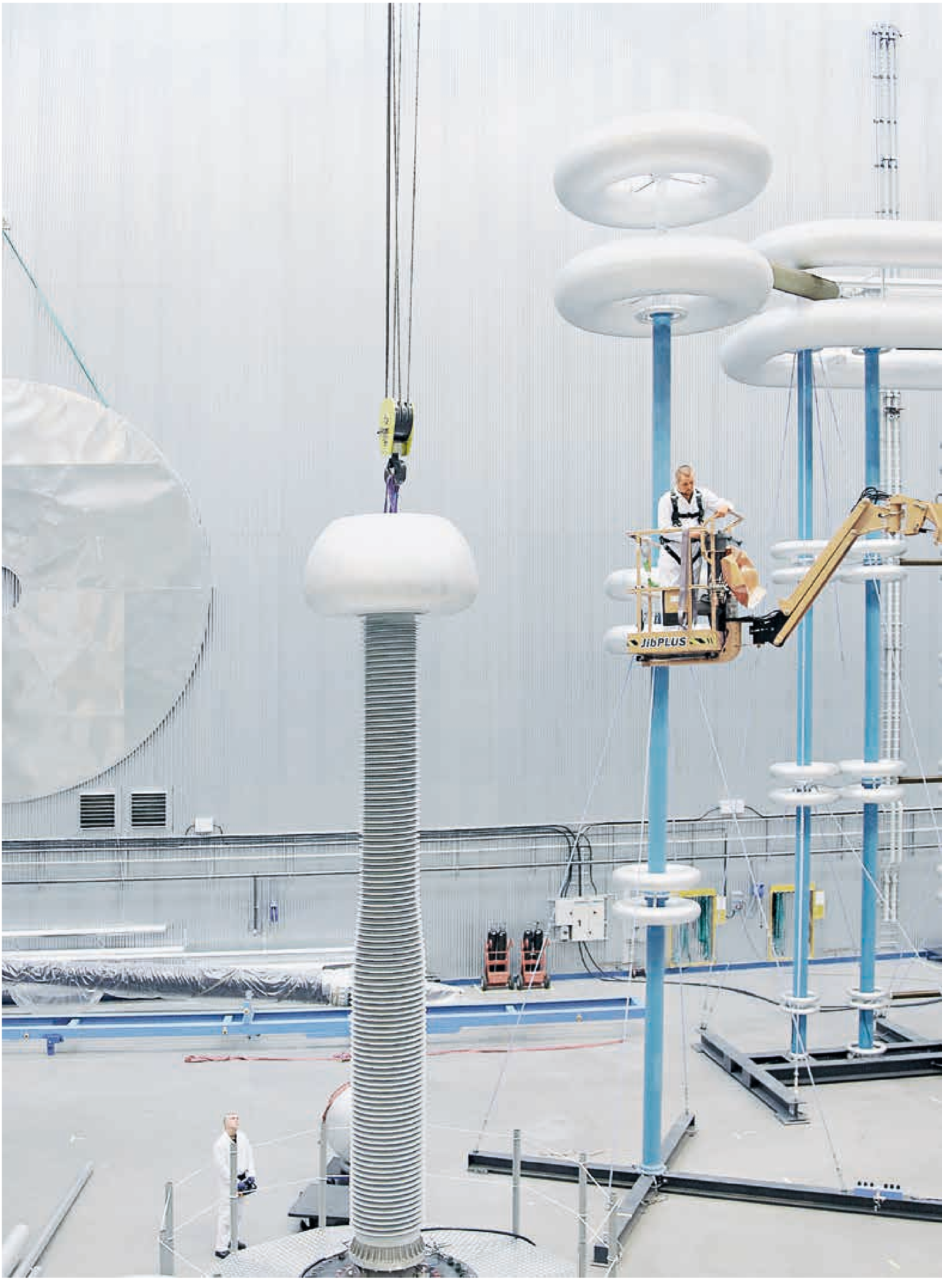
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Break-through!

