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A Review paper on HVDC Circuit Breakers

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***Abstract*- Over the last 60 years High Voltage Direct Current (HVDC) power transmission has gained serious popularity; suggesting a valid alternative to the currently, almost exclusively used, AC power transmission. The technological innovations of the last 20 years on the electrical converters made HVDC an even more promising solution on energy distribution and transmission. A lot of work has been done on the area but only two three terminal systems have been realized. 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.**

***Index Terms*—HVDC circuit breakers (CBs), HVDC interrupters, HVDC transmission, HVDC converters, VSC, CSC.**

I. INTRODUCTION

There is now greater attention to careful and thorough studies of the dynamic interactions between the dc and ac systems, because of the increasing interest in the use of hvdc transmission to carry large amounts of power between weakly interconnected ac systems [2]. High voltage direct current (hvdc) technology has characteristics that make it especially attractive for certain transmission applications.

HVDC transmission is widely recognized as being advantageous for long-distance bulk-power delivery, asynchronous interconnections, and long submarine cable crossings. The number of HVDC projects committed or under consideration globally has increased in recent years reflecting a renewed interest in this mature technology. [4]

The scene of electric power systems has changed drastically and will continue to do so in the years to come.

Causes of this evolution are the liberalization of the electricity markets and the increased use of intermittent renewable energy. Uncertainty in the transmitted power and congestion of the lines raise the need for new technologies. High Voltage Direct Current (HVDC) is one of these emerging technologies that may have a major impact, and more specifically Voltage Source Converter (VSC) HVDC[6].

In recent years, the interest in HVDC multi terminal sys- tems has been revived. The continuously increasing demand for electric power and the economic access to remote renew-able energy sources such as off-shore wind power [1] or solar thermal generation in deserts require an electric energy transmission system that bridges very long distances with low losses. Traditional HVDC point-to-point systems can help to serve this duty and are available today. Linking more than two HVDC terminals to form a meshed multi terminal HVDC system (network) would have several advantages: the reduction in the number of terminals (reduced costs and losses), the outage of one dc line does not interrupt the power flow at any terminal, each terminal can operate at different power and current, and the power exchange with all ac connection points can be fully controlled. It is thus very attractive to explore the realization of HVDC networks. There was considerable interest in multi terminal HVDC systems in the 1980s, but only two three-terminal systems were realized [3].

During the 20th century, HVDC systems used exclusively current source converters, while at that point VSC technology did not exist. Things changed in the 90s when insulated gate bipolar transistors (IGBT) which were a new type of self-commutation high power switches became available [12].

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 appli-cations. All comprise different series and parallel connections of classical ac interrupters, resonance circuits with inductors and capacitors, semiconductors, charging units, varistors, or resistors. Each of the numerous concepts has certain advantages and drawbacks [3].

This paper is structured as follows. Section II tells about the uses of HVDC networks. Special emphasis is placed on the differences be-tween the classical current-source converter (CSC) and the more recent VSC technology and the consequences for HVDC networks. Section III reviews about the HVDC circuit breakers, types of HVDC breakers, their working principle and the related technologies. Section IV concludes the paper.

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 revive 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. HVDC NETWORKS

HVDC systems have two main uses: 1) to connect two ac net-works with different frequencies or different frequency-control philosophies (back-to-back) or 2) to transmit large amounts of power via long distances. Two basic converter technologies are used in modern HVDC transmission systems. These are conventional line-commutated current source converters (CSCs) and self-commutated voltage source converters (VSCs).CSC is based on Thyristor technology and VSC is based on IGBT (Insulated gate bipolar transistor) technology [3][4][12].

IGBTs are three-terminal power semiconductor devices. They offer both high efficiency and fast switching, two factors which are of great importance for HVDC power systems. In addition, they allow the system to be much smaller compared to the use of other more conventional devices. CSC systems could not benefit from the new IGBTS and hence became inferior to VSC-HVDC.

CSC point to point transmission does not require HVDC circuit breakers, since AC circuit breakers can be used instead. Multi-terminal systems though, which use VSC technology, will require HVDC circuit breakers so that the whole system does not have to shut down. We will next analyze circuit breakers and their use in DC grids [12].

