HVDC Fault Current Interruption Technology

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***Abstract*—This paper describes the interruption principles and technology of fault current interruption in HVDC systems. First, an overview on switching in HVDC systems is provided, followed by a description of the technology of fault current interruption using HVDC circuit breakers. Then, the actual state-of-the-art of HVDC circuit breaker technology and its application is highlighted. Finally, recommendations on testing of HVDC circuit breakers and the actual status of standardization activities are discussed.**

I. Introduction: Switching in HVDC systems

The common denominator of switchgear is that this equipment changes the energy flow, the current. It can do so in two ways. One is *commutation*: transferring a current into an alternative path, and the other is *interruption*: stopping the current right away.

As in AC, also in DC a distinction is made between switches and circuit breakers. Switches commutate current, deal with currents up to the normal load current and are not designed to interrupt fault currents, whereas circuit breakers can interrupt any current below their rated short-circuit breaking current.

Interruption is a far more onerous duty for a switching device than commutation [1]. The main difference is in the voltage across the switching device after the current flow has ceased. In case of commutation, the current continues to flow in a parallel path and the voltage across the open contact of the switch is only the voltage drop across the parallel impedance. This voltage is much lower than the system voltage, including its transients, that would appear when no parallel path would be present. The situation is outlined in Fig. 1, showing interruption (left) and commutation (right).

In addition, the current level to be dealt with by a commutation switch is far below the fault current level. Another major difference is the required operation speed: commutation processes in DC switchyards do not need to be performed with great urgency, whereas fault currents need to be cleared extremely rapidly because of the high rate-of-rise of the fault current and (in VSC systems) a quick collapse of the system voltage after a fault.

Last but not least, circuit breakers have the function to dissipate energy that is stored in the HVDC system. This is a major function of this type of switching device.

In 2017, CIGRE Technical Brochure 683 “Technical requirements and specifications of state-of-the-art HVDC Switching Equipment” [2] was issued. In this document, a large variety of HVDC switchgear is summarized, explained and analysed. Based on their functions DC switching devices are categorized as:

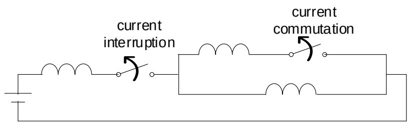

Fig. 1: The two switching duties: current interruption and current commutation

- DC commutation (or transfer) switches: Type of high-speed (< 1 s) DC switch specifically designed to commutate load current into an alternative parallel current path;
- DC earthing switches and disconnectors: providing high- or normal speed safety earthing and/or isolation of components or conductors;
- DC parallel switches: allowing two or more lines to be connected in parallel or to revert to single-line operation while conducting load current (line paralleling); allowing additional converter(s) to be connected in parallel or disconnected without affecting the load current in the other converter (converter paralleling);
- DC bypass switches: designed to close rapidly in order to bypass a converter group that is being taken out of service and commutate the current back into a valve group that is being taken back into service;
- DC circuit breakers: having the duty to make and break fault current. This is the main focus of this paper.

In order to start up standardization, mid-2019 IEC TC17/17A has set-up six working groups covering requirements and tests of DC switchgear (>1.5 kV). In addition, Chinese standards have been issued on DC switches[1], and a draft standard on DC circuit breakers is in preparation.

In CIGRE, JWG B4-A3.80 is presently studying HVDC circuit breakers, whereas WG A3.40 is focusing on MV DC circuit breakers.

II. Fault current Interruption in DC systems

Fault current, and thus its interruption in DC systems differs from that in AC because of the following [3]:

1. There is no natural current zero in DC. This implies that there is no moment where the magnetic energy $½Li^2$ is

[1] GBT25091-2010 on HVDC disconnectors and earthing switches; GBT25307-2010 on HVDC bypass switches and GBT25309-2010 on transfer switches

zero (L is the system inductance). In AC interruption, current zero is the opportunity to interrupt. AC current interruption takes place when there is no more energy in the system [4]. In DC, the DC circuit breaker has to absorb the energy in the (faulted part of the) system. As an example, the energy stored in a 100 km faulted line, where 15 kA of current passes through is around 11 MJ. Converted into mechanical terms this is equivalent with the kinetic energy of a 30 ton truck running at 100 km/h, that has to be stopped in a matter of milliseconds. Whereas a buffer would be designed to stop the truck, sustained *counter voltage*, generated by the DC circuit breaker has to counteract the DC fault current.