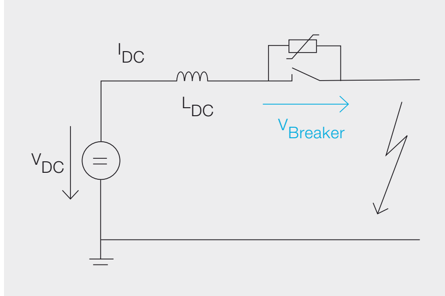
ABB's hybrid HVDC breaker, an innovation breakthrough enabling reliable HVDC grids

MAGNUS CALLAVIK, ANDERS BLOMBERG, JÜRGEN HÄFNER, BJÖRN JACOBSON – ABB and its predecessor companies pioneered HVDC (high-voltage direct current) technology, permitting low loss transmission of power over long distances. All HVDC lines realized so far have been point-to-point links. The scope of application of the technology could be greatly increased if lines could be built with more than two terminals, enabling them to develop into HVDC grids. However, the absence of a suitable breaker for the required voltages and speeds and with acceptable losses has hitherto prevented the advent of such topologies for HVDC. All this has changed with the launch of ABB's new HVDC breaker.

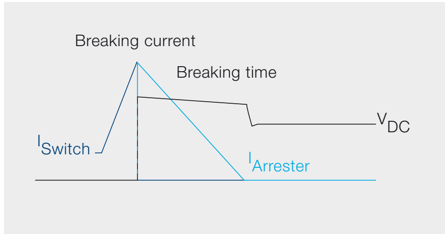
Title picture
ABB's hybrid circuit breaker is one of the greatest innovations in the company's history. Finally DC grids can become a reality.

1 Representation of an HVDC grid and principle of HVDC breakers

1a Blue dots represent converter stations in HVDC grid.



1b HVDC breaker



1c Principle of operation

Compared to high-voltage AC grids, active power conduction losses on HVDC lines are relatively low and losses related to reactive power are zero, making HVDC grids an attractive proposition for transmission over long distances [1] – a topic that is of especial interest in view of the rapid growth in generation from renewables.

But the hybrid breaker does not need to await the full-scale emergence of HVDC grids to come into its own. Many present transmission proposals involve point-to-point HVDC links and hybrid breakers have a part to play here too. Besides converting power, HVDC converter stations can simultaneously contribute to the AC network's stability through reactive-power control. If the converter can be rapidly disconnected from the HVDC line in case of a fault, the converter station can go directly into stand-alone operation as a static compensation unit (STATCOM), and so continue to support the AC network's stability.

Technical demands on HVDC breakers are high. The time permitted to interrupt a current flow is shorter than for a comparable AC application due to the lower impedance of the lines (meaning the voltage drop caused by a fault can spread faster). A short-circuit fault typically has to be cleared within 5 ms in order to not affect converter stations as far away as 200 km. Because converter stations typically rely on the DC voltage being at least 80 percent of its nominal value to assure normal operation, faults must be cleared within milliseconds.

A shorter fault clearance time implies reduced requirements for power dissipation in the arrester bank, but requires a higher voltage capability of the arrester.

A purely mechanical HVDC breaker can clear a line within several tens of milliseconds, but this is too slow to fulfill the requirements of a reliable HVDC grid [2]. Nevertheless, mechanical breakers are used for such purposes as the extinguishing of fault currents. Further drawbacks of mechanical breakers are that they require additional components to generate the current zero crossing so that the current can cease to flow.

HVDC breakers based on semiconductors can easily overcome the limitations of operating speed, but because the semiconductors are permanently in the path of the current, they generate conduction losses that are typically in the range of 30 percent of the losses of the converter station.