Line-Commutated Current Source Converter

Conventional HVDC transmission employs line-commutated CSCs with Thyristor valves. Such converters require a synchronous voltage source in order to operate.

Since thyristors are only turn-on devices, the active power flow of CSC systems is controlled by adjusting the turn-on (firing) and the extinction time instant (overlap) prior to commutation to another valve. Reactive power is consumed by the rectifier at the sending, and by the inverter at the re-ceiving end. This has to be compensated for by filters and additional capacitors on the ac sides. In particular, under transient conditions, the amount of reactive power consumed varies greatly. The power flow is unidirectional. The reversal of the power-flow direction requires a change in polarity of the system, which could be problematic, in particular, for polymeric cable connections. The technology is quite mature and two 800-kV systems have been put in operation recently with power levels of up to 6400 MW (800 kV, 4 kA, bipolar). The losses in one terminal are $\sim$0.7% at rated current, of which the converter transformer contributes $\sim$50% [1][4]. Any surplus or deficit in reactive power from these local sources must be accommodated by the ac system. This difference in reactive power needs to be kept within a given band to keep the ac voltage within the desired tolerance. The weaker the ac system or the further the converter is away from generation, the tighter the reactive power exchange must be to stay within the desired voltage tolerance [4]. This system has lower cost and less station losses than VSC HVDC [13].

Self-Commutated Voltage Source Converter

With the advances in power semiconductor devices and the availability of high-power transistors (IGBTs), it is also possible to use pulse-width modulation (PWM) or multi-level concepts for HVDC power transmission[3]. HVDC transmission using VSCs with pulse-width modulation (PWM), commercially known as HVDC Light, was introduced in the late 1990s. Since then the progression to higher voltage and power ratings for these converters has roughly paralleled that for thyristor valve converters in the 1970s. These VSC-based systems are self- commutated with insulated-gate bipolar transistor (IGBT) valves and solid-dielectric extruded HVDC cables [4].

VSC acts as a constant current source with no need for large filters and reactive power supply. Their roles are reversed when we move on to the DC side. VSC uses a capacitor to store energy and due to this capacitor no additional DC filtering is required. This is not the case for CSC. Another advantage of VSC-HVDC systems is that the power flow in VSC-HVDC can simply be changed by changing the direction of the current, while in the case of CSC the DC voltage polarity had to be altered which is hard to achieve. Therefore it is clear that multi-terminal systems are only feasible with the use of VSC technology [12]. VSC HVDC technology transmits active power and can provide the required amount of reactive power at both the power sending and the power receiving end. This also allows a reduction of the filter size. However, the losses in one VSC terminal are ∼1.6%, of which the converter valves contribute almost 70%. The largest realized VSC-based HVDC system is 150 kV, 400 MW and a 300-kV, 800-MW system is in the planning phase [3]. Due to this vulnerability to dc-side faults, VSC HVDC stations are preferably connected by cables rather than overhead lines since cables are much less sensitive to environ-mental influences.

VSC technology is advancing rapidly. New concepts have been proposed and partly demonstrated on a small scale. The aim is to reduce losses to <1%, to reduce the harmonics content, and even to have the ability to limit and extinguish the current in case of dc-side faults.

The question as to whether it is better to base an HVDC network on CSC or VSC cannot be answered unambiguously. To each technology, there are certain advantages and disadvantages. CSC HVDC is well established and has a higher power rating combined with lower losses. But a fault on the ac side can lead to commutation failures which results in a collapse of the dc line voltage.. A CSC-based network is thus vulnerable to ac-side faults. A VSC-based network, in turn, is vulnerable to a dc-side fault. As stated before, any dc-side fault will result in a fault cur-rent with steeply increasing amplitude. Moreover, CSC requires relatively strong ac sources and consumes reactive power at every terminal location. In contrast, a VSC-based network could help to strengthen regions with weak ac systems by its independently controllable active and reactive power. A reversal of power-flow direction for one terminal of the network is straight-forward for VSC-based systems. In CSC-based systems, the voltage polarity would have to be changed, subsequently affecting the power-flow direction at all terminals connected to the common dc voltage line. . The choice of technology is particularly important for the HVDC CBs since it determines the requirements on the HVDC CB, which would be consider-ably different. If the basis is VSC, the breaker has to be very fast and has to have very high current interruption capability [3].

