HVDC CIRCUIT BREAKER: A REVIEW ON CHALLENGES AND INNOVATIONS

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ABSTRACT
The inevitable shift from fossil fuels to regenerative sources imposes a great challenge for future power transmission scenario. A large and meshed HVDC-Grid is proposed by experts as the best and most efficient solution. And for meshed DC-Grids, the most essential requirements are guarantee for fast and reliable handling of DC-faults without disturbing the energy flow in the whole grid. The following paper presents the key component i.e. DC-Breakers in large meshed HVDC-Grids. This paper aims at summarizing functional analysis of HVDC circuit breakers technologies including recent challenges and attempts in development of improved HVDC circuit breakers. Additionally, different technologies from derived information from literatures are compared. And finally, recommendations for improvement of circuit breakers are presented.

Key words: Current Source Converters, Circuit Breakers, Discharging Current, High Voltage Direct Current, Voltage Source Converters.

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1. INTRODUCTION
The AC transmission and distribution was eventually opted and grew due to transformers that allow seamless control over voltage levels for power transfer. However today, with the ever increasing demand of energy, with larger distances between generation and load centres and dearth in natural resources; has caused the inevitable change in the nature of power transmission. Ironically, DC proves to be the favourable option realizing growing need of economical, efficient and flexible transmission technology instead of prevailing inefficient system. Recently, there has been an upward growing trajectory in the percentage of renewable source generation as compared to overall generation added to the power system and thus the way power is generated and transmitted has changed in the past few years, as these renewable
sources are located far from the load. This trend is expected to increase and hence HVDC transmission proves to be the economical and feasible option.

For HVDC practical applications mostly transfer and load current switches are used which are based on two major HVDC technologies: - current source converters (CSC) and voltage source converters (VSC). After, considering the differences between the two, researchers have agreed on VSC-HVDC as the enabling technology for realization of future offshore HVDC grid and thus for efficient operation of a system it is advantageous to set up a multi-terminal type network based on VSC [1][2]. But, the main problem is in a multi-terminal network where one faulty section will affect the stability of the entire system. To prevent this, therefore, it is necessary to use an HVDC circuit breaker that can quickly isolate a faulty section from the system [4]. Also the usability of HVDC networks with respect to efficiency, reliability, and controllability is largely dependent on the performance of HVDC circuit breakers, making them a key enabling technology.

Various proposals for breaker designs had been presented in papers and patent applications but most of the innovations address only a few aspects of the many requirements, but no significant contribution has been given to conclude with an overall picture. So, the main aim of this paper is to represent the current working scenarios and areas where research and development is required in HVDC CBs. Such that by reviving the discussion on this subject and citing relevant literature, it might serve as a reference path for others working with HVDC technologies.

This paper is structured as follows. Section 2 reviews the literature on breaker design requirements and standardization for HVDC, followed by current challenges of HVDC CBs with a suitable case study in Section 3 and Section 4, respectively. Innovation in the CBs technology is covered in Section 5, discussing recent inventions and proposals in market contributing in improvement of the breaker technology. By this, future research needs are outlined and summarized in Section 6, which concludes this paper

2. BREAKER DESIGN REQUIREMENTS

2.1. Classical Design

The classical breaker structure combines a series of mechanical and electronic circuit-breaking devices, which redirect a surge in current and then shut it off. Existing mechanical HVDC breakers so far were capable of interrupting DC currents within several milliseconds, but this is still slow and incapable to fulfill the requirements of a reliable HVDC grid function [7]. Therefore understanding the operational aspects and fault clearing methodology of a circuit breaker can help in underscoring the ideal design requirements and scope for an improved circuit breaker.

2.2. Required Design Parameters

In a HVDC Circuit Breaker system, total fault clearing time is comprised of two main parts: breaking time corresponding to a period of rising current, and fault clearing corresponding to a period of decaying current [5][6]. Both of these time intervals are necessary considerations in the design and cost of the HVDC breaker. Practically, breaking time is dependent on the response time of the protection, and the reaction time of the HVDC switch. A longer breaking time means the HVDC switch should have increased maximum current breaking capability. This further increases the energy to be handled by the arrester and correspondingly leads to a costlier HVDC breaker. Therefore it is required to keep breaking time as short as possible. When the
maximum breaking current capability and the breaking time are given, the only adjustable parameter is the HVDC reactor’s inductance, which governs the rate of current rise [6]. Hence, the HVDC reactor needs to be selected in such a way that current should not exceed the maximum breaking current capacity of the HVDC breaker within the breaking time. However, the size of the HVDC reactor may be restricted by factors like cost, and the stability of the grid system.

