



# The Hybrid HVDC Breaker

## An innovation breakthrough enabling reliable HVDC grids

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### SUMMARY

Existing mechanical HVDC breakers are capable of interrupting HVDC currents within several tens of milliseconds, but this is too slow to fulfill the requirements of a reliable HVDC grid. HVDC breakers based on semiconductors can easily overcome the limitations of operating speed, but generate large transfer losses, typically in the range of 30 percent of the losses of a voltage source converter station.

To overcome these obstacles, ABB has developed a hybrid HVDC breaker. The hybrid design has negligible conduction losses, while preserving ultra-fast current interruption capability.

This paper will present a detailed description of the hybrid HVDC breaker, its design principles and test results. The modular design of the hybrid breaker for HVDC applications is described. Furthermore, the application of the hybrid breaker associated with the design of a HVDC switchyard will be discussed.

**KEYWORDS:** HVDC grid; HVDC breaker - hybrid; Semiconductor breaker

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### 1. INTRODUCTION

The advance of voltage source converter-based (VSC) high-voltage direct current (HVDC) transmission systems makes it possible to build an HVDC grid with many terminals. Compared with high-voltage alternating current (AC) grids, active power conduction losses are relatively low and reactive power conduction losses are zero in an HVDC grid. This advantage makes an HVDC grid more attractive [1]. However, the relatively low impedance in HVDC grids is a challenge when a short circuit fault occurs, because the fault penetration is much faster and deeper. Consequently, fast and reliable HVDC breakers are needed to isolate faults and avoid a collapse of the common HVDC grid voltage. Furthermore, maintaining a reasonable level of HVDC voltage is a precondition for the converter station to operate normally. In order to minimize disturbances in converter operation, particularly the operation of stations not connected to the faulty line or cable, it is necessary to clear the fault within a few milliseconds.

Recently, plans for large scale use of embedded VSC-HVDC transmission in point-to-point overhead lines have been proposed, e.g. Germany, in the so-called Netzentwicklungsplan (NEP - Network Development Plan). New generation from remote sites such as renewable sources, are driving the case for VSC-HVDC systems in the areas of active power transmission and reactive power compensation. Here the hybrid HVDC breaker can provide the additional benefit of interrupting HVDC line faults.

Fast fault handling would enable the converter stations to operate as stand-alone static compensation units (STATCOMs) to stabilize voltage and increase transmission capacity in the AC grid during fault clearance.

Existing mechanical HVDC breakers are capable of interrupting HVDC currents within several tens of milliseconds, [2] but are too slow to fulfill the requirements of a reliable HVDC grid. Furthermore, building mechanical HVDC breakers is in itself challenging and requires the installation of additional passive components to create the resonance circuit, and generate the current zero crossing so the breaker will succeed in breaking the current once it opens. Existing HVDC switches have been used for more than 30 years in the neutral switchyard of bipolar HVDC installations. Here they perform various functions, such as rerouting HVDC current during reconfiguration of the main circuit, or helping to extinguish fault currents. For example, the Metallic Return Transfer Breaker (MRTB) is used to commutate the current from the ground path to a metal conductor, when there are restrictions on how long an HVDC current can be routed through the ground. Other examples include the Ground Return Transfer Switch (GRTS), Neutral Bus Switch (NBS) and Neutral Bus Grounding Switch (NBGS). The two main differences between these transfer breakers and the hybrid HVDC breaker is that the transfer breakers operate considerably slower than the hybrid breaker, and that part of the current is transferred, rather than interrupted. These high-voltage switches or breaker systems use an AC-type of high-voltage breaker; the zero crossing of the HVDC fault current is imposed by discharge of a capacitor bank to generate a current opposite to the fault current, in order to extinguish the arc. These are large outdoor pieces of equipment, situated partly on air-insulated platforms in the HVDC converter station neutral switchyard. The direct apparent voltage for these applications is usually only a few tens of kilovolts (kV).

Developing a very fast mechanical HVDC breaker is a demanding task [3]. Semiconductor-based HVDC breakers easily overcome the limitations of operational speed and voltage, but generate large transfer losses - typically in the range of 30 percent of the losses of a voltage source converter station. The hybrid HVDC breaker has been developed to overcome these obstacles,

This paper is structured as follows. First, the performance requirement of HVDC breakers as the main apparatus determining the system performance of an HVDC grid is highlighted. Next, a detailed description including the design principle is illustrated for the proposed hybrid HVDC breaker. Finally, some test results from a prototype of the main switch branch and the complete hybrid HVDC breaker are presented.