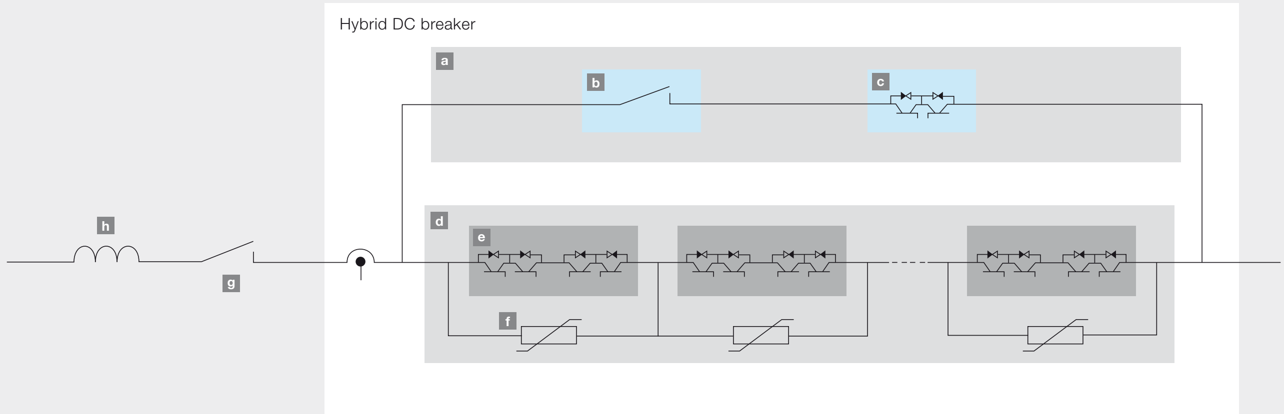
An HVDC grid is shown in → 1a. A circuit with a mechanical HVDC breaker and an arrester is shown in → 1b, and the transients that occur during breaking in → 1c. The current starts to rise when the fault occurs (the rate at which it rises is determined by the inductance of the line reactor). When the switch opens, the current is commutated to the arrester and starts to decrease. The fault current in the arrester bank establishes a counter voltage, and this reduces the fault current to zero by dissipating the energy stored both in the HVDC reactor and in the fault current path.

The total time to clear the fault consists of:
- the time during which the current rises prior to commutation
- the duration of its subsequent decrease while the line is cleared.

Both time intervals are important considerations in the design and cost of the HVDC breaker, as well as that of the line reactor.

The breaking time is governed by the response time of the protection and the action time of the HVDC switch. A longer

2 Hybrid HVDC breaker



a Main current branch (when current is flowing) consisting of:
b Fast mechanical disconnector HVDC breaker
c Load-commutation switch (semiconductor-based)

d Main HVDC breaker consisting of:
e Semiconductor interrupter
f Arrester bank

g Residual current breaker
h Current limiting reactor

breaking time requires the HVDC switch to have a higher maximum current breaking capability. This also increases the energy handled by the arrester and correspondingly leads to a higher cost for the HVDC breaker. It is therefore important to keep the breaking time as short as possible. When the breaking time and the maximum breaking current capability are given, the only remaining adjustable parameter is the inductance of the HVDC reactor (which governs the rate of current rise). The size of the HVDC reactor may in turn be limited by factors such as cost and the stability of the HVDC grid system.

The time allowed for fault clearance will affect the required voltage capability of the arrester as well as that of pole voltage protection. A shorter fault clearance time implies reduced requirements for power dissipation in the arrester bank, but requires a higher voltage capability of the arrester. This spells 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. 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 an 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.

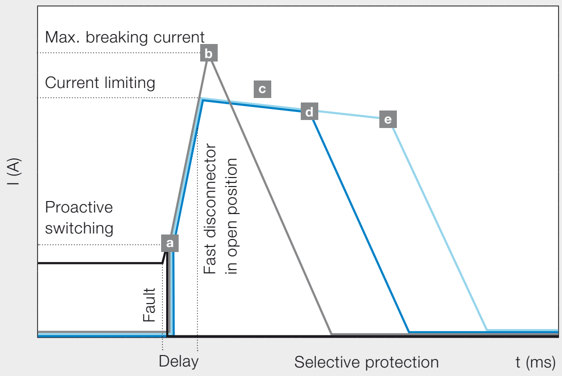
The hybrid HVDC breaker

The hybrid HVDC breaker → 2 is based on the arrangement of → 1b but features an additional branch → 2a. This branch consists of a semiconductor-based load commutation switch → 2c connected in series with a fast mechanical disconnector → 2b.

