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Hybrid HVDC breaker – Technology and applications in point-to-point connections and DC grids

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SUMMARY

This paper presents the Hybrid HVDC breaker concept and the achievements in its implementation. HVDC breakers are essential building blocks for selective protection and thus system stability in HVDC networks. If an HVDC grid is built without fast-acting breakers capable of interrupting and isolating DC faults, the DC system voltage will quickly collapse in the event of a fault and the effects of the fault will propagate very quickly throughout the network due to low impedance of the DC network. Beyond enabling DC grids, HVDC breakers can improve the stability and availability of AC grids connected to point-to-point HVDC transmission systems. In case of DC failures, the converter stations can be quickly isolated from the faulty DC side, thus continuing to stabilize the AC grid by generating or absorbing reactive power.
This paper contains a detailed description of the Hybrid HVDC breaker, its control and design principles with focus on reliability. The results from functionality and failure tests on the prototype will be presented. The paper also summarizes the test results of its main components such as the semiconductor modules and the ultra-fast disconnector. The results show that the Hybrid HVDC breaker is a feasible concept ready to be used in future HVDC systems. Through a sectionalized design using breaker cells a controlled current limitation as well as dc-voltage post-fault recovery is demonstrated. The handling of dc-faults in point-to-point dc-overhead line transmission is discussed enabling fast fault clearing action while providing continuous reactive power support. The HVDC-breaker thereby significantly boosts the capability and functionality of dc-circuit protection in order to enable a flexible future expansion of point-to-point transmission into multi-terminal or meshed configuration.

KEYWORDS

Hybrid DC breaker, Ultra fast disconnector, DC grid, Load commutation switch, Main breaker, Semiconductor, Fault clearing, Voltage restoration, Multi-terminal

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1. Introduction

The hybrid DC breaker as shown in Figure 1, consists of two parallel paths. One path, called main breaker, is made of series connected IGBT modules, and the other path is made of lower number of matrix connected IGBT modules and an ultra-fast disconnector which is called load current path. In normal situation of DC system, the current passes through the load current path. [1]

The hybrid DC breaker can be designed either as unidirectional or bidirectional in order to interrupt fault currents in one direction or in both directions, respectively. The hybrid DC breaker can be integrated in the DC converter station or it can be a stand-alone installation. The stand-alone hybrid DC breaker is more applicable for DC grid applications.

A modular, sectionalised design of the DC breaker enables load current transfer without introducing high voltage transients, fault current limiting mode, and replacement of pre-insertion resistors for DC line energization.

The IGBT-based load commutation switch according to Figure 1 opens proactively at a certain fault current level in order to commutate the fault current almost instantaneously into the main breaker. Thereafter, the mechanical ultra-fast disconnector (UFD) opens within less than 2 ms to disconnect the load commutation switch from the main circuit. After the UFD is opened, the main circuit breaker is ready for operation.

The main circuit breaker opens depending on the breaking command of the DC yard control and protection. The DC breaker provides current limiting functionality for self-protection to avoid damage caused by fault currents exceeding the maximum breaking current limit of the applied IGBT modules until the breaking command is received.

Opening of the main current breaker forces the fault current to commutate almost instantaneously into the nonlinear resistor path formed by an arrester bank. The arrester bank reduces the fault current to zero by dissipating the energy of the fault. To achieve a short duration for fault current reduction, the total protective level of the arrester banks is selected to be 1.5 times the nominal dc-voltage. Furthermore, the arrester bank will serve as over-voltage protection of the IGBT modules in the main breaker.

The protective voltage level of the arrester bank is a design parameter for the DC breaker voltage rating. However, the minimum energy dissipation capability of the arrester bank depending on the number of parallel ZnO legs will be project-specific and can be scaled depending on the project requirements given by the frequency of fault events, the number of restart attempts at a fault event or by the current limiting action that is considered for the system protection strategy.

The main current breaker is sectionalized into individually controllable cells designed for a nominal DC voltage of 80 kV.

The DC breaker equipment will be installed as an indoor DC switchyard. The mechanical integration results in a small footprint and is designed based on standard earthquake and radio interference requirements.

Individual turn-off of the main current breaker sections will allow adaptation of the total protective voltage level of the arrester banks in order to provide different voltages counteracting the fault current. As an example, a protective level corresponding to the instantaneous dc voltage of the healthy pole will freeze the fault current in strong DC grids to the level observed at the time instance at which the current commutation into the individual sections of the arrester bank occurs.

The control interface of the modular hybrid DC breaker sections will allow external control of the fault breaking, current limitation and normal load current transfer.