## **2. SYSTEM DESIGN REQUIREMENTS**

An HVDC grid is formed when more than two converter stations are interconnected on the HVDC side via HVDC cables or overhead lines. Each converter station or each terminal of the HVDC grid couples the HVDC grid to an AC grid. In order to maintain the converter's active and reactive power control capability, it is normally requested that the HVDC voltage be above at least 80 percent of the nominal HVDC voltage. If the converters lose control capability due to low HVDC voltage, the consequences can be voltage collapse in the HVDC grid and high current or voltage stresses for the converter. This can also affect the coupled AC grid voltage. An HVDC short-circuit fault can, in the worst case, make HVDC voltage suddenly drop from nominal level to near zero at the fault location. The voltage reduction in other places of the HVDC grid depends mainly on the electrical distance to the fault location and HVDC reactors installed near the converter stations. For an HVDC grid connected by HVDC cables, a short-circuit fault typically has to be cleared within 5 milliseconds (ms), in order not to disturb converter stations as far away as 200 km, a - significantly different challenge compared to AC fault clearing times.

HVDC grid system performance is not the only reason fast HVDC switches are necessary. From the point of view of HVDC breaker design, fast fault current breaking is crucial, as is shown in the following examples.

Due to the voltage source converters and the capacitive nature of HVDC grids with interconnecting cables, an HVDC grid independent of the actual configuration has been depicted in the simplified equivalent shown in Figure 1(a) during the short time period representing the occurrence of an HVDC fault. The equivalent circuit includes an infinitely strong HVDC source, an HVDC reactor and the HVDC switch in parallel with an arrester.

Figure 1(b) shows the electromagnetic transients when the current is broken. The current starts to rise when the fault occurs. When the switch opens, the current starts to decrease as it is commutated to the arrester. The fault current in the arrester bank establishes a counter voltage, which reduces the fault current to zero by dissipating the fault energy stored in the HVDC reactor and fault current path of the HVDC grid. The protective level of the arrester bank must exceed the HVDC voltage in the HVDC grid.