During normal operation, the current only flows through the bypass → 2a. When an HVDC fault occurs, the load commutation switch immediately commutates the current to the main HVDC breaker → 2d. With the branch → 2a no longer carrying current, the disconnector → 2b opens, thus protecting the load commutation switch → 2c from the primary voltage that builds up across the main HVDC breaker. The required voltage rating of the load commutation switch is thus significantly reduced in comparison to a component that remains in the main current path throughout the switching cycle. Its voltage rating must only exceed the on-state voltage of the main HVDC breaker, which is typically in the kV range for a 320 kV HVDC breaker. On account of this reduced load-blocking voltage, the on-state voltage of the load commutation switch is typically in the range of several volts only. The on-state losses of the hybrid HVDC breaker are thus reduced to a percentage of the losses incurred by a pure semiconductor breaker, ie, 0.01 percent of the transmitted power.

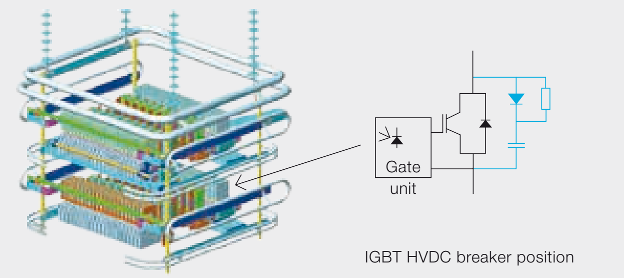
Besides converting power, HVDC converter stations can simultaneously contribute to the AC network's stability through reactive power control.

3 Control of hybrid HVDC breaker

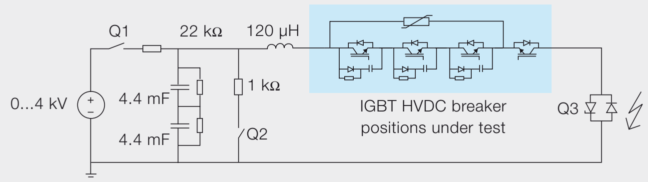


a LCS opens (LCS: load commutation switch)
b Main HVDC breaker max. current protection
c Current limiting
d External trip signal of selective protection to main HVDC breaker
e Main HVDC breaker max. temperature protection

4 Design of 80 kV main HVDC breaker cell



5 HVDC breaker component test circuit



The main semiconductor-based HVDC breaker ➔ 2d is separated into several sections with individual arrester banks ➔ 2f dimensioned for full voltage and current breaking capability. After fault clearance, a disconnecting circuit breaker ➔ 2g interrupts the residual current and isolates the faulty line from the HVDC grid to protect the arrester banks from thermal overload.

The mechanical switch ➔ 2b opens at zero current and with low voltage stress, and can thus be realized as a disconnector with a lightweight contact system. The fast disconnector will not be exposed to the maximum pole-to-pole voltage defined by the protective level of the arrester banks until after having reached the open position. Thomson drives [4] result in fast opening times and a compact disconnector design using SF_6 as insulating medium.

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. 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 ➔ 3a. The main HVDC breaker delays current breaking until a trip signal is received or the faulty line current is close to the maximum breaking current capability of the main HVDC breaker ➔ 3b.

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 limitation mode prior to current breaking ➔ 3c. The main HVDC breaker controls the voltage drop across the HVDC reactor to zero to prevent a further rise in the line current. The maximum duration of the current limiting mode depends on the energy dissipation capability of the arrester banks ➔ 3d.