The different functions of the hybrid DC breaker concepts are available directly after the UFD has opened. The fault breaking command opens all cells of the main breaker; current limitation will require opening more than 2/3 of the cells. Sequential turn-on of the DC breaker cells reduces the inrush current of the DC line during energizing.

After the fault current is transferred to the main breaker path, all main breaker cells shall open. In the case of current limitation all cells will finally open, depending on the identified location of the fault by the DC system control and protection.

After fault breaking, the residual current disconnecting circuit breaker opens within 1 s to protect the arrester bank from thermal overload due to residual currents.

The main breaker does normally not need forced cooling since the current does not pass for a long time through it. However, for the load commutation switch a cooling system is required related to normal load current in a closed breaker. The cooling system is dependent on the installation location of the hybrid DC breaker. If the hybrid DC breaker is installed close to a converter station, the cooling system can be integrated with the water cooling system of the station. If the hybrid DC breaker is stand-alone, a separate cooling system is needed. Cothex cooling which is based on passive two-phase evaporation/condensation concept with air cooling is considered for stand-alone installations.

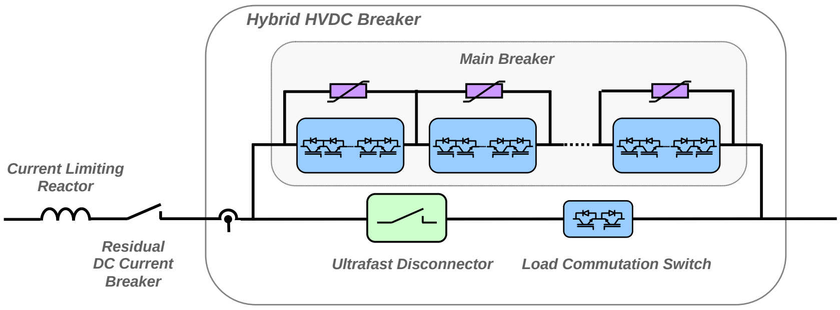


Figure 1. The hybrid DC breaker concept

The functionality of the hybrid DC breaker and its components has been verified by extensive testing. Figure 2 illustrates the hybrid DC breaker test circuit that has been used. The capacitor bank C1 builds up the desired DC voltage level of 80kV, supplied by a 150kV DC switchyard. The spark gap Q5 initiates the short-circuit fault while the reactor L1 controls the fault current rise rate, di/dt, during the conduction time.

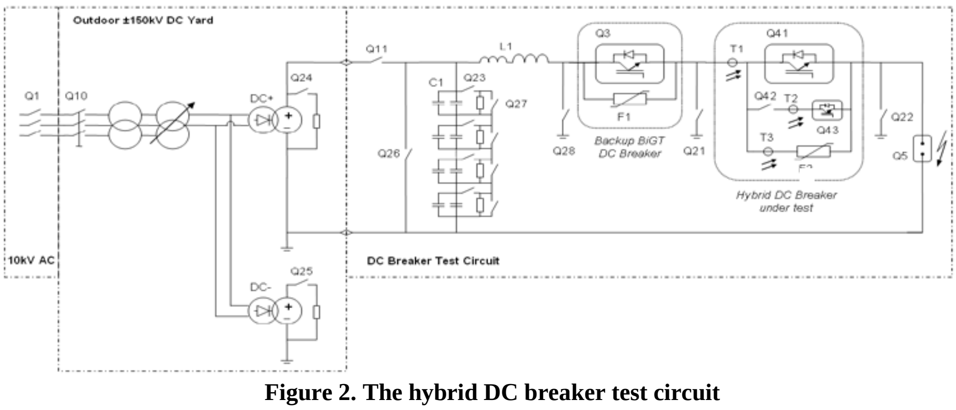


Figure 2. The hybrid DC breaker test circuit

2. Hybrid DC breaker components

2.1. Main breaker

The main breaker consists of 80 kV cells. For higher voltage levels, the number of cells will be increased. There is an arrester bank over each DC breaker cell which helps to operate them individually. During current interruption the voltage over each cell is increased to the maximum protection level of the arrester bank which is 120 kV (1.5 times the module voltage). Each stack includes 10 IGBT modules which makes the main breaker cell. Each main breaker cell in the unidirectional hybrid DC breaker consists of 4 stacks which are connected in series. In bidirectional hybrid DC breaker each cell consists of 8 stacks which are connected in anti-series as shown in Figure 1. The mechanical structure of a double cell which can take 160 kV is shown in Figure 3. With double cell structure the footprint will be decreased. In the double cell structure, each 80 kV module is independent and has its own arrester bank. The cell structure of a double cell, a single stack and a single position can be seen in Figure 3.