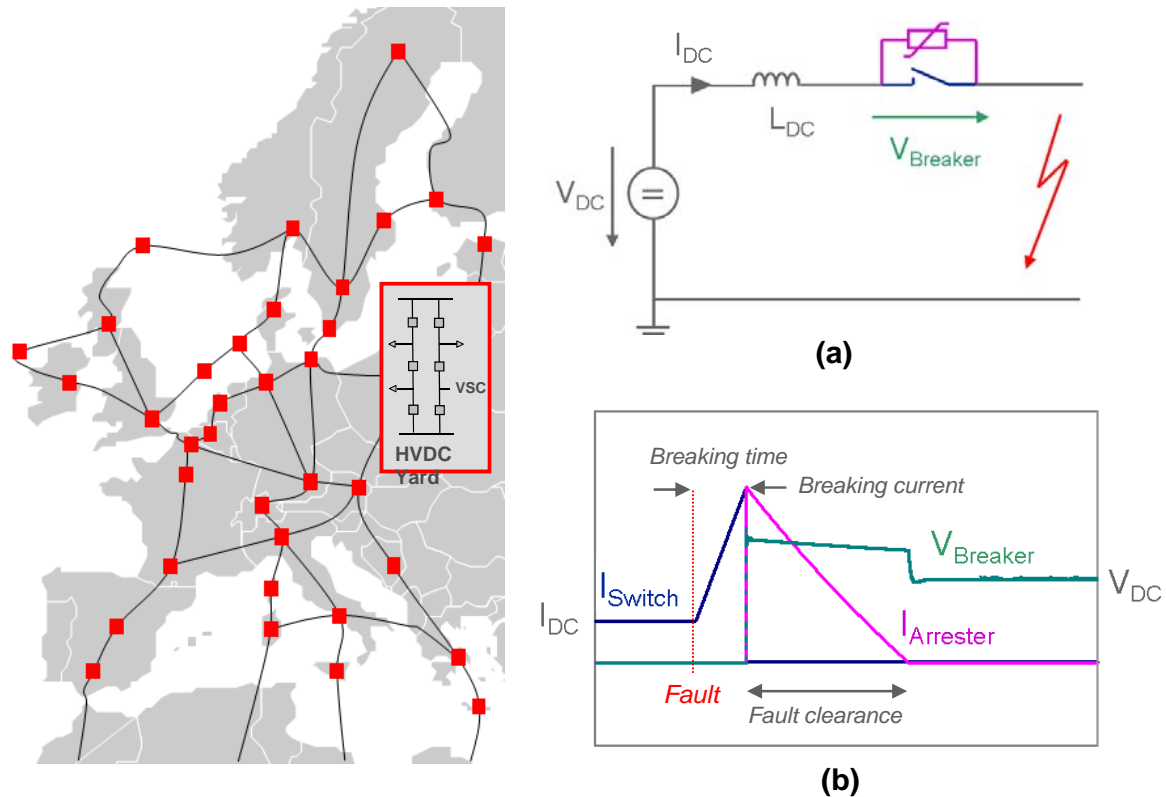


Figure 1: Representation of an HVDC breaker in an HVDC grid

Total fault clearing time consists of two parts: breaking time corresponds to a period of rising current, and fault clearing corresponds to a period of decreasing current. Both time intervals are important considerations in the design and cost of the HVDC breaker, as well as the reactor.

In practice, breaking time is governed by the response time of the protection, and the action time of the HVDC switch. A longer breaking time requires the HVDC switch to have an increased maximum current breaking capability. This increases the energy handled by the arrester and correspondingly leads to a higher cost for the HVDC breaker. Therefore it is important to keep breaking time as short as possible. When the breaking time and the maximum breaking current capability is given, the only adjustable parameter is the inductance of the HVDC reactor, which decides the rate of current rise. The HVDC reactor therefore needs to be selected in such a way, that within the breaking time, current does not reach a level higher than the maximum breaking current capability of the HVDC breaker. However, the size of the HVDC reactor may be limited by factors like cost, and the stability of the HVDC grid system.

The time duration for fault clearance will affect voltage dimensioning of the arrester as well as the pole voltage protection. A shorter fault clearance implies reduced power dissipation in the arrester bank, but it requires a higher voltage dimensioning of the arrester. On the other hand, an increase of the protective level of the arrester will result in a higher pole-to-pole voltage rating, and thus adds to the costs of the HVDC breaker.

The following example provides a general impression of the relationship between the parameters mentioned above. Assuming a breaking time of 2 ms, which is possible for semiconductor-based HVDC switches, and an HVDC line fault close to the HVDC switchyard, the maximum rise of the fault current will be 3.5 kA/ms for a HVDC reactor of 100 mH in a 320 kV HVDC grid with 10 percent maximum overvoltage. For a given rated line current of 2 kA, the minimum required breaking capability of the HVDC breaker is 9 kA.

### 3. HYBRID HVDC BREAKER

As presented in Figure 2, the hybrid HVDC breaker consists of an additional branch, a bypass formed by a semiconductor-based load commutation switch in series with a fast mechanical disconnecter. The main semiconductor-based HVDC breaker is separated into several sections with individual arrester banks dimensioned for full voltage and current breaking capability, whereas the load commutation switch matches lower voltage and energy capability. After fault clearance, a disconnecting circuit breaker interrupts the residual current and isolates the faulty line from the HVDC grid to protect the arrester banks of the hybrid HVDC breaker from thermal overload.

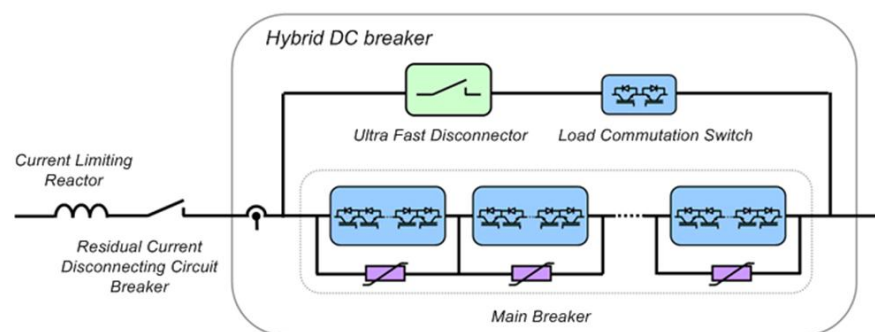


Figure 2: Hybrid HVDC breaker

During normal operation the current will only flow through the bypass, and the current in the main HVDC breaker is zero. When an HVDC fault occurs, the load commutation switch immediately commutates the current to the main HVDC breaker and the fast disconnecter opens. With the mechanical switch in open position, the main HVDC breaker breaks the current.

