transfer breaker (GRTB), high-speed bypass switch (HSBS) for parallel line switching, and isolation switches also exist. Interrupters to break dc short-circuit currents have only been realized in very limited numbers and maximum ratings are 250 kV, 8 kA or 500 kV, 4 kA, which is not more than 1.6 times the rated nominal current. The breaking time is in the

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order of 35 ms, but as stated before, for CSC-based systems, the large inductances limit the rate of rise of fault current, and this time is sufficiently fast. However, the components of these breakers are very large and more costly than ac CBs with comparable current and voltage ratings [1] [2]. In point-to-point HVDC transmission systems, the function of dc breakers has thus typically been substituted by de-energizing the converter stations (e.g., by acting with the station control or by operating the breakers on the ac side and the opening of isolation switches). In low- and medium-voltage dc applications, short-circuit current interrupting breakers have been realized based on several different technologies (e.g., switching arcs or solid-state switches).

### 2.1 Circuit Topology

Current-limiting DC circuit breakers are based on the power electronic composite switch, and the topology is shown in figure 1. Mechanical switch S using high-speed repulsion switch, the device action time is short, which can significantly shorten the breaking time of DC circuit breakers. Power electronic switch is composed of IGBT valve group T1 and SCR valve group T2 in series, since SCR has larger capacity and static resistance, the voltage-sharing (current-sharing) technology is relatively mature, the combinatorial electronic switch can effectively reduce quantity of power electronic devices and difficulty of voltage-sharing (current- sharing). Current-limiting circuit is composed of the current limiting inductor L, thyristor DL, DL' and energy release resistor RL. When the fault occurs, L is used to limit the rise of short-circuit current. After the fault is removed, the stored energy in L is released by DL, DL' and RL, and the induced overvoltage of L is limited. The freewheeling diode D is used to release the energy stored in the line impedance between the power outlet and the short-circuit point. After the fault is removed, the line impedance freewheels through the freewheeling diode and the short-circuit point. The induced overvoltage will not affect other devices [18] [2].

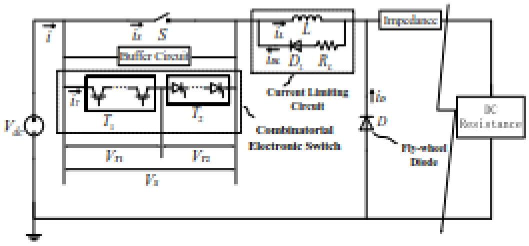

Fig.1 Topology of the current limiting DC hybrid circuit breaker based on a combinatorial electronic power switch

### 2.2 Basic Working Principles of HVDC CBs

The current in a dc circuit can be brought to zero by generating a counter voltage of similar or larger amplitude than the system voltage. This counter voltage can be produced by inserting additional resistance or inductance in the current path. The energy of the dc system is dissipated across this device. The larger the counter voltage, the smaller the time needed to interrupt, but the larger the energy that is dissipated in the device. DC breakers with current limiting and energy dissipating function of an arc are commonly used in LV and MV applications. Some proposals for high-voltage systems have been made, but none of them has proven efficient and successful in real applications [2], [4], [17].