The time duration of fault clearance will greatly affect voltage dimensioning of the arrester and the pole voltage protection. A shorter fault clearance means reduced power dissipation in the arrester bank, but also a higher voltage dimensioning of the arrester is required. In contrary, an increase in the level of protection of arrester will cause a higher pole-to-pole voltage rating, and thus increasing the costs of the HVDC breaker. Thus, in a HVDC grid connected via HVDC cables, a short-circuit fault must be cleared within 5 milliseconds, in order prevent a converter stations as far away as 200 km or more [6].

This example provides a general idea of the relation between the parameters discussed above [7]. Assuming the breaking time to be 2 ms, possible for semiconductor-based HVDC switches, given that HVDC line fault occur near to the HVDC switchyard, and for a HVDC reactor of 100 mH in a 320 kV HVDC grid, the highest rise of the fault current will be 3.5 kA/ms, provided with 10 percent of maximum overvoltage. For a given rated line current of 2 kA, the least required breaking capability of the HVDC breaker is 9 kA.

2.3. Standardization

In year 2008, IEC (International Electrotechnical Commission) had a new Technical Committee ‘TC 115’ for “High Voltage Direct Current (HVDC) Transmission for DC voltages above 100 kV” [8] and which were treated as standards for HVDC Circuitry and system design. The committee started an operational group WG B4-52 “HVDC grid feasibility study” [9] during the beginning of year 2009. The participants represented were mostly the European research institutes, manufacturers, other potential users and consultants. In the discussion topics of WG B4 were interoperability of a DC Grid with the AC grid, the impact of distant faults (as any fault in a DC grid are notable at a very long distance), costs and various grid configurations with respect to reliability and controllability.

In view of reliability, the grid structure was discussed related to have sufficient redundancy and need for sectionalisation of the net by HVDC breakers and protections for various zones. While DC breakers and protections are yet to be developed effectively, the WG looked at identifying the required breaking current capabilities and operational times. Starting from the standard voltage levels used for AC networks, the WG looked at the possibility of recommending standard voltages for DC Grids [9]. The WG also discussed the aspects of the converter station design that required to be standardised, allowing stations from multiple manufacturers to be connected to a DC grid [9].

3. CURRENT CHALLENGES

As Existing HVDC breakers are capable of controlling HVDC currents within several milliseconds, but practically are too slow to meet the requirements of a reliable HVDC grid operation. Furthermore, building mechanical HVDC breakers is very challenging and requires the installation of additional passive components for creating
a resonance circuit and generating the current zero crossing so the breaker can succeed in breaking the current once it opens.

In present point-to-point HVDC transmission, DC interrupters are used as various different switching duties. A neutral bus switch, neutral bus ground switch, metal return transfer breaker, ground return transfer breaker, high-speed bypass switch for parallel line switching also exist [11]. Interrupters to break DC short-circuit currents have been realized in a 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 order of 35 ms, but for CSC-based systems, the increased inductance values limit the rate of rise of fault current, and this time is sufficiently not fast [12]. Also, the components of these breakers are large and very costly than AC breakers with comparable current and voltage ratings.

The difficulties in realizing HVDC breakers can be attributed to the exacting requirements on breakers in DC systems which are quite different than those of ac CBs. One of the major difference is the absence of natural current zero occurring in DC systems. The breakers have to fulfil the basic requirements as follows:-

1. Obtain a current zero crossing to interrupt the current.
2. Dissipate the energy stored from the system inductance.
3. Withstand the voltage response after current interruption.

In particular, the first two requirements lead to interaction between the breaker and DC system, an attribute which is also very different than AC breakers. In addition to these basic requirements there are additional secondary requirements as per the breaker application, as follows:-

1. In VSC-based systems, the HVDC breaker should be able to interrupt instantaneously.
2. The maximum voltage generated by the breaker must be less enough to comply with the insulation system of the DC system. This is important for switching of load currents where the network is at nominal voltage [12].