The mechanical switch isolates the load commutation switch from the primary voltage across the main HVDC breaker during current breaking. Thus, the required voltage rating of the load commutation switch is significantly reduced. A successful commutation of the line current into the main HVDC breaker path requires a voltage rating of the load commutation switch exceeding the on-state voltage of the main HVDC breaker, which is typically in the kV range for a 320 kV HVDC breaker. This result in typical on-state voltages of the load commutation switch is in the range of several volts only. The transfer losses of the hybrid HVDC breaker concept are thus significantly reduced to a percentage of the losses incurred by a pure semiconductor breaker, i.e. 0.01% of the transmitted power.

The mechanical switch opens at zero current with low voltage stress, and can thus be realized as a disconnecter with a lightweight contact system. The fast disconnecter will be exposed to the maximum pole-to-pole voltage defined by the protective level of the arrester banks after first being in open position while the main HVDC breaker opens. Thomson drives [4] result in fast opening times and compact disconnecter design using SF<sub>6</sub> as insulating media.

Proactive control of the hybrid HVDC breaker allows it to compensate for the time delay of the fast disconnector, if the opening time of the disconnector is less than the time required for selective protection. As shown in Figure 3, proactive current commutation is initiated by the hybrid HVDC breaker's built-in overcurrent protection as soon as the HVDC line current exceeds a certain overcurrent level. The main HVDC breaker delays current breaking until a trip signal of the selected protection is received or the faulty line current is close to the maximum breaking current capability of the main HVDC breaker.

To extend the time before the self-protection function of the main HVDC breaker trips the hybrid HVDC breaker, the main HVDC breaker may operate in current limiting mode prior to current breaking. The main HVDC breaker controls the voltage drop across the HVDC reactor to zero to prevent a further rise in the line current. Pulse mode operation of the main HVDC breaker or sectionalizing the main HVDC breaker as shown in Figure 3 will allow adapting the voltage across the main HVDC breaker to the instantaneous HVDC voltage level of the HVDC grid. The maximum duration of the current limiting mode depends on the energy dissipation capability of the arrester banks.

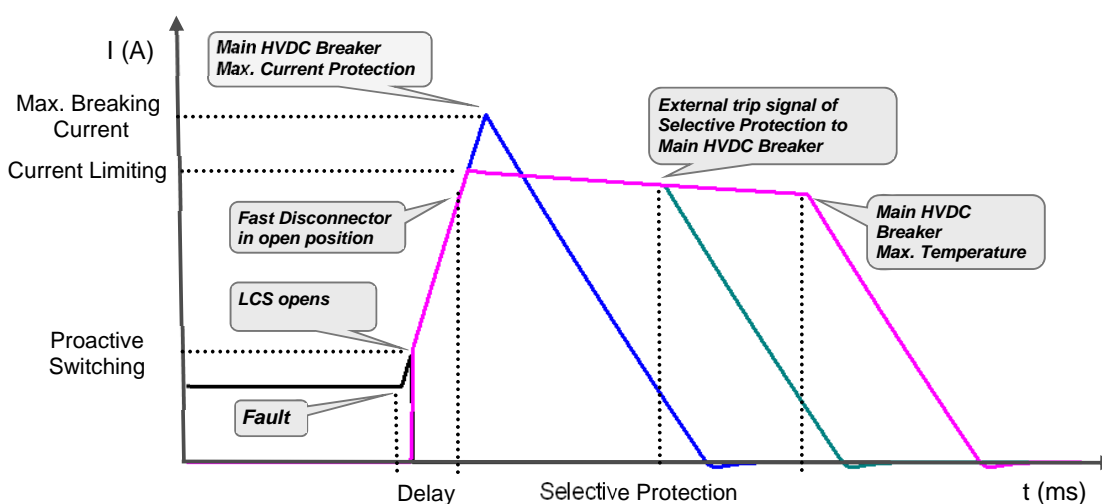


Figure 3: Proactive control of hybrid HVDC breaker. LCS denotes load commutation switch

On-line supervision allowing maintenance on demand is achieved by scheduled current transfer of the line current from the bypass into the main HVDC current breaker during normal operation, without disturbing or interrupting the power transfer in the HVDC grid.