In the HVDC breaker the new semiconductor device from ABB, the BIGT, will be used. BIGT modules have higher current and voltage capability than the current IGBT modules. The nominal current of the hybrid HVDC breaker is 2.6 kA and the maximum current breaking capability is 16 kA.

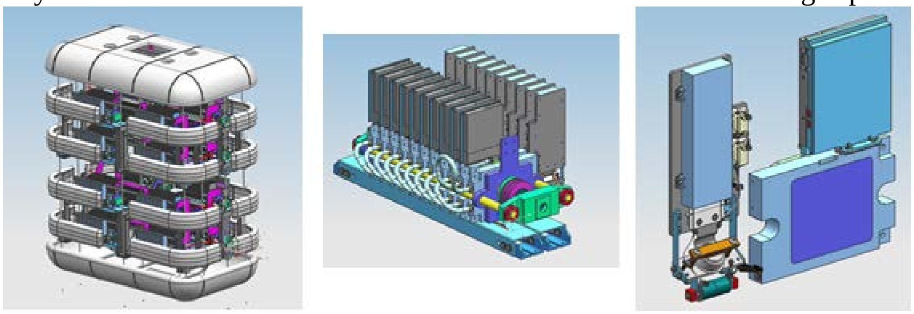


Figure 3. The main breaker design

The first test that has been done on the main breaker was a current breaking test. The main breaker module, the UFD and the load commutation switch are initially closed. The capacitor bank has been charged through the DC supply. The capacitor bank is discharged through the hybrid DC breaker and then the fault is applied by igniting the spark gap. After fault initiation, the current increases. The load commutation switch opens at 1.5 kA and then the UFD is opened providing contact separation and dielectric voltage withstand capacity in 2 ms. At the end the main breaker opens to interrupt the current. In Figure 4, the current commutation and interruption process can be seen.

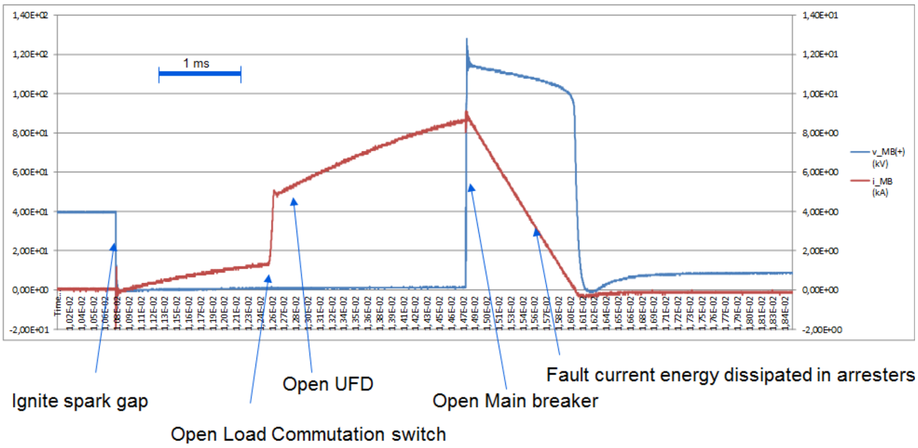


Figure 4. Test results for current breaking

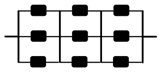
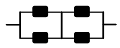
The hybrid DC breaker has been tested for possible failures to verify its redundancy. The most important failure is the failure of one IGBT module. This failure can happen during the current commutation from the load current path to the main breaker. If one position fails the IGBT module goes to short circuit failure mode and the hybrid DC breaker can still interrupt the fault current, but the positions beside it shall survive. In this case the current will increase in the snubber circuit of the failed IGBT module, but it shall not have any current effect in the neighbour positions. According to tests, the maximum current in positions beside the failed IGBT module has 0.6 kA and the IGBT module and its snubber survive.

2.2. Load commutation switch

The load commutation switch is designed to provide a low-loss load current path in order to decrease the power losses of the hybrid DC breaker in the normal situation of the power system. It contains only a low number of IGBT modules just sufficient to commutate any fault current over to the main breaker. For the bidirectional hybrid DC breaker, the IGBT modules should be placed anti-series, so it can interrupt the current in both directions.