An alternative is to have several parallel paths in the breaker and to separate the requirements to different elements. The simplest is one nominal current path and one parallel path with a linear or nonlinear resistive element. The nominal current path typically consists of an interrupter with low ohmic losses in closed position, which is, so far, only possible with movable metallic contacts. Upon opening of these contacts, an arc is established and its arcing voltage is used to commutate the current to the resistive path where the energy of the system is then dissipated. The advantage is that the interrupter in the nominal current path only needs to produce a voltage sufficient for commutation and not for counteracting on the full system voltage. In addition, the breaker does not have to have a large energy dissipating function, which typically improves its interruption capability. If the commutation path only consists of a linear resistor, the arc voltage of the interrupter still has to be very high. A gradual insertion of resistors or nonlinear resistors to limit the required commutation voltage would be better. The commutation process can be eased by adding other elements, such as a capacitor which temporarily takes the current flow. More recent developments make use of actively controllable resistances of solid-state devices. For most of the practically realized HVDC CBs, separate commutation and energy absorbing paths have been used, as sketched in Fig. 2. The commutation path may then be a series resonance consisting of a capacitance Cc and inductance Lc so that current oscillation between the nominal and the commutation path can occur at the natural frequency $\omega^2 0=1/Lc\ Cc$. If the amplitude of the oscillating current in is larger than the system dc current $I_0$, a current zero crossing occurs in the nominal path, and the interrupter Sn can interrupt the current. Current $I_0$ continues to flow, charging the capacitor Cc in the commutation path. If the capacitor voltage exceeds a given value, typically chosen to be the voltage capability of the breaker or the insulation coordination of the HVDC system, the energy absorption path acts, causing the system current I0 to decrease. If the differential arc resistance dU/dI of the interrupter in the nominal path is negative, a current oscillation between the nominal and the commutation path with increasing amplitude occurs, started by the natural fluctuation in the arc voltage. [2]

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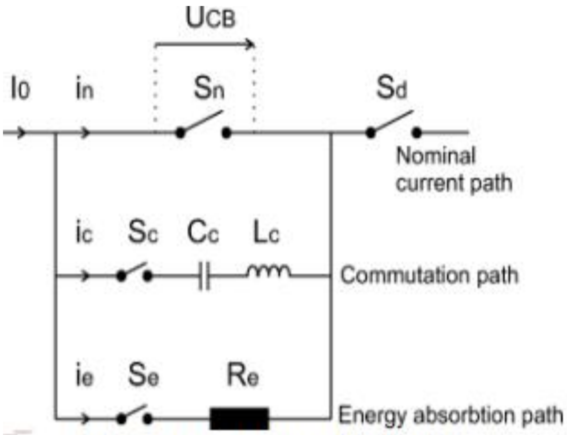

Fig. 2. Basic arrangement of the HVDC CB

## III. MORE RECENT ACTIVITIES AND RELATED FIELDS OF TECHNOLOGY

### 1. Adaptions of the Basic Principle

The basic principle of HVDC CBs, as shown in Fig. 2, and described in the previous section, has been continuously optimized. Special focus is on making better use of the most costly components, the capacitors, and varistors. Methods have been derived to calculate and select the optimum value of the capacitor Cc and to extend the current interruption range. In a configuration with a passive commutation path, a set of criteria is derived based on the characteristic surge impedance Lc/Cc and the characteristic frequency ω0.The criteria are chosen to minimize the interruption time and to enhance the interruption performance. If the configuration of active current injection with the precharged capacitor is chosen, a large Cc/Lc ratio is advantageous since it leads to larger injected current with the same energy stored in the capacitor. Also here, a set of criteria combining the Cc/Lc-ratio with the natural frequency ω0 is chosen to maximize the interruption performance. The current oscillations in the nominal and commutation path of passive arrangements grow if the arc characteristic is negative. A fast-growing oscillation at a high natural frequency leads to faster current interruption. The ac CBs that are typically used as elements in the nominal path are by no means optimized for this. Thus, dedicated investigations studying the arc characteristics under different conditions have been performed and optimizing the breaker was tried. Depending on the selected HVDC technology, the focus of future research in optimizing the existing schemes is placed on one of the directions mentioned before. The requirement of fast interruption will be especially challenging to meet with a classical configuration [1],[6],[7].

### 2. Combined Optimization of Topology, Control, and Breaker

Most of the research on HVDC, multiterminal schemes, and HVDC CBs focuses only on a particular individual aspect. Sometimes the breaker is assumed to be known, and the network control is designed around it. Other times, the requirements for HVDC CBs are set by the system control activities and the breaker has to be designed accordingly. No combined attempts to optimize the system as a whole are reported. It would be thinkable to adjust the control scheme to ease the requirements for CBs. Adding additional inductance to the dc side in VSC-based networks would limit the rate of rise of the short-circuit current and simplify the hard breaking time requirement, but would lead to slower control in normal operation. If high impedance grounding is used, the short-circuit current during dc-line-to-ground faults is limited. Focusing on only one aspect is most probably not optimum as only a combined optimization could lead to the globally best solution. Another example for combined optimization is for VSC schemes using multilevel converters. Voltage levels at a fraction of the total dc line voltage occur inside the valve and, in principle, it would be possible to interrupt at these levels. The respective dc breakers would have a lower voltage rating, but the topology of the valves needs to be redesigned to incorporate dc breakers. Only a combined effort of valve and breaker design would lead to a satisfying result.