Fast backup protection similar to that of pure semiconductor breakers is possible for hybrid HVDC breakers in HVDC switchyards. Over-currents on the line or higher-level switchyard protection can 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 case of a breaker failure, backup breakers can be activated almost instantaneously – typically within less than 0.2 ms. This avoids major disturbances in the HVDC grid, and keeps the required current-breaking capability of the backup breaker at reasonable values.

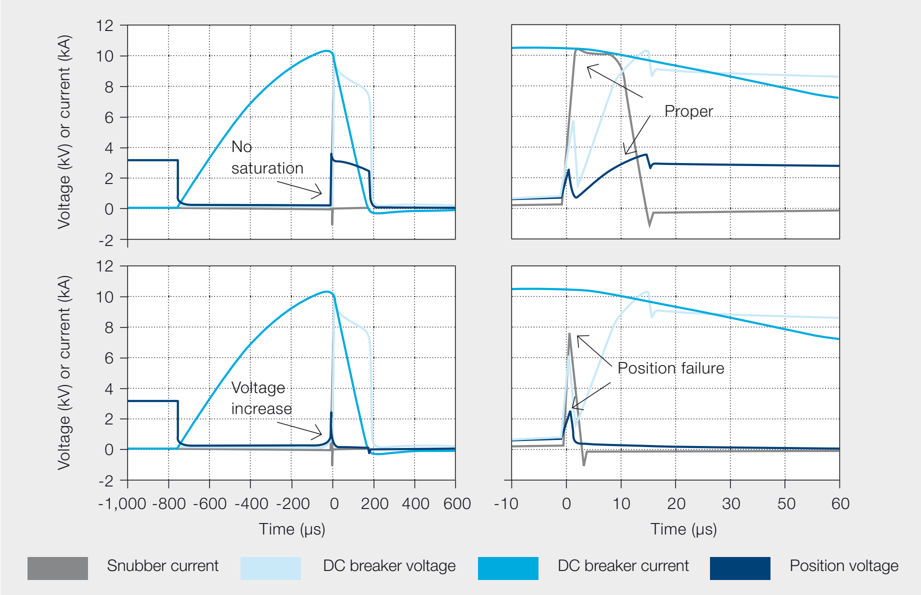
Prototype design

The hybrid HVDC breaker prototype is designed to achieve a current breaking capability of 9.0 kA in an HVDC grid with a rated voltage of 320 kV and rated transmission current of 2 kA. The maximum current breaking capability is independent of the current rating, depending on the design of the main HVDC breaker only. The fast disconnector 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 ➔ 2d consists of several HVDC breaker cells with individual arrester banks limiting the maximum voltage across each cell ➔ 2e to a specific level during current breaking. Each HVDC breaker cell contains four HVDC breaker stacks ➔ 4. Two stacks are required to break the current in either current direction.

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.

6 Maximum stress tests on IGBT HVDC breaker positions (traces on the right are zoomed)



The mechanical switch opens at zero current and with low voltage stress, and can thus be realized as a disconnector with a lightweight contact system.

Each stack is composed of up to 20 series-connected IGBT HVDC breaker positions. Due to the large di/dt stress during current breaking, a mechanical design with low stray inductance was adopted. 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, as the main HVDC breaker cells are not exposed to the line current during normal operation.

For the design of the load commutation switch → 2c, 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 3 × 3 IGBT positions for each current direction was chosen for the present design. A cooling system is required due to the switch's continuous exposure to the line current.