TABLE I
KEY DIFFERENCES BETWEEN THE CSC- AND VSC-BASED HVDC SYSTEMS [3][4][12]

	CSC based	VSC based
Basic element	Thyristor	IGBT
Losses	0.7%	1.6%
Reversal of power flow direction	Change of pole voltage	Adjust PWM voltage but keep voltage
DC side inductors	Large	Small
DC side capacitors	Small	Large
Reactive/Active power	Consumes large amount of reactive power	Reactive and active power can be fully controlled on both ends
Maximum polar rating	Upto 6400MW(800kV,4 kA)	Greater than 400-800MW(300kV)
Requirement of HVDC circuit breaker	Point to point based on CSC does not require HVDC circuit breakers	Multi terminal systems using VSC

		technology require HVDC breakers.
Black start	No	Yes
Cost	Low	High

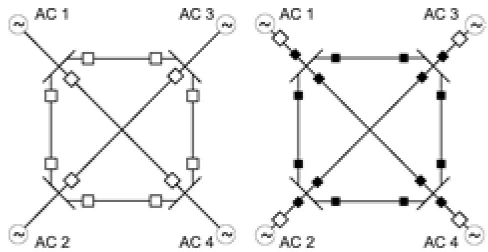

Fig1:Samplecomparison of the HVDC network configuration based on point-to-point systems (left) or with the use of HVDC CBs (right). Converter terminal□, HVDC CB:■. [3]

From figure 1 we can see that there are various advantages with the system having HVDC circuit breaker and these advantages are:

1.) There are less number of converter stations with the use of HVDC CB so the cost is reduced.
2.) In point to point system, in case a fault occur at the sending end then the whole system will fail but in other case the fault will be recovered by the HVDC breakers so the system won't shut down.
3.) each station can transmit (send or receive) power individually and can even change from receiving to sending power without requiring that another station do the opposite.

The availability of HVDC CBs is thus a key enabling technology for the reliable and economic operation of multi terminal HVDC systems. Supporting HVDC CBs with fast action of the terminal controls is undoubtedly advantageous and should be investigated further[3].

III. HVDC CBS

Circuit breakers will be positioned on DC grids and act when a fault occurs. Breakers would have to fulfill some basic requirements. Current zero crossing should be created to interrupt the current once a fault occurs. At the same time the energy that is stored in the system's inductance should be dissipated and the breaker should withstand the voltage response of the network [12].

HVDC circuit breakers are used in the HVDC transmission
lines to reroute the direct current (DC) current during reconfiguration of the main circuit and to help extinguish fault current while system fault occurs. In multi-terminal systems the HVDC circuit breakers give the operational circuit changes with an uninterrupted power flow or rapid restoration of the power flow following a fault [11].

HVDC circuit breakers have to fulfill some requirements:

1.) Create a current zero crossing to interrupt the current.

2.) Dissipate the energy stored in the system inductance.

3.) Withstand the voltage response of the network after current interruption.

There are two types of HVDC circuit breakers:
1.)Electromechanical and
2.) Solid-state

Electromechanical Circuit Breakers

The breaker consists of three parts:

-The **nominal current path** is where DC current passes through and the switch is closed during normal operation

-The **commutation path** consists of a switch and a resonant circuit with an inductor and a capacitor and is used to create the inverse current

-The **energy absorption path** consists of a switch and a varistor.[12][3]

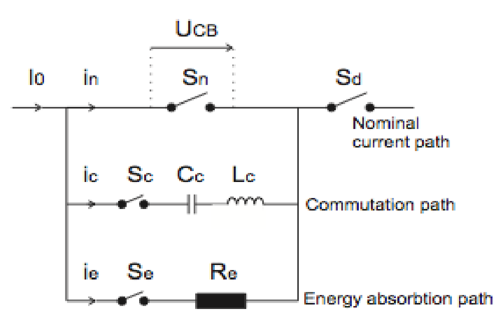

Fig 2: Electromechanical Circuit Breaker

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 [3].The commutation path has a series resonance. When interruption is required, current oscillation can occur between the nominal and the commutation path at the natural frequency (1/LC). If the amplitude of the oscillating current is larger than that of the input current then zero crossing occurs and the switch can interrupt the current in the nominal path. Current (Io) will continue to flow and will charge the capacitor. If the capacitor voltage exceeds a given value, which is chosen to be the voltage capability of the circuit breaker, the energy absorption path will act causing the current to decrease.