As it is mentioned before, use of VSC for developing multi-terminal HVDC systems is advantageous but there are many significant drawbacks in implementing multi-terminal systems based on VSC-HVDC. One of the problems about the VSC systems is the power losses. Switching valves of the VSC are responsible for large losses. Research activities are being carried out to reduce the losses to <1% [12].

Additionally, the anti-parallel diodes integrated with IGBT modules in VSC act as an uncontrolled rectifier even if IGBTs are turned off. For this reason the VSC becomes defenceless against a DC short-circuit fault and the fault is only limited by AC side of VSC. Moreover because of small inductance of DC side of the VSC-HVDC systems, the rate of rise of DC fault current is comparatively very high and even in some faults the capacitors of DC link of VSC discharge and thus contributing to the fault current and increase rate of rise of it.

Developing a fast and reliable mechanical HVDC breaker is a really demanding task. Semiconductor-based HVDC breakers can easily overcome the limitations of the operational speed and voltage, but they also generate large transfer losses - in the range of 30% of the losses of a VSC station.

4. CASE STUDY

NorNed is a HVDC link connecting the 300 kV transmission systems in Norway with the 400 kV transmission system in the Netherlands [13]. The transmission capacity is
700 MW with the voltage of ±450 kV. The 580 km HVDC cable is the longest submarine cable in the world that was commissioned in 2007.

In case of AC power system faults like phase-to-phase short circuits and phase-to-earth faults, there was a risk that commutation failures may occur in the HVDC converter which might result in discharge of the DC cable capacitance and the discharge current in some instances be injected into the AC system through the valve bridge and converter transformers. As the NorNed cable is very long the discharge current will be of considerable large magnitude. The DC discharge current will so be superposed on the AC fault current. The resulting shape and magnitude can vary depending on different factors but the DC discharge pulses often cause total fault currents without any zero crossings.

The fault currents were calculated from a PSCAD model of the Statnett 300 kV transmission system including both Skagerrak and NorNed HVDC links [14]. Each test series comprised 350 intentionally difficult shots, 175 internal and 175 external faults. It was repeated three times, all together 525 internal and 525 external shots. There were all together 6 unwanted operations and all were three-phase faults in the future case with NorNed link duplicated with a second HVDC cable and with 75 % remanence. Further fine-tuning of some setting should probably prevent also these operations. For the internal faults the average operate time was 24 ms, minimum 20 ms and maximum 38 ms. The operate time was > 30 ms for 14 faults. All of them were in cases with low fault currents and with 85 % remanence.

It was also concluded that the relay manufacturers’ guidelines regarding requirements for dimensioning of breakers are based on normal conditions in AC power systems and do not consider such extreme cases as DC discharge currents from HVDC cables. Therefore, dimensioning of the breakers should be based on additional studies in these cases. Also, the standard setting recommendations from the relay manufacturers are based on conditions in normal AC power systems but it should be possible to use the final settings of the protection identified during these tests as default settings in similar applications.

5. INNOVATIONS IN BREAKER TECHNOLOGY

There have been a number of innovations in HVDC transmission, such as ABB’s Light [15], Siemens’ HVDC Plus and Alstom’s HVDC Maxine in the field of Voltage Source Converter based solutions. However all these technologies are improved versions of existing technologies. Therefore, they can be viewed as incremental innovations, given that their role is limited to improving the performance of existing structures.

5.1. Hybrid HVDC Circuit Breaker

The methodology of integrating solid-state devices and a mechanical breaker in a combined configuration is called the hybrid switching method. Normally, in a hybrid CB, the commutation path is introduced by solid state switch that only operates during the interruption process, where all the switches are controlled by electronic circuits.

In November 7, 2012 ABB [16] announced a breakthrough in the technology to interrupt DC by developing the world’s first Hybrid circuit breaker for HVDC. It combines mechanics with power electronics, making it capable of interrupting power equal to output of a large power station within 5 milliseconds. Following that, recently there are many on-going researches on hybrid HVDC circuit breakers that combine power semiconductors and mechanical switch in an effort to improve
problems of classical DC circuit breakers and solid-state circuit breakers. A brief idea and working structure of a basic Hybrid HVDC CB is described as follows.