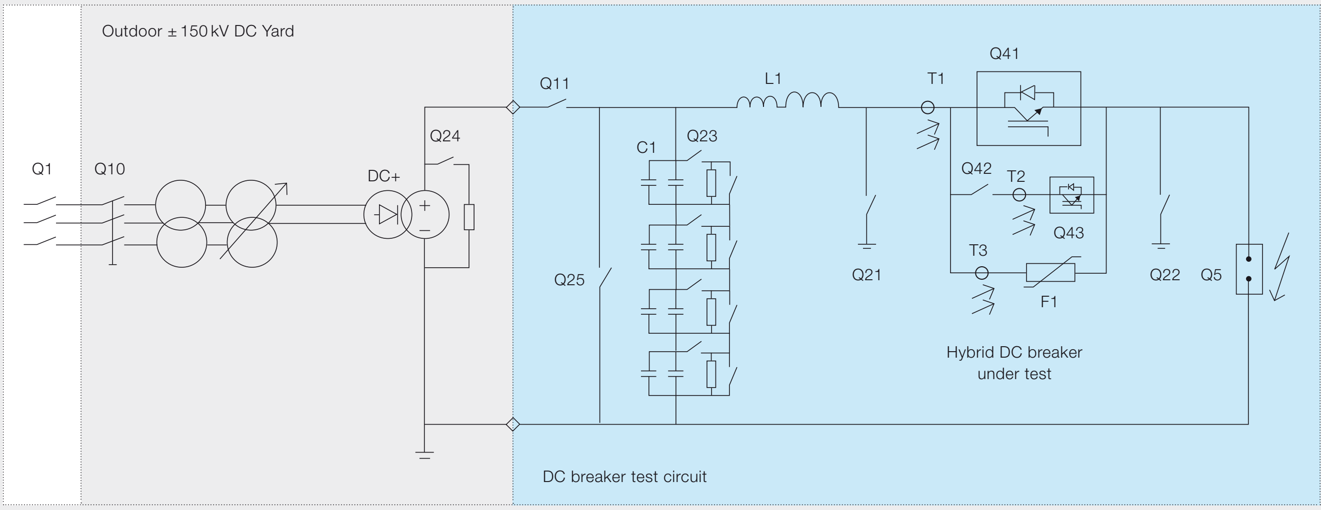
Each stack is composed of up to 20 series-connected IGBT HVDC breaker positions.

Test results

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 → 5. A fourth IGBT module was connected in the 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, represented pole-to-ground faults in the HVDC grid.

The maximum current breaking capability of the IGBT HVDC breaker cell is determined by the saturation current of the IGBT modules → 6 (rather than the safe operation area as is typical in voltage source converter applications). The series-connected HVDC breaker IGBT positions can commutate the line current into the RCD snubber circuits within 2 μs, limiting the rate of rise in voltage across the positions to 300 V/μs. Zero voltage switching reduces the instantaneous switching losses and ensures equal voltage distribution independent of the

7 ABB's containerized HVDC breaker test circuit



Successful verification testing at device and component level demonstrated the performance of the components. The complete hybrid HVDC breaker has now been verified in a demonstrator setup at ABB facilities.

tolerances in the switching characteristics of the applied IGBT modules.

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 causes an immediate voltage drop across the IGBT modules. During a purposely destructive test, the resulting internal heat dissipation within the IGBT module destroyed the encapsulated IGBT chips. Due to the use of presspack IGBTs, a reliable short circuit was created without mechanical destruction of the failed IGBT module. Since only one of the IGBT modules failed during the test, the fault could still have been 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 required significantly more space. The test circuit for the hybrid HVDC breaker concept is shown in ➔ 7. The desired HVDC voltage level was built up by charging the capacitor bank C1. The reactor L1 is selected to assure the expected current derivative (di/dt) during a short-circuit fault. The short-circuit fault was initiated by the triggered spark gap Q5.