Fast backup protection similar to pure semiconductor breakers is possible for hybrid HVDC breakers applied to HVDC switchyards. Due to the proactive mode, over-currents in the line or superior switchyard protection will activate the current transfer from the bypass into the main HVDC breaker or possible backup breakers prior to the trip signal of the backup protection. In the case of a breaker failure, the backup breakers are activated almost instantaneously, typically within less than 0.2 ms. This will avoid major disturbances in the HVDC grid, and keep the required current-breaking capability of the backup breaker at reasonable values. If not utilized for backup protection, the hybrid HVDC breakers automatically return to normal operation mode after the fault is cleared.

## PROTOTYPE DESIGN OF THE HYBRID HVDC BREAKER

The hybrid HVDC breaker is designed to achieve a current breaking capability of 9.0 kA in an HVDC grid with rated voltage of 320 kV and rated HVDC transmission current of 2 kA. The maximum current breaking capability is independent of the current rating and depends on the design of the main

HVDC breaker only. The fast disconnecter and main HVDC breaker are designed for switching voltages exceeding 1.5 p.u. in consideration of fast voltage transients during current breaking.

The main HVDC breaker consists of several HVDC breaker cells with individual arrester banks limiting the maximum voltage across each cell to a specific level during current breaking. Each HVDC breaker cell contains four HVDC breaker stacks as shown in Figure 4. Two stacks are required to break the current in either current direction.

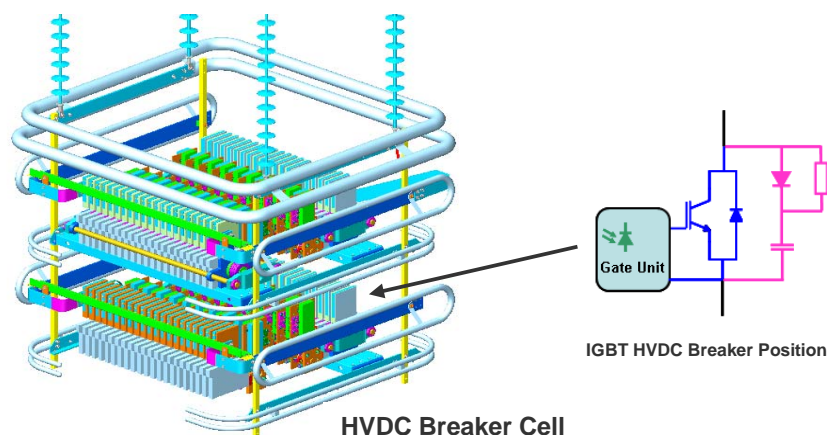


Figure 4: Design of 80kV main HVDC breaker cell

Each stack is composed of up to 20 series connected IGBT (insulated gate bipolar transistor) HVDC breaker positions. Due to the large di/dt stress during current breaking, a mechanical design with low stray inductance is required. Application of press pack IGBTs with 4.5 kV voltage rating [6] enables a compact stack design and ensures a stable short circuit failure mode in case of individual component failure. Individual RCD snubbers across each IGBT module ensure equal voltage distribution during current breaking. Optically powered gate units enable operation of the IGBT HVDC breaker independent of current and voltage conditions in the HVDC grid. A cooling system is not required for the IGBT stacks, since the main HVDC breaker cells are not exposed to the line current during normal operation.

For the design of the load commutation switch, one IGBT HVDC breaker module for each current direction is sufficient to fulfill the requirements of the voltage rating. Parallel connection of IGBT modules increases the rated current of the hybrid HVDC breaker. Series connected, redundant IGBT HVDC breaker modules improve the reliability of the load commutation switch. A matrix of 3x3 IGBT positions for each current direction is chosen for the present design. Since the load commutation switch is continuously exposed to the line current, a cooling system is required. Besides water cooling, air-forced cooling can be applied, due to relatively low losses in the range of several tens of kW only.

## 5. TEST RESULTS MAIN BREAKER

During the design of the hybrid HVDC breaker prototype, different tests were performed in order to verify expected performance. The first test setup reported earlier focuses mainly on the control of semiconductor devices and their current breaking capability. The second test setup verifies both the voltage and current capability of one cell of the main HVDC breaker. The ongoing extension of this test setup will focus on the overall performance of the hybrid HVDC breaker. Due to big differences in voltage levels in the test setup, construction of the test circuits is quite different but the test procedure is similar.

A scaled-down prototype of the main breaker cell with three series connected IGBT modules and a common arrester bank was used to verify the current-breaking capability of 4.5 kV StakPak IGBTs [6] in the first test circuit as shown in Figure 5. A fourth IGBT module was connected in opposite primary

current direction to verify the functionality of the incorporated anti-parallel diode. Discharge of a capacitor bank by a thyristor switch, limited only by a minor DC reactor, represents pole-to-ground faults in the HVDC grid. The HVDC voltage level prior to the fault and after fault clearance is less critical, since the voltage stress across the IGBT HVDC breaker positions during current breaking depends on the applied arrester bank only.