2. The final value of the fault current in DC systems is only limited by the resistance (R) in the current path, whereas in AC systems it is the inductance (L) of the conductors that limits the fault current. In power systems, $R << \omega L$ (standardized value of $\omega L/R = 14\text{-}17$). This implies that, provided the DC source is strong enough, very high DC fault currents can emerge. This means DC breakers need to act fast, in the order of 10 times faster than AC breakers, in order to interrupt at a reasonable momentary current (15-25 kA in HVDC systems). Though this current is much lower than the rated short-circuit breaking current of AC breakers (up to 63 kA), in DC much faster action is required in order to limit the damage to the power electronic components in the converter. In addition, with rate-of-rise of fault current (*di/dt*) in the range of a few to several kA/ms [5], breaker operation time may not exceed several milliseconds in order to enable handling of reasonable values momentary fault current by the breaker. This rapid response also calls for the need of very rapid DC fault protection [6]. Values of one to few ms of relay time (ΔT_{relay}) are reported as feasible.

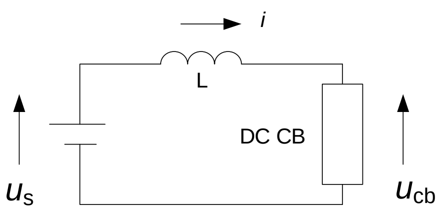

Fig. 2: Basic circuit lay-out for DC interruption

To understand current interruption in a DC system, an illustrative circuit shown in fig. 2 is used. Its basic circuit equation is as follows (U_s is supply voltage, U_{cb} is voltage across the circuit breaker):

$$U_s = L\frac{di}{dt} + U_{cb} \rightarrow \frac{di}{dt} = \frac{1}{L}(U_s - U_{cb})$$

This implies that a decrease of current ($di/dt < 0$) can only be achieved when the voltage across the circuit breaker (the counter voltage) exceeds the system voltage: $U_{cb} > U_s$.

All DC breakers are based on the above principle: *generation of counter voltage that exceeds the system voltage for a sufficiently long duration*. During the presence of the counter voltage, the fault current is suppressed to zero within the fault current suppression time (ΔT_{fs}). It is thus important not only to generate a counter voltage, but also to maintain it sufficiently long.

Many different technologies have been proposed to generate and to maintain counter voltage. For voltages up to 10 kV, a counter arc voltage can be achieved, mainly by elongating, cooling and splitting the arc. In fact, also every domestic LV miniature AC circuit breaker works on this principle. However, in MV and HV applications arc voltage based DC current interruption cannot be used, rather commutation based DC circuit breakers are designed and applied.

Current commutation based HVDC breakers consist of three parallel branches, see fig. 3:

1. Continuous current branch: this is of very low resistance for low-loss conduction of the continuous current.
2. Commutation branch: this branch has a high impedance and generates adequate counter voltage when current is commutating into this branch.
3. Energy absorption branch: this maintains the counter voltage while absorbing the energy trapped in the system.

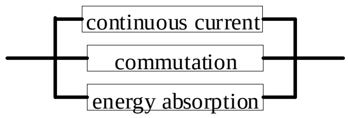

Fig. 3: Basic HVDC circuit breaker lay-out

When a DC breaker is called upon to operate, the following sequence of events unfolds:

1. At first, current is interrupted in the continuous (main) current branch, by power electronics or by mechanical switchgear with an auxiliary circuit to create artificial current zero or by a combination of both. (HV)DC breakers basically differ in the way artificial current zero is created and what mechanical switching element is used for interruption and/or insulation. In every design, mechanical switchgear is present to interrupt or to isolate. This can be vacuum or SF_6 insulated switchgear, but one key requirement is that it must be very fast acting (few milliseconds of contact separation) and therefore differs from AC switchgear that never achieves contact separation on the first rising edge of the fault current. After the continuous current branch is blocked for current passage, current is forced to commutate into the commutation branch, a parallel path of high impedance, usually a capacitance. The current charges the capacitor by which a fast-rising voltage, termed as transient interruption voltage (TIV), will develop. This voltage stresses the insulating gap in the continuous current branch.
2. The voltage rise will continue until the protection level of a metal-oxide surge arrester (MOSA) bank in the third parallel branch is reached. From that moment on, current starts to flow through this branch. Because MOSA protection voltage (U_{MOSA}) is higher than the system voltage, now the current through the MOSA will steadily decline to zero. When the current is suppressed