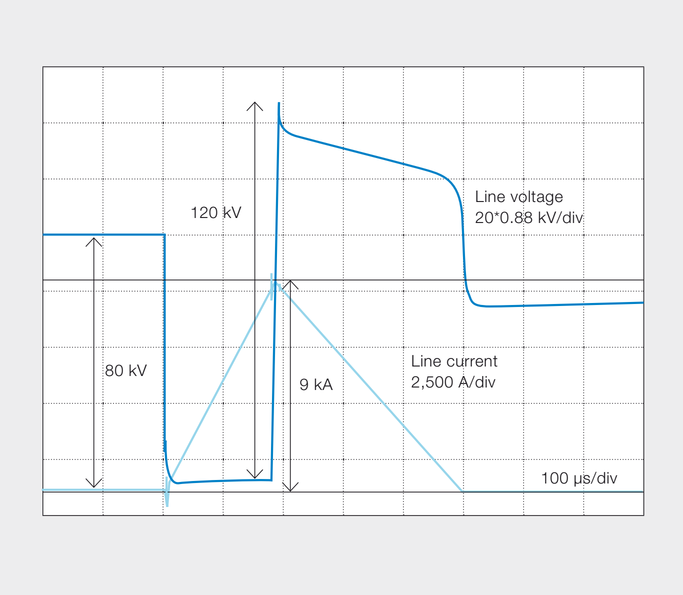
A typical test result is shown in ➔ 8. A maximum breaking current of over 9 kA is verified. The voltage across the HVDC breaker cell exceeds 120 kV during current commutation. The breaking capability of one 80 kV HVDC breaker cell thus exceeds 1 GVA. Furthermore, equal voltage distribution with a maximum 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.

Test results

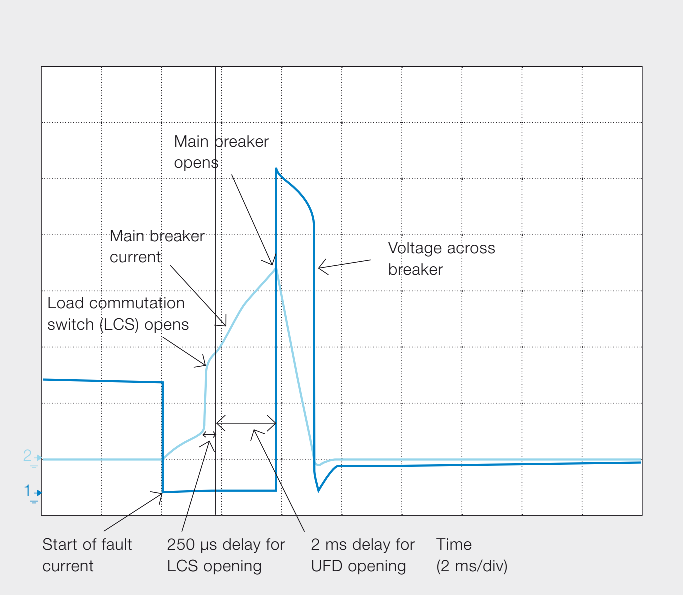
The main breaker test setup was expanded to verify the complete hybrid HVDC breaker concept. A second capacitor bank and large reactors were installed to limit the rate of line current rise to typical HVDC grid values. The ultra-fast disconnector and load commutation switch are included in the system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

Introduction of bimode insulated gate transistor (BIGT) technologies will double the current breaking capability of presspack modules.

8 Verification of modular IGBT HVDC breaker cell



9 Verification of the hybrid HVDC breaker system



The next step is to test such a breaker in a real HVDC transmission line.

Successful verification testing at device and component level demonstrated the performance of the components. The complete hybrid HVDC breaker has now been verified in a demonstrator setup at ABB facilities. A breaking event with a peak current of 9 kA and 2 ms delay time for opening the ultra-fast disconnector in the branch parallel to the main breaker is shown in → 9. 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 disconnector. The assembly under test consisted of one 80 kV unidirectional main breaker cell, along with the ultra-fast disconnector and load commutation switch. The higher voltage rating is accomplished by connecting several main breaker cells in series. Tests have not only been carried out for normal breaking events, but also for situations with failed components in the breaker.

Outlook

Introduction of bimode 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 (see also “The two-in-one chip” on pages 19–23 of this edition of *ABB Review*).

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 for HVDC voltages up to 320 kV and rated currents of 2 kA, removing a major obstacle in the realization of HVDC grids. The next step is to test such a breaker in a real HVDC transmission line.

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