As presented in Figure 1, the hybrid HVDC breaker is made of an additional branch, a bypass formed by a semiconductor load-commutation switch in series with a mechanical disconnector [17][18]. The main semiconductor based HVDC breaker is separated into different sections with individual arrester banks designed for full voltage and current breaking capacity, whereas the load-commutation switch matches low voltage and energy capacity. After fault clearance, a disconnecting breaker isolates the line from the HVDC grid by interrupting the residual current and, thus protecting the arrester banks of the HVDC breaker from thermal overload.

![Figure 1 Hybrid Circuit Breaker Block Design][16]

During the normal operation, current will only flow through the bypass, while the current in the main breaker is zero. When HVDC fault occurs, the load-commutation switch opening the fast disconnector immediately and commutates the current to the HVDC breaker. With the mechanical switch opened, the main HVDC breaker interrupts the current. During current breaking, the mechanical switch isolates the load-commutation switch from the voltage across the main HVDC breaker. Thus significantly reducing the required voltage rating of the load-commutation switch. A successful commutation of the line current in the main HVDC breaker path requires a voltage rating of the load-commutation switch more than the on-state voltage of the breaker, which is typically in the range for a 320 kV HVDC breaker.

Pulse mode operation of the main HVDC breaker, Fig 2, will allow adapting the voltage across the main breaker to the instantaneous voltage level of the HVDC grid [18]. Due to the proactive mode, over-currents in the line or switchyard protection will initiate the current transfer from the bypass into the HVDC breaker prior to the trip signal of the backup protection. As shown in Figure 2, proactive current commutation is started by the hybrid breaker’s built-in overcurrent protection at the moment when HVDC line current exceeds a certain overcurrent level[18]. The HVDC breaker delays the process of current breaking until a trip signal of chosen protection is received. A further rise in the line current is prevented by the main breaker by controlling the voltage drop across the HVDC reactor to zero.
The transfer losses of a hybrid HVDC breaker are thus reduced to a percentage of the losses incurred by a semiconductor breaker (which is only 0.01% of the transmitted power). The mechanical switch opens at zero current with very low voltage stress, and can thus be recognized as a disconnector with a lightweight contact system. However, the fast disconnector will be exposed to the pole-to-pole voltage defined by the protection level of the arrester banks after being in open position while the HVDC breaker opens. Hybrid switching devices are also in great demand, especially for DC traction systems, but that will have to be accompanied by the availability of high power rated semiconductors, having turn-on and turn-off times of microseconds.

The Hybrid breaker has several advantages as follows:

1. The hybrid design has very less losses, while preserving the ultra-fast current interruption capability.
2. The hybrid breaker has relatively low contact resistance and hence low power loss.
3. The hybrid breaker has better frequent switching ability.
4. They have the good overload capability than mechanically operated breaker and have good level of contact reliability.
5. Size and volume of the hybrid breaker is lower than the solid state breaker.

5.2. 5000A DC Commutation Breaker

Siemens recently implemented DC commutation breaker for largest rated DC current of 5000A that successfully passed switching test at the Shuanglong converter station in China [19], as shown in Figure 3. Siemens supplied DC commutation breakers for the ultra-high-voltage DC (UHV DC) transmission project Xiluodu-Zhejiang. The DC commutation breaker is applied in the DC yard as Metallic Return Transfer Breaker (MRTB) allowing the re-configuration of DC circuit. It basically provides capabilities to commutate the inter-path DC currents i.e from metallic return to earth return. With this new innovative technology Siemens enables reliable transmission which is also clean & CO2 free power at highest loads. Starting operation in July 2014 the 1670 kilometer (km) [19] power link transports clean hydropower at a voltage level of ± 800 kilovolts (kV) from Xiluodu hydropower station in Sichuan province to the highly industrialized Zhejiang province.
5.3. Bi-Directional Breaker Prototype

A recent experimental study done at KONKUK University, South Korea undertaken by Choul Kim and Hwan Chung, proposing a novel HVDC circuit breaker suitable to DC grid [20]. Their proposed HVDC circuit breaker features bi-directional conduction and interruption and can interrupt a high current in a very short time. In this study, a prototype of the proposed HVDC circuit breaker was developed and a test of current interruption was conducted. A fault current was generated by charging up a large capacitor bank to a certain voltage level and discharging through an inductor for limiting current rise rate. The generated fault current was energized to the DC circuit breaker and then interrupted when it reaches a certain current level.