### 3. Solid-State DC Breakers

Also discussed are pure semiconductor switches, not only for HVDC, but also for low- and medium-voltage dc and ac. The clear advantage is that the switching time can be as low as a few microseconds, compared to a few (ten) microseconds of a mechanical switch with separating metal contacts. The main drawbacks are costs and the fact that the resistance in conducting mode is in the order of a few mΩ and, thus, considerably higher compared to a few μΩ for a mechanical switch. The full forward conduction losses of the solid-state devices are ~0.10.1–0.4% of the transmitted power. The application of semiconductor switches was thus typically limited to applications where high PQ is of crucial importance and the minimum breaking time is absolutely needed. As stated before, the rate of rise of short-circuit current in VSC-based HVDC networks is very high. So far, no other HVDC CB concept is available with breaking times in the order of

1 ms and, thus, a solid-state switch is the only feasible solution today. A single semiconductor device is not able to withstand the full voltage and current rating, but a series and parallel arrangement of several switches is possible to achieve HVDC CB ratings.

### 4. Semiconductor Devices

The performance of semiconductor devices continues to increase constantly, not only in blocking voltage rating, but also in maximum current rating for a single chip. In the future, HVDC valves and potentially also HVDC CBs can be realized with fewer components, which improves the performance and decreases the losses. Today, all devices are based on silicon and an even bigger step ahead would be the change of semiconductor material to a wide bandgap material. SiC, GaN, and diamond have been discussed and are intensively investigated.

### 5. Hybrid CBs

It was already stated in the previous section that semiconductors have high conduction losses and are thus not optimal as inline switches or CBs. Hybrid switching schemes are therefore proposed. Here, the nominal current path contains a mechanical breaker with low-resistive metal contacts that are separated quickly, causing the current to commutate to a parallel path with the semiconductor switch. When the current is transferred and the dielectric strength between the metallic contacts has recovered, the semiconductor switch is operated. Schemes are proposed for ac CBs; ac capacitor switches; fault-current limiting units; and for dc CBs. [1],[8],[10].

### 6. Fast Switches

One of the key devices for hybrid dc CBs using solid-state switches is a very fast mechanical switch with low conduction losses in the nominal current path. These fast switches have to operate in <1 ms and to build up sufficient arc voltage to cause the current to commutate to the interruption path. Concepts for fast switches based on electromagnetically driven contacts in air or vacuum CBs have been developed. In low-voltage networks, these switches also have a current limiting function and ratings for CBs have reached 4 kA/1.5 kV with breaking time ∼300 μs. The requirements for fast switches in hybrid breakers operating in <1 ms are independent of ac or dc. For high-voltage systems, new concepts or series arrangements of many switches would be necessary and research should be carried out in this area.

### 7. Fault Current Limiters

Many of the concepts to fulfill the basic requirements of an HVDC CB, as discussed before, are also applicable for fault current limiters (FCL) in ac and dc systems. The task of fault current limiters is, as the name implies, to limit the maximum overcurrent in a power system when a fault occurs. The FCL thus needs to increase the impedance of the systems, either self-triggered or externally triggered. The FCL has to be effective before the peak current is reached, typically 1–3 ms in 50-Hz ac systems. In addition, the FCL has to handle the large amounts of energy dissipated during the limitation. In addition, some FCLs also interrupt the current. If they cannot do so, a load break switch has to be placed in series to interrupt the limited current. Some review articles have been published and the details of FCL will not be repeated here. Amongst the different operation principles are solid-state fault current limiters (SSFCLs) and hybrid concepts using fast mechanical switches. Both concepts have been discussed before, but have not been realized for high voltages so far. Medium-voltage fuses work as self-triggered FCL with interruption capability, but they are one-shot devices which have to be replaced manually and are widely available only up to 10–20 kV. Superconducting fault current limiters (SCFCLs) of resistive type make use of the intrinsic physical property that superconductors lose their zero resistance above a critical current density. These types of fault current limiters have low conduction losses in nominal operation, are fast and resettable, but require extensive cooling of the material to reach the superconducting state. Resistive SCFCLs could be used as fast-acting commutation switches placed in the nominal current path, but disconnectors have to be placed in series since the SCFCL has no voltage withstand capability.