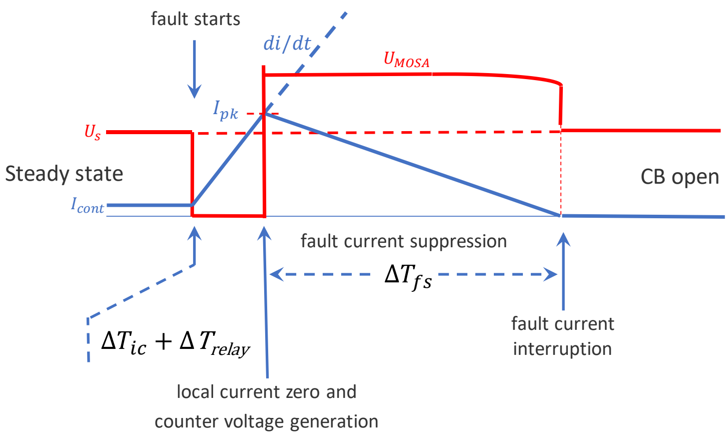

Fig. 4: Fault interruption in an HVDC circuit breaker

to (near) zero, the very small residual current can be interrupted by another switch and system voltage re-appears across the open DC breaker. Note that the system voltage is restored as soon as counter voltage has been fully developed, limiting the impact of the fault on the system basically to the relay time + breaker operation time, the sum of which is called fault neutralization time. After this time, the fault(current) is not yet removed from the system, but its impact is compensated by the MOSA temporarily acting as the system voltage source.

This process is schematically outlined in fig. 4.

The current interruption process in DC systems can be easily understood and formulated using a simple analytical model. For this, the following parameters are relevant:

- System parameters: Rated system voltage: U_s; rate-of-rise of fault current at breaker location: di/dt.
- Protection parameter: Relay time: ΔT_{relay}.
- Circuit breaker parameters: Peak value of fault current to be interrupted: I_{pk}; internal current commutation: ΔT_{ic}, counter voltage developed and maintained by MOSA: U_{MOSA}.

The inductance L of the circuit causing the rate-of-rise, the required breaker operation time ΔT_{ic} (this is the time between trip of the breaker and the generation of counter voltage) and the fault current suppression time and the energy to be absorbed by MOSA E are derived using the basic equations below.

$$L = \frac{U_s}{\frac{di}{dt}}; \quad \Delta T_{ic} = \frac{I_{pk}}{\frac{di}{dt}} - \Delta T_{relay};$$

$$\frac{I_{pk}}{\Delta T_{fs}} = \frac{1}{L}(U_{MOSA} - U_s) \rightarrow \Delta T_{fs} = \frac{I_{pk} * L}{U_{MOSA} - U_s}$$

$$E = U_{MOSA} * \frac{1}{2} * I_{pk} * \Delta T_{fs} = \frac{1}{2}\frac{U_{MOSA} * I_{pk}^2 * L}{U_{MOSA} - U_s}$$

This basic and simple set of equations is sufficient to estimate the main parameters of HVDC circuit breakers. of critical importance is the energy that is to be absorbed by the MOSA. This subcomponent must be designed to be able to deal with this. The energy consists of two components: one is the energy stored in the system inductance at the moment of peak current and the other is the energy that is supplied by the system during the fault suppression time.

$$E = \int_{\Delta T_{fs}} U_{cb} i \, dt = \frac{1}{2} L I_{pk}^2 + \int_{\Delta T_{fs}} U_s i dt$$

In order to get an example of the practical value of parameters, the data of a 500 kV HVDC circuit breaker [7] is used as shown in table 1. Note that the energy absorption requirement (E) refers to a single breaking operation. In cases where faults are non-persistent, like secondary arcs in overhead line systems, two or more opening operations may be required, basically doubling the energy dissipation, since the cooldown time of the large MOSA bank is much longer than the time between successive opening operations.