As shown in Figure 4; it has no on-state loss as there is no semiconductor switch on the conduction path in normal operation, and provides bi-directional interruption despite using only one fast mechanical switch. The proposed HVDC circuit breaker uses a method of interrupting a fault by generating a forced zero current by injecting a reverse current through active resonance [20].

When a fault occurs in the opposite direction, the circuit breaker can interrupt it through a similar movement. Interruption of a unidirectional fault using PSIM (when

![Figure 3 Siemens DC commutation breaker][19]

![Figure 4 Bi-Directional HVDC Circuit Breaker Design][20]
a fault occurs in the right side of the DC circuit breaker) was simulated. It is expected that the proposed HVDC circuit breaker can be made at relatively lower costs as it uses a smaller number of thyristors and mechanical switches, while still providing the performance similar to that of classical hybrid HVDC circuit breakers [20].

6. FUTURE RESEARCH NEEDS

Through the previous sections of the paper, several technological limitations and physical barriers are discussed that are hampering the effectiveness and reliability of a HVDC CB [21]. So, a great deal of future research and developments are required in order to improve and overcome the aforementioned conundrums. These areas are summarized as follows:

1. Optimization of the existing basic HVDC CB technology by optimizing the size of elements, such as capacitors and inductors or charging units. The main goal is to reduce the size, interruption time and overall costs [22].

2. Optimization of switching arcs for the growth of oscillations and the capability to be interrupted, by detailed investigation of arc characteristics under different conditions of gas and vacuum CBs.

3. Use of Pure semiconductor switch with negligible on-state losses. Like, with use of various wide bandgap semiconductor devices such as SiC or GaN.

4. Extension of medium-voltage to higher voltage level CBs by either improving the methodology of series connection and by connecting breakers across medium level voltages in multilevel converter topologies.


6. Combined optimization of the whole system, mainly by breaker-control protection.

7. Fast mechanical switches with high recovery voltage threshold and low on-state losses. Ideally, these switches have sufficient arcing voltage for fast commutation.

8. New testing methods for HVDC CBs and its individual components. As there is strong interaction between breaker and network, power-hardware looping techniques can be advantageous.

9. Establishing further standards and norms for multi-terminal HVDC.

Like, plans for using embedded VSC-HVDC transmission across overhead lines as point-to-point system have been proposed, e.g. Germany, in the plan called Netzverwaltungspolitik (Network Development Plan), 2012. New generation from remote and offshore sites such as renewable sources, are implementing the technology for VSC-HVDC systems in the areas of active power transmission and reactive power compensation. In this the hybrid VDC breaker can provide the additional benefit of interrupting HVDC line faults and the fast fault handling would make it possible for the converter stations to operate as stand-alone static compensation units (STATCOMs), empowering the stations to stabilize voltage and augment to transmission capacity in the AC grid during fault clearance.

7. CONCLUSION

Privatization and deregulation are posing various challenges to the existing transmission systems. Active elements will be loaded up to their maximum thermal limits and wide-area power trading with rapidly changing load patterns will contribute to dangerously increasing power congestion. In addition, the dramatic global climate developments calls for changes in the way electricity is supplied. Consequently, we
have to deal with an area of conflicts for reliability of supply, environmental sustainability and economic stability.

So, the power grids of the future must be secure and reliable, cost-effective and environment compatible. With use of Power Electronics, they provide features which are mandatory to avoid technical problems in the power system, as they increase the transmission capacity and system stability very efficiently and help in prevention from cascading disturbances. Reliable and zero loss HVDC breakers and current limiters designed on the hybrid HVDC breaker concept are under continuous development and also have been verified at component and system levels at high power laboratories in Sweden and Switzerland for DC voltages up to 320 kV and rated currents of 2 kA.

The next step is to deploy these breakers in a real HVDC transmission line to test under extreme full load conditions. Innovative solutions for HVDC have the potential to cope with the new challenges.

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