This is a basic circuit that would need further implementations to be efficient in high voltages. Reduction in cost and better use of the costly components (varistor, capacitor) will be required. Also, the optimum capacitance value would minimize the breaker's interruption time and improve the whole interruption performance. Furthermore, current oscillations grow when the arc resistance (dU/dt) of the switch on the nominal path is negative. Growing oscillations can lead to faster current interruption. At the same time a large C/L ratio can help maximize the breaker's interruption performance [3][12].

Fig. 3 shows the cur-rents in the different paths of the breaker and the voltage across it. At timet_0, a fault occurs and the current I_0 starts to increase. The interrupter contacts of the nominal current path separate att_1, and an instable oscillation starts due to the characteristics of the arc voltage. Att_2, the amplitude of the oscillation is sufficiently large so that i_n crosses zero and S_n interrupts. The current quickly charges C_c until the threshold voltage level of the energy absorbing elements in the third path is reached at timet_3. Fig. 3 shows the cur-rents in the different paths of the breaker and the voltage across it. At time t_0, a fault occurs and the current I_0 starts to increase. The interrupter contacts of the nominal current path separate at t_1, and an instable oscillation starts due to the characteris-tics of the arc voltage. At t_2, the amplitude of the oscillation is sufficiently large so that i_n crosses zero and S_n interrupts. The current quickly charges C_c until the threshold voltage level of the energy absorbing elements in the third path is reached at time t_3. Nonlinear resistors that are inserted with switch S_e or be non-linear ZnO varistors that become partly conductive only above a certain applied voltage and, thus, do not need an insertion device. The voltage is limited by these elements, current only flows through the energy absorbing path, and the current I_0 of the system ceases [3].

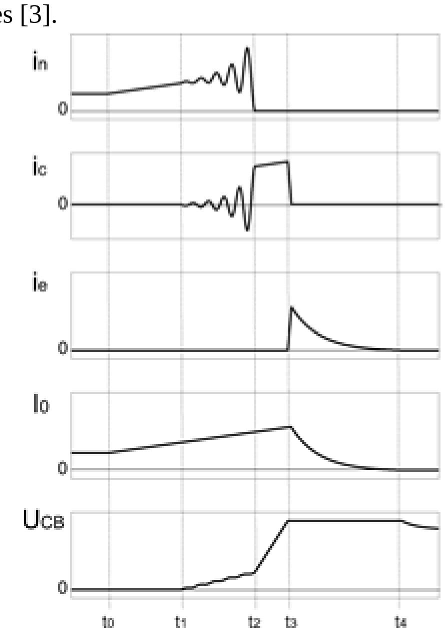

Fig.3: Basic current and voltage development during interruption [3]

Solid state circuit breakers

The second type of circuit breaker we will be analyzing is the solid-state circuit breaker. In the following figure we can see that a solid-state circuit breaker uses gate-commuted thyristors instead of integrated gate-commuted thyristors for semiconductor devices, this is due to the fact that in this topology our immediate concern is lowering the on-state losses.

When there is no circuit failure detected current flows through the GCTs. Once it is detected, the semiconductors are switched-off. This leads to the rapid increase of the voltage until the varistor begins to conduct. Any voltage higher than the grid voltage is blocked due to the design of the varistor. This in turn, leads to the demagnetization of the line inductance[12]

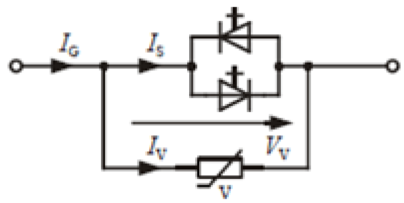

Fig 4: Solid State Circuit Breaker

A.)Comparison between HVAC and HVDC

HVDC and HVAC are the responsible for transmitting high amounts of energy. Although HVDC is not economical for short distances, due to the high cost of the converter stations, it is more suitable for long distances than HVAC. HVAC system has no converter losses when the distance is minimum, however it increases when the length grows [13].