TABLE 1: PARAMETERS OF A 500 KV HVDC CIRCUIT BREAKER

Name	symbol	value	unit
Input parameters			
System voltage	U_s	500	kV
Peak fault current	I_{pk}	25	kA
Internal commutation time	ΔT_{ic}	2.5	ms
Relay time	ΔT_{relay}	2	ms
MOSA voltage	U_{MOSA}	800	kV
Derived parameters			
Fault current rate of rise	di/dt	5.6	kA/ms
Inductance	L	90.0	mH
Fault current suppression time	ΔT_{fs}	7.5	ms
Energy supplied to MOSA	E	75.0	MJ
Stored energy	$\frac{1}{2}LI_{pk}^2$	28.1	MJ

Note that DC circuit breakers fundamentally differ from AC breakers in the way they interact with the power system. AC breakers are designed to deal with a rated system-imposed short-circuit breaking current under standardized system-imposed transient recovery voltage (TRV) waveshapes. HVDC breakers, on the contrary, are highly interactive with the DC system: the fault current breaking capability depends on their operation time (a mechanical quantity) whereas the TIV across the mechanical switching gap is not system- but circuit breaker design dependent.

In all HVDC circuit breakers, ultra-fast acting mechanical switching devices are used. Key component in this are electromagnetic pulse actuators, so-called Thomson coils based on rapid repulsion of coils, electrically activated by a capacitor discharge [8]. This again emphasized the importance of the mechanical switching component in such devices.

III. APPLICATION OF HVDC CIRCUIT BREAKERS

Almost all of the HVDC systems in operation in the world are point-to-point systems: a single HVDC link connecting two HVDC stations nearby large scale generation, e.g. a large hydro power plant and a large load center. In case of a fault, the total link needs to be de-energized, either by AC circuit breakers or by converter control (in LCC systems). During system restoration, there is no or limited energy flow. Especially in systems having submarine connections, repair times can be very long; a survey among European TSOs reports an average repair time of 60 days [9]. Dedicated DC circuit breakers for DC fault current interruption at DC side are not necessary for point-to-point links.

With the need of connecting huge amounts of large sized generators (commonly offshore windfarms) spread across a large surface, meshed HVDC grids or multi-terminal HVDC systems [10] are being realized in small scale and conceived in a large scale, aimed to harvest hundreds of gigawatts in a few decades from now [11]. The meshed or multi-terminal topology greatly enhances reliability, system stability and electricity trade.

A key requirement of such meshed HVDC grids is the possibility to de-energize faulted branches of the grid, without endangering the integrity of the system as a whole. A good candidate to fulfill this requirement, is the HVDC circuit breaker [12], [13]. This device needs to interrupt any possible DC fault current and to isolate the faulted section from the grid in a very short time.

Fig. 5: Left: 160 kV HVDC circuit breaker in service [20];
Right: 200 kV HVDC prototype [17].

Other options of HVDC grid protection include the use of converters having fault-blocking capability (full-bridge topology). In this case, the grid de-energizes shortly and fault current is reduced to levels allowing separation of the faulted line under near-zero voltage and current conditions [14], [15]. This requires fast mechanical disconnectors to be installed at the ends of each DC line.

HVDC circuit breakers are in service at the time of writing in two projects. First, hybrid HVDC breakers were installed in the ±200 kV Zhoushan five terminal island link (2014) [16], [17], [18] from State Grid Co. of China. The other is in ±160 kV three terminal Nan'ao project (2013) [19], operated by China Southern Power Grid, where active current injection HVDC circuit breakers are installed [20], see fig. 5.

The realization of the ±500 kV Zhangbei meshed HVDC onshore grid [21], [22] also a project in China, will initially include 16 HVDC breakers of five different Chinese suppliers offering three designs of current injection and hybrid type [23], [24], see fig. 6.

Several types of HVDC circuit breakers are under development, all for application in future meshed grids. Whereas HVDC switches are from technology point of view based on AC switching devices, having only slight modifications for typical HVDC arcing and insulation requirements, HVDC circuit breakers are totally different from AC breakers.