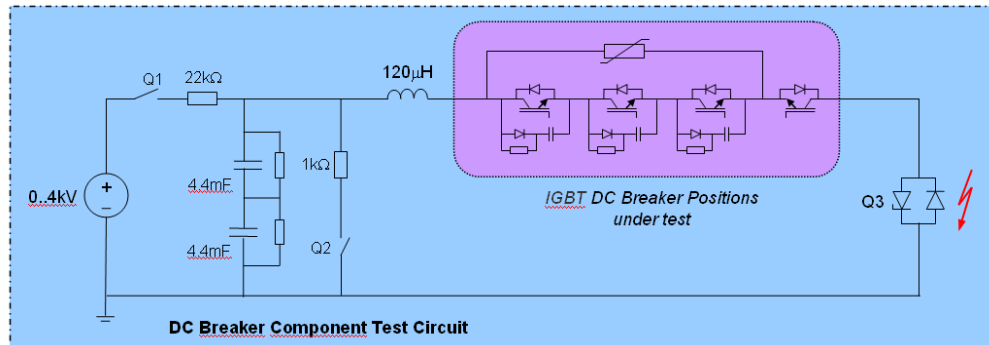


Figure 5: HVDC breaker component test circuit

As shown in Figure 6, the maximum current breaking capability of the IGBT HVDC breaker cell is determined by the saturation current of the applied IGBT modules rather than the safe operation area (SOA) as is typical in voltage source converter applications. The series connected HVDC breaker IGBT positions commutate the line current within 2  $\mu$ s (microseconds) into the RCD snubber circuits, which limits the rate of rise in voltage across the positions to 300 V/ $\mu$ s. Zero voltage switching reduces the instantaneous switching losses and ensures equal voltage distribution independent of the tolerances in the switching characteristics of the applied IGBT modules.

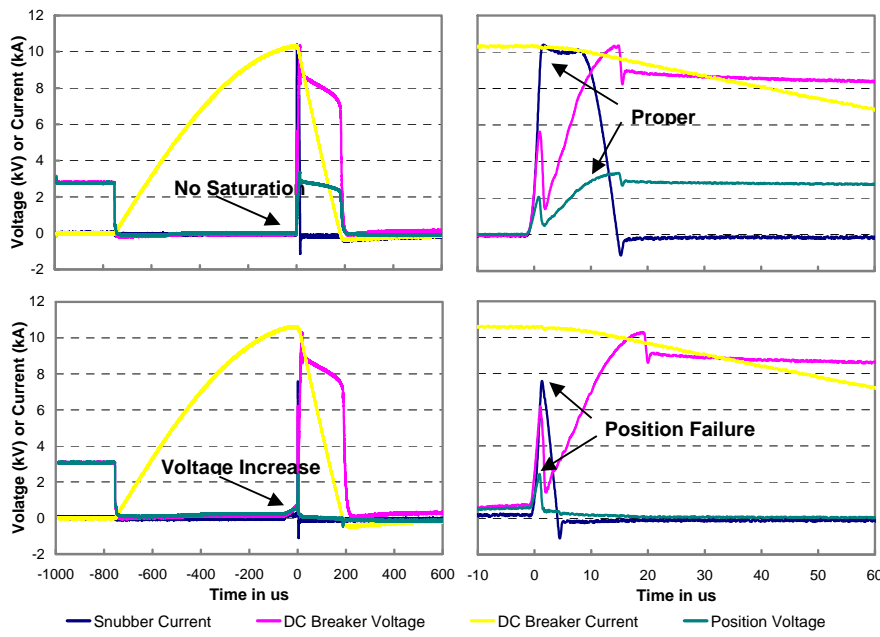


Figure 6: Maximum stress tests on IGBT HVDC breaker positions (left: Zoom)

The line current commutates from the RCD snubber circuit into the arrester path after the common voltage across the IGBT HVDC breaker positions reaches the protective level of the arrester bank.

The IGBT HVDC breaker positions passed the stress tests for breaking currents below 10 kA. For higher currents, the IGBT saturation current level is reached by the internal current limitation in the

breaker, causing an immediate voltage drop across the IGBT modules. During a purposely destructive test, the resulting internal heat dissipation within the IGBT module destroys the encapsulated IGBT chips. Due to the use of presspack IGBTs, a reliable short circuit without mechanical destruction of the failed IGBT module is enabled. Since only one of the IGBT modules failed during the test, the fault can still be cleared by the two other modules.