## IV. COMPARISON OF TECHNOLOGIES

In this section, different technologies are compared in terms of interruption time, power losses, voltage and current rating.

### 1. Interruption time

As it is expected the mechanical circuit breakers have the snappiest switching response up to 60ms while the pure semiconductor based circuit breakers are expected to reach the interruption times below than 1ms. Between these two topologies, hybrid circuit breakers with disconnection time of 2~30ms also represent attractive characteristics for application in high power systems [1], [5]-[17].

### 2. Power losses

The mechanical circuit breakers and the hybrid ones with no semiconductor devices in main path of current have the lowest power losses among all configurations. The reason for this is a very low voltage drop on the metal contacts of main circuit breaker. The power losses for these topologies are less than 0.001% of the VSC station power losses. Additionally, the hybrid topologies with low rating semiconductor switches in the main path of current also represents

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reasonable power losses. In this type of circuit breaker, the power losses are no more than 0.1% of power losses of a VSC system. On the other hand, pure solid-state configurations suffer from high power losses. Since there are many IGBTs or other semiconductor devices in main path of current in these topologies the total voltage drop of circuit breaker is relatively high. The power losses for this technology in comparison with a VSC station can reach to 30% [5]-[17].

**3. Voltage rating**

Nowadays, mechanical HVDC circuit breakers with nominal voltage up to 550kV are available. Hybrid circuit breakers also have been verified by experimental tests up to voltage rating of 120kV and it is expected that to reach up to 320kV level. Pure semiconductor circuit breakers are not available in high voltage and power ratings and only have been designed and implemented for operation in medium voltage applications. But considering the developments in semiconductor devices it is anticipated that 800 kV voltage rating is achievable [5]-[17].

**4. Current rating**

Mechanical HVDC circuit breakers are able to interrupt currents up to 4kA with passive resonance system while they can interrupt up to 8kA with active resonance circuit. For hybrid circuit breaker topologies, current interruption level of 9 kA has been proved experimentally and in theory levels up to 16kA is achievable. Considering the expected high voltage rating for pure semiconductor circuit breakers, 5kA current interruption rating is reasonable for them [5]-[17].

## V. CONCLUSION

Nowadays, the main obstacle against the realisation of HVDC grids is lack of mature HVDC fault current breaking technologies. In this paper the present technologies of HVDC circuit breakers were summarised and compared. All of presented breaking schemes have limited capabilities in interruption of permanent fault current and need to be significantly improved. In terms of mechanical circuit breakers as the basic devices for fault current interruption, attempts should be concentrated in optimization of size of resonance circuit's elements. Also the behaviour of arc chamber needs to be improved to reach higher current rating.

Since hybrid circuit breakers present more efficiency and acceptable interruption speed, the development of faster mechanical switches with high surge voltage withstand and low concoction losses can lead to more improvements in this area. In terms of solid-state circuit breakers, application of new wide-band-gap semiconductors like SiC or GaN based switches should be investigated. Also active gate driving technologies can improve the performance of semiconductor switches in pure solid-state circuit breaker. Moreover, accurate dynamic models for semiconductor switches with validity in high voltage and high currents to be used in designs and simulations are necessary to be implemented. In order to provide the possibility of distinguishing the permanent faults from transient grid events applications of DC fault current limiters in HVDC networks can be interesting to study.[1] [2]

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