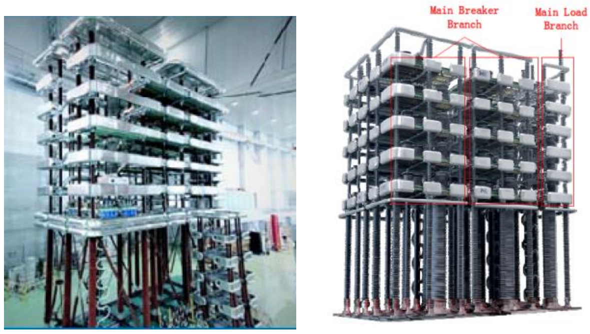

Fig. 6: 500 kV Prototype HVDC circuit breakers. Left: [21]; right: [23].

IV. Technology of DC Circuit Breakers

Low-voltage DC systems (roughly below 1.5 kV) are mostly applied for public and for mine traction, with various types of drives and converter systems. In these systems the method of arc elongation are used. By increasing the arc (counter) voltage to a value exceeding the system voltage, the arc current is forced to zero and the current is interrupted. The energy absorption is done by the arc.

In medium voltage DC systems ranging (1.5 - 3 kV), the method of arc elongation can still be used, but technically complicated measures are necessary to create the high arc voltage that should serve as counter voltage. For higher voltages, other interruption strategies need to be followed. DC circuit breaker technology is developing already since the first experiments in electrification and has gained increasing importance in the light of HVDC grid development.

Two major technologies can be distinguished:

1. Active current injection in which the switching - current zero creation in the continuous current branch - is undertaken by (a series of) high-speed arcing vacuum interrupters and an auxiliary injection circuit;
2. Hybrid technology, where the active switching is accomplished by power electronics, while the mechanical switching element has the function to conduct the continuous current and to isolate the power electronics in the continuous current branch.

A. *Active current injection technology*

This concept is the applied and demonstrated in MVDC [25], [26], [27] and HVDC technology [20], [30]. In this case current zero in the continuous current branch is created by artificially creating a current zero crossing in one or more arcing vacuum gaps. This is carried out by an active injection circuit, which generates a high-frequency (HF) current which, super-imposed upon the DC fault current, creates a current zero crossing, see fig.7.

When the sum of fault current and the superimposed HF counter current reaches zero, interruption can result, provided a number of criteria are met [28]:

- Arcing current prior to current zero must remain below a certain threshold;
- Steepness of current must be below a certain threshold. In many designs, a saturable reactor reduces *di/dt* at low current immediately before the zero crossing;
- Minimum gap spacing must have been reached in order to withstand the voltage across the gap during and after the interruption process.

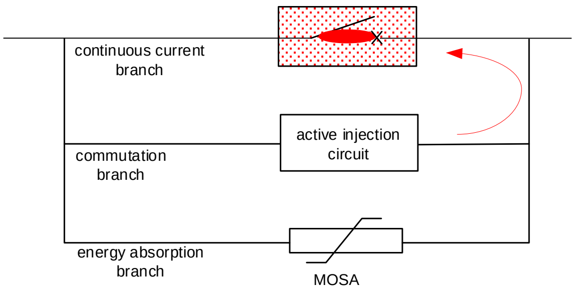

Fig. 7: Basic circuit of active injection technology HVDC breaker

A1. Capacitor discharge current injection

The most common design is with the active injection circuit consisting of a pre-charged capacitor bank that is able to produce a HF (few kHz) oscillating current in an LC circuit [29], [30], [31]. This current is actively injected into the arcing vacuum gaps to create an artificial current zero as soon as possible after contact separation. For the initiation of the injection, ultra-fast mechanical making switches or power electronic switches are required.