The nominal HVDC voltage per IGBT HVDC breaker cell is 80 kV. Due to the high voltage level, the second test setup requires a significantly larger space. In Figure 7, the test circuit for the hybrid HVDC breaker concept is shown. A  $\pm 150$  kV HVDC switchyard supplies the containerized test equipment to verify the functionality of the main IGBT HVDC breaker represented by two series connected IGBT HVDC breaker stacks and a common arrester bank. The desired HVDC voltage level is built up by charging the capacitor bank C1. The reactor L1 is selected to give the expected current derivative ( $di/dt$ ) during a short-circuit fault. The short-circuit fault is initiated by the triggered spark gap Q5.

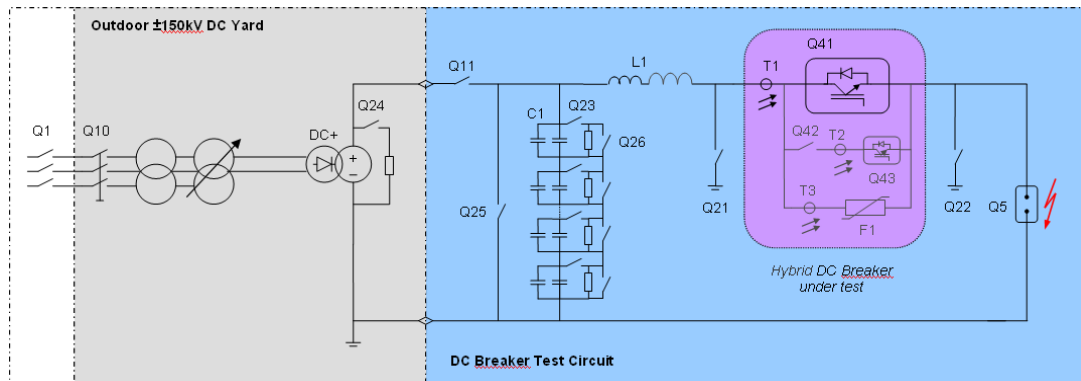


Figure 7: ABB's containerized HVDC breaker test circuit

Figure 8 shows a typical test result. A maximum breaking current of over 9 kA is verified. The voltage across the HVDC breaker cell exceeds 120 kV during current commutation. The breaking capability of one 80 kV HVDC breaker cell thus exceeds 1 GVA. Furthermore, equal voltage distribution with a maximum voltage drop of 3.3 kV and a spread of less than 10 percent was only observed for the individual IGBT HVDC breaker positions in the HVDC breaker cell.

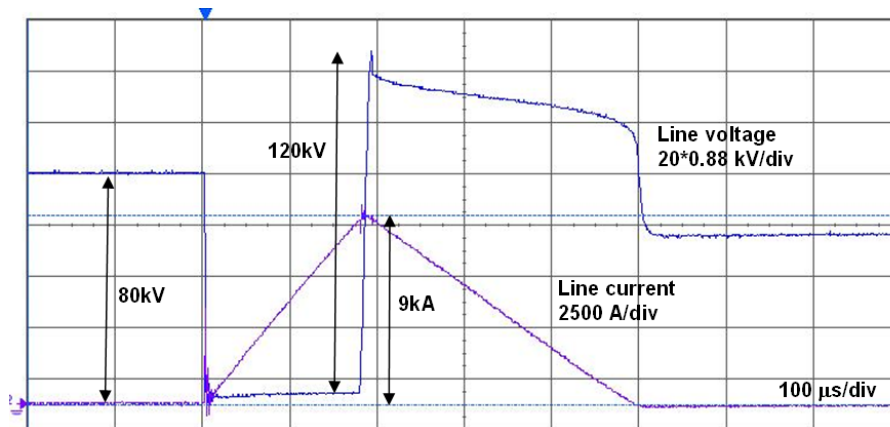


Figure 8: Verification of modular IGBT HVDC breaker cell



## 6. TEST RESULTS HYBRID HVDC BREAKER

The main breaker test setup described in Section 5 and reported earlier [8] was expanded to verify the complete hybrid HVDC breaker concept. A second capacitor bank and large reactors were installed to limit the rate of line current rise to typical HVDC grid values. The ultra-fast disconnecter and load commutation switch are included in the system configuration.