High Voltage Direct Current has been used for decades for transmission of power over long distances. The fact that capacitance in cables doesn't cause losses means that it makes up for drawbacks in the conversion process from AC, since HVDC conversion stations are more expensive than the AC ones. On the other hand, long distance HVDC lines cost in general less than the respective AC lines [12].

Although AC/DC conversion technologies have improved greatly recently, in order to operate a practical HVDC grid, circuit breaker technology still doesn't exist to satisfactorily isolate a single branch line of the grid, meaning that the whole grid would have to be shut down in the event of a malfunction. This means that development of a successful HVDC circuit breaker would be a significant breakthrough for the future of power transmission.

B.)Most recent activities and related fields of technology

1.)Adaptations of basic principle

Vacuum CBs have been proposed as building elements for HVDC CBs [63], [64] since they combine a high interruption performance (large dI/dt with large dU/dt) with small breaking times (<5 ms). Unfortunately, the maximum voltage withstand of vacuum interrupters is limited to MV levels ($U_n \leq 36$ kV) and only a series arrangements could reach high-voltage levels. This is mechanically very demanding and needs to be studied in further detail [3].

Another application of a similar configuration is for the ***magnetic coils of the planned fusion experiment ITER***, which are planned to operate with 70-kA dc current. This leads to a stored magnetic energy of 40 GJ. If a fault in the superconducting coils is detected, this current need to be interrupted and the energy dissipated within $\sim$11 s. The interrupter scheme is composed of a bypass switch in parallel with an interrupter and a counter current injection from a pre charged capacitor. The cur-rent is commutated to a discharge resistor where the energy is dissipated. The nominal current and energy rating are consider-ably higher than for HVDC CBs, but the rated voltage is only 17.5kV and the interruption time is 500 ms.

2.)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 $\sim 300 \mu$s. 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 [3].

3.)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. Most fault current limiters have been designed for distribution voltage levels (<36 kV). For the higher voltages on the sub transmission and transmission level, only limiting reactors and resonance links with inline capacitors have been realized[3].

4.)Testing

A synthetic test circuit, based on the parallel current injection method, was developed in ABB at Ludvika, Sweden, to test the HVDC circuit breakers used in the Three Gorges- Changzhou HVDC Transmission Project [11].

With power-hard-ware-in-the-loop methods, individual component tests could be accelerated and simplified. In this method, only the component of the system which is under investigation is a real physical de-vice. All other components and their interaction with the test object are simulated with a real-time simulator [3].

5.) HVDC Applications

HVDC transmission applications can be broken down into different basic categories. Although the rationale for selection of HVDC is often economic, there may be other reasons for its selection. HVDC may be the only feasible way to interconnect two asynchronous networks, reduce fault currents, utilize long underground cable circuits, bypass network congestion, share utility rights of way without degradation of reliability, and to mitigate environmental concerns. In all of these applications, HVDC nicely complements the ac transmission system[4].

IV. SUMMARY OF FUTURE RESEARCH NEEDS

Throughout the previous sections of the text, several techno-logical areas where research and development is needed in order to improve or enable HVDC CBs were identified and discussed. These areas are summarized in the list below as follows[3].

- Optimization of the existing basic HVDC CB scheme by optimizing the size of elements, such as capacitors, inductors, varistors, or charging units. The main goal is a reduction in size, interruption time, and costs.
- Optimization of switching arcs with respect to the growth of oscillation and capability to interrupt by detailed investigation of arc characteristics under many different conditions for gas and vacuum CBs. Derivation and verification of the parameters are in mathematical arc models.
- Multi physics simulation of HVDC arcs are for high current (growing current oscillation) and interruption phase.
- Extension of medium-voltage CBs to higher voltage levels by either improving the technology, series connection, or by applying breakers across medium-voltage levels in multilevel converter topologies.
- Pure semiconductor switch with minimal on-state losses. Use of new wide band gap power semiconductor devices (e.g., SiC or GaN).
- Fault current limiters for medium and high voltage.
- Combined optimization of the whole system: breaker-control protection.
- New testing methods for HVDC CBs or its individual components. Due to the strong breaker-network interaction, power-hardware-in-the-loop techniques would be advantageous.
- Standards and norms for multi terminal HVDC.

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