Immediately after current interruption in the vacuum gap, initially the vacuum gap is stressed by a very steep voltage spike originating from the residual charge on the injection capacitor. This might lead to re-ignition of the HF current and a slightly delayed interruption. When at a later moment in the process a breakdown of the switching gap occurs, due to lack of dielectric withstand, this is

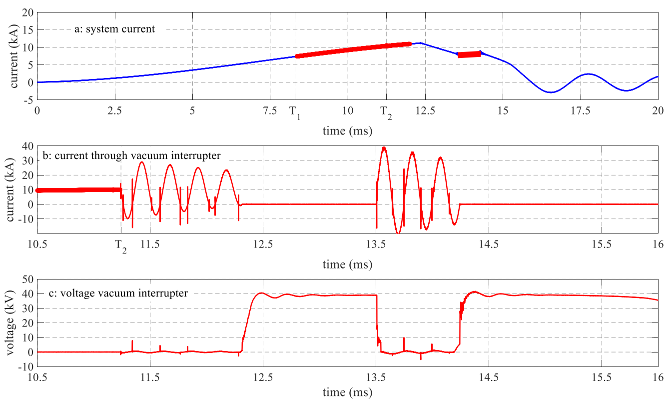

Fig. 8: Fault interruption of an experimental active current injection type DC breaker using commercially available 38 kV AC vacuum interrupters [34].
Top: Fault current, red areas indicate arcing of the vacuum gap
Centre: Nine times re-ignition of HF current arc (T_2-12.4 ms); restrike during fault current suppression (13.5 ms) followed by another 4 re-ignitions leading to prolongation of fault current suppression and increased energy absorption.

called a "restrike" which might lead to transients in the breaker circuitry. In the case of vacuum, restrike of the gap(s) not necessarily leads to failure of interrupting the DC fault current because vacuum gaps recover and can interrupt again, see fig. 8. Restrike, however, leads to an increased energy absorption requirement and delayed interruption and should therefore be avoided. Breakdown of an SF_6 gap will not recover.

Successful independent full-power tests of a two-module device of 160 kV rated system voltage, having two HV vacuum interrupters in series and interrupting 16 kA have been finalized June 2019, see fig. 11.

Another design that draws industrial attention is based on thyristor controlled current injection [32].

A2: VSC assisted resonant current injection

In this design, the active injection circuit consists of a voltage source converter (VSC), that generates a HF current having an increasing amplitude [33]. The process of current excitation continues until the sum of injected current and DC fault current is zero, usually in less than half a millisecond. The converter installed operates at a voltage around 1 kV and consists of IGBT modules.

Successful independent full-power tests of this design has been demonstrated with a single module [33], equipped with a 24 kV high-speed vacuum circuit breaker producing 40 kV of counter voltage and interrupting 10 kA. Early 2020 test of a three-module device is planned.

After successful interruption of the injected HF current, the fault current (I) first commutates in the LC branch which causes the voltage to rise with a rate-of-rise until a voltage level is reached that leads to commutation to a parallel connected MOSA bank, able to absorb the energy in the circuit.

Unlike for medium voltage, vacuum circuit breakers for high-voltage are not readily available, and several to many are switched in series, depending on the rated voltage of each interrupter. This makes proper voltage grading under steady state as well as under transient conditions essential.

Special designs of vacuum interrupters are necessary, because standard AC vacuum interrupters may have difficulty in consistently interrupting the HF injected current (see fig. 8) and may not be able to withstand the dielectric DC stresses during and after the interruption process.

Especially during the fault current suppression period (ΔT_{fs}), the switching gap experiences an over-voltage U_{MOSA}, around 1.5 times the DC system voltage, see fig. 8 [34].

Normally, current injection type of HVDC breakers allow bi-directional fault current interruption.

B. Hybrid switching technology

This technology exploits the combination of mechanical contacts and power electronics, but in contrast to the current injection technology the contacts are non-arcing. The continuous current branch (see fig. 9) consists of a series combination of a power electronics load commutation switch and an ultra-fast mechanical disconnector.

The load commutation switch is mostly a series-parallel matrix of IGBTs for reducing losses and increasing reliability. Because the continuous current passes through this switch, it needs water cooling. The (ultra-)fast disconnector is either an SF6 insulated switch with a single gap for the full TIV voltage [35] or a series combination of (up to 12) vacuum gaps, each with its ultra-fast actuator [7], [36]. In both cases, the disconnecting switch opens only after current has been interrupted by the load commutation switch, in order to isolate it against voltages during the switching process.