Successful verification testing at device and component level has proven the performance of the components. The complete hybrid HVDC breaker has now been verified in a demonstrator setup at ABB facilities. The diagram in Figure 9 shows a breaking event with peak current 9 kA and 2 ms delay time for opening the ultra-fast disconnecter in the branch parallel to the main breaker. The maximum rated fault current of 9 kA is the limit for the existing generation of semiconductors. The next generation of semiconductor devices will allow breaking performance of up to 16 kA. The purpose of the tests was to verify switching performance of the power electronic parts, and the opening speed of the mechanical ultra-fast disconnecter. The test object consisted of one 80 kV unidirectional main breaker cell, along with the ultra-fast disconnecter and load commutation switch. The higher voltage rating is accomplished by connecting in series, several main breaker cells, but the switching stress per cell is the same as in the demonstrator. This series connection approach is also used to test conventional HVDC Light and HVDC Classic valves. Tests have not only been carried out for normal breaking events, but also for situations with failed components in the breaker, in order to verify reliable detection and safe operation in such cases.

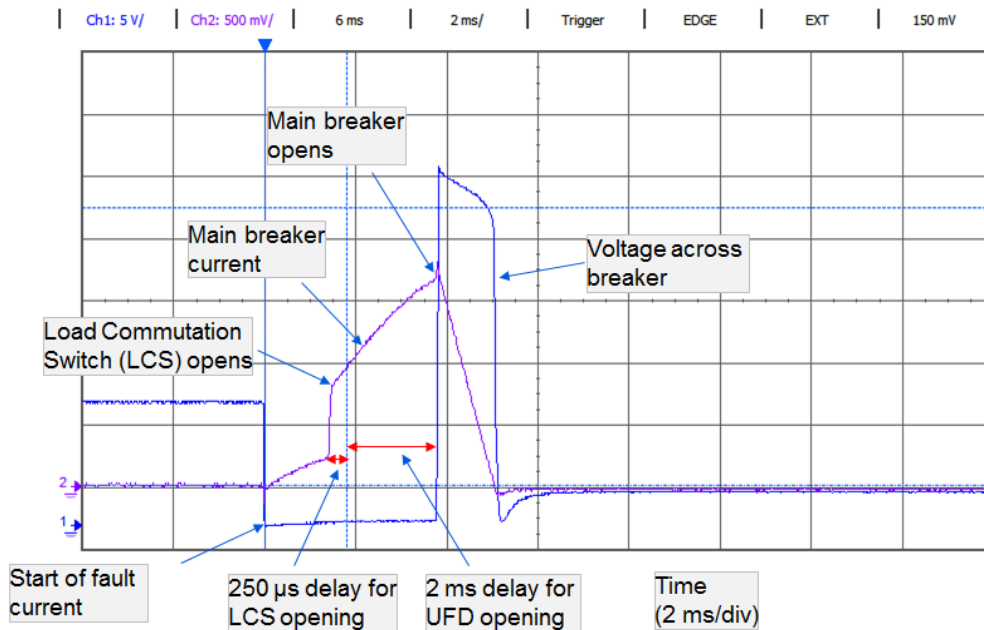


Figure 9: Verification of the hybrid HVDC breaker system

## 7. OUTLOOK AND CONCLUSIONS

For onshore installations and typical HVDC grid switchyards, the HVDC reactor and disconnecting residual current breakers are installed outdoors, which significantly reduces the size of the valve hall required for the hybrid HVDC breaker. Sharing the HVDC reactors with other HVDC breakers installed in the switchyard can further reduce the size of the installation.

Introduction of Bi-mode Insulated Gate Transistor (BiGT) technologies [7] incorporating the functionality of the reverse conducting diode on the IGBT chips will double the current breaking

capability of existing presspack modules. With maximum breaking currents of up to 16 kA and operating times less than 5 ms including the time delay of the protection system, proactive hybrid HVDC breakers are well suited for use in HVDC switchyards to prevent the collapse of multi-terminal HVDC systems due to HVDC line faults.

Fast, reliable and nearly zero loss HVDC breakers and current limiters based on the hybrid HVDC breaker concept have been verified at component and system levels at ABB's high power laboratories in Sweden and Switzerland, for HVDC voltages up to 320 kV and rated currents of 2 kA. Thus HVDC grids can now be planned. The next step is to deploy the breaker in a real HVDC transmission line to test under continuous full load conditions.

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