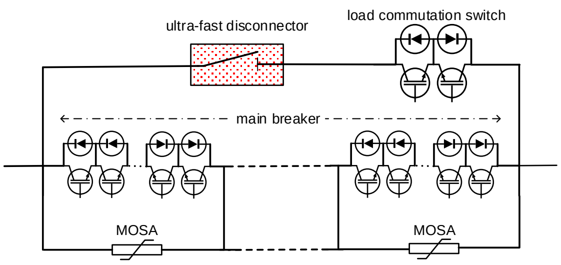

Fig. 9: Example circuit of hybrid technology HVDC breaker (after [35])

The load commutation switch can interrupt the full fault current in its branch, because the commutation branch has been switched into a low-impedance mode at the moment of fault detection by switching the main breaker into conduction, so only very limited voltage falls across the load commutation switch.

In the next step, the impedance of the commutation branch is changed from very low to very high. This is accomplished by the main breaker, a stack of a large number of power electronic components. One design has a stack of IGBTs [35] as main breaker, another design [7] has a number of diode based H-bridge modules in full-bridge rectifier topology which is claimed to reduce the amount of IGBTs by 50%. Yet another design [36] uses H-bridge diode-based commutation modules and IGBT based unidirectional breaking modules, integrating the energy absorption function (MOSA) in the commutation branch. The last two designs offer bi-directional operation.

Another design, though not fully realized in practice, is based on stepwise commutation into a number of parallel branches containing thyristors and capacitors [37]. The use of a new type of a plasma-discharge tube as main breaker, largely avoiding IGBTs is under investigation [38].

In general, hybrid HVDC breakers have higher on-state losses than current injection type and need active cooling, because of the presence of power electronics in the continuous current branch.

V. Testing of HVDC Circuit Breakers

Testing of HVDC circuit breakers is largely unknown territory, because international standards do not yet exist and hardly any multi-terminal project is gaining experience with these devices under fault conditions.

Many DC fault studies have been presented on model HVDC grids [5], [39], the most prominent one being the CIGRE B4.58 benchmark system [40].

However, in the absence of HVDC grids, very little operational experience is available yet.

Nevertheless, HVDC breakers are being developed and there exists a need for verification of their specified performance. In the recent past, several tests on prototype HVDC breakers were carried out as part of the development process. In all cases, capacitor bank discharge circuits are used that produce an oscillating current with a single [35], [17], [23], [24] or two frequencies [37]. In this way, a proper rate-of-rise of DC fault current can be realized, and the capability of current zero creation in the continuous current branch and commutation followed by counter voltage creation can be verified. However, energy absorption and TIV withstand cannot be verified.

As part of the European Horizon's 2020 "PROMOTioN" project [11], alternative test schemes and circuits are developed and demonstrated that can verify performance and withstand during all six critical stages of DC fault interruption, see fig. 10:

1. Rate-of-rise of fault current;
2. Current zero creation in continuous current branch;
3. Counter voltage generation;
4. Energy absorption;
5. TIV overvoltage withstand (around 1.5 pu);
6. System recovery voltage withstand.

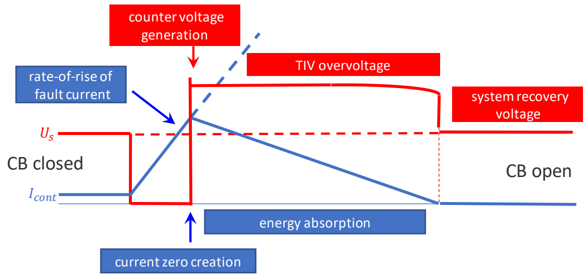

Fig. 10: The six critical stages of HVDC current interruption

The main motivation of including also the stages 4-6 in interruption tests is the following:

- Mechanical switches are key components of all HVDC circuit breakers. In some applications they switch high current, in some they isolate high voltage, or both. Short-time dynamic (stage 5) overvoltage withstand and long duration static dielectric withstand (stage 6) shall be an essential part of a verification program.
- Surge arresters in HVDC circuit breakers are used in a different application than for overvoltage protection, the usual application. The unusual amount of energy to be absorbed requires a large number of parallel arrester columns and an even current sharing between the non-linear ZnO elements [34]. CIGRE WG A3.39 is studying the specific HVDC breaker MOSA application.

An obstacle in testing larger HVDC circuit breakers is that the "synthetic" test methods, commonly applied in AC breaker testing up to the highest voltages, cannot work for HVDC breakers. For HVDC breaker testing, sources providing real power, megawatts, are needed to prove the breaker's energy dissipation capability.

A suitable 'one shot' method of applying all stresses as outlined above is covered by the application of AC short-circuit generators running in low-frequency mode (15-30 Hz) [41]. Because of the short duration of the interruption process (order 10 ms), the duration of a low-frequency AC voltage waveshape (some tens of milliseconds) is long enough to mimic the DC system voltage and power during the entire process. Only for stage 6, system recovery voltage has to applied in a "synthetic" way, i.e. from a separate DC voltage source.

Adequate circuits up to 350 kV rated DC voltage have been designed and partly demonstrated [42] using six short-circuit generators and up to ten step-up transformers.

The advantage of the low-frequency AC method is that such sources are available in major high-power laboratories around the world.

TABLE 2: TEST REQUIREMENTS FOR BREAKING TESTS OF HVDC CIRCUIT BREAKERS AS DEFINED IN THE PROMOTIoN PROJECT.

Name	Current	Breaking test
TC10+	10% of rated continuous current	2 tests in positive current direction
TC10-	10% of rated continuous current	2 tests in negative current direction
TC100+	100% of rated continuous current	2 tests in positive current direction
TC100-	100% of rated continuous current	2 tests in negative current direction
TF100+	100% of peak fault current	2 test at specified energy absorption*, positive current direction
TF100-	100% of peak fault current	2 test at specified energy absorption*, negative current direction
TDT+	TBD	2 test at rated fault current suppression time**, positive current direction
TDT-	TBD	2 test at rated fault current suppression time**, negative current direction
	*: Specified energy absorption based on specified value of energy absorption (MJ) of the test-object delivered **: Rated fault current suppression time based on U_S, U_{MOSA}, ΔTic, I_{pk}, as would be present in service condition	
	All tests are single opening operations	

Table 2 shows the breaking test requirements, as agreed among three HVDC circuit breaker manufacturers within the PROMOTioN project. These are taken as guidelines in the testing of three HVDC circuit breakers rated 80 kV 16 kA (VSC assisted resonant type), 160 kV 16 kA (active current injection type) - see fig. 11, 350 kV 16 kA (hybrid type), to be completed March 2020.

VI. CONCLUSIONS

HVDC circuit breakers differ entirely both from the DC side switching devices already in service for decades and well as from AC circuit breakers. Recently, HVDC grids have been recognized for their capability to evacuate huge amounts of (renewable) energy, and several HVDC grid studies are under way. One major technological hurdle in the realization of HVDC grids is the virtual absence of commercially available HVDC circuit breakers. Though, except for China, major HVDC grid projects seem not appear within a short horizon, a huge effort in academic research and industrial product development is observed in HVDC grid protection, transient studies and fault current interruption.

HVDC circuit breakers are large, expensive and technically complicated devices, that depend on the proper coordination of many components: mechanical, power-electrical, electronical and control. New, and common to all designs of HVDC circuit breakers is the combination of ultra-fast mechanical switchgear, power electronics and energy absorption.

The Chinese Zhangbei multi-terminal project [21] will give a huge impetus towards mature HVDC circuit breakers, though service experience is still lacking.

Testing and standardization is also still in the development phase, which may be surprising given the many new, unusual and unproven combinations of technology.

The European project "PROMOTioN", aims to remove technical (and non-technical) hurdles in the deployment of a large meshed offshore HVDC transmission grid in the Northern Seas, necessary to harvest huge wind generated energy [43].

In this project, full-power testing of HVDC circuit breakers is underway to be demonstrated for three different prototypes of HVDC circuit breakers up to 350 kV. It is recognized that it is essential to verify the correct performance of HVDC circuit breakers during each of the stages in the fault current interruption process, and not focus at the initial interruption stages only.

Critical assessment by standardization committees is needed, leading to a true understanding of the interdisciplinary and interactive nature of HVDC switching technology, a combination of a new generation of mechanical switchgear and power electronics.

A sizeable spin-off of the HVDC interruption technology may be the development of high-speed AC fault current limiting devices, taking advantage of the maturation of high-speed mechanical switching devices in combination with power electronics [44]. After all, fast counter voltage generation is as effective in fault current suppression in AC as in DC.

Fig. 11: 160 kV current injection breaker in the test laboratory

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