The electrical and mechanical design provides redundancy and low power losses. Table 1 shows two alternatives of IGBT modules placing. Alternative 1 has been chosen, since it has lowest power losses and highest redundancy. The power losses in this topology will increase to the value of power losses in alternative 2 when 5 IGBT modules fail, and it shows that the reliability in this topology is in a good range. Thus alternative 1 is selected to be the final topology, but in order to design the cooling system and snubber circuit, altenative 2 is considered.

Table 1. Different designs of the load commutation switch (Power losses are per component)

Case #	Max. IGBT conduction loss	Max. diode conduction loss	Topology
1	1.5 kW	1.3 kW	
2	2.5 kW	2.2 kW	

If the hybrid DC breaker is installed in a converter station the same water cooling system can be used for the dc breaker equipment. The water cooling technology will be the same technology that has been used in ABB HVDC valves.

If the hybrid DC breaker is installed as a stand-alone line breaker, cothex cooling will be used. The Cothex cooling, an air-cooled thermosyphon based cooling system, was developed for the load commutation switch to propose an alternative solution to de-ionized water cooling system. A thermosyphon is a hermetic passive device partially filled with a pure fluid that changes phase from liquid to vapor and vapor to liquid. The fluid circulation is based on natural convection due to the liquid / vapor density difference and does not require any mechanical pump, so that it can comply with long time of operation without maintenance. Figure 5 shows the working principle of the cooling system. The power modules are thermally in contact on both sides with the evaporator base plate where the heat is applied. The liquid is partially evaporated; the vapor rises up to the condenser. When releasing the heat to the air stream, the vapor condenses back into liquid and flows down by gravity to the bottom of the evaporator. As the energy is transferred by the latent heat of vaporization, large heat flow can be dissipated from small areas with small temperature differences.

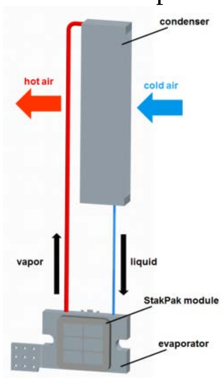


Figure 5. Schematics of the thermosyphon cooling system

The thermosyphon cooling system is entirely made of brazed aluminum which makes it cost-competitive and lightweight. Connections between evaporator and condenser can be partly or entirely made of flexible pipes which make it easy to install in a press-pack system. Figure 6 shows the load commutation switch press-pack assembly including the thermosyphon coolers.

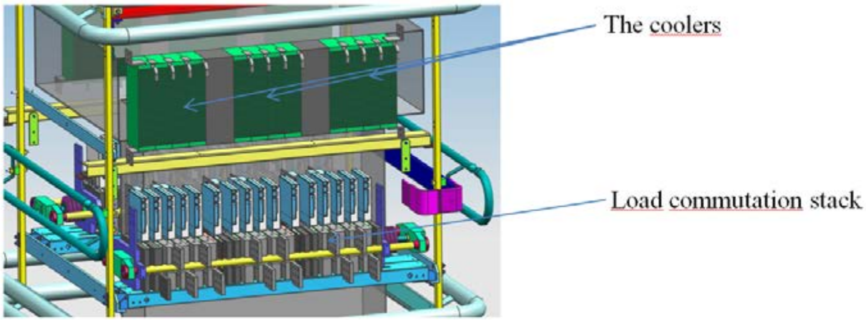


Figure 6. Press-pack assembly of the LCS with thermosyphon cooling system

2.3. Ultra-fast disconnector

In order to realize the low-loss load current path of the hybrid DC breaker scheme, the load commutation switch has to be complemented by an ultra-fast mechanical disconnector (UFD) installed in series (compare Figure 1). This low-loss path allows a reduction of the on-state losses by at least a factor 10 compared to a pure semiconductor DC breaker lacking such an UFD and load commutation switch. A significant amount of energy can thus be saved during the hybrid DC breaker's lifetime. The load commutation switch commutates any fault current over to the main breaker path before the UFD is opened. Thus, it disburdens the UFD of the need to interrupt the load or fault current, just requiring the UFD to switch a small residual direct current. In turn, the UFD protects the load commutation switch against the main breaker switching voltage transient. Sufficient dielectric insulation between the UFD's poles of e.g. 1.5 times the operating voltage (see section 1) must therefore be established before the main breaker is opened to interrupt fault currents. Hence, the maximum opening time of the UFD is determined by the maximum fault current (limited by the main breaker) and the fault current rise rate (limited by the current limiting reactor and the line impedance). For the UFD presented here, the time from trip signal to dielectric insulation is lower than 2 ms, with rated DC voltage of 320 kV and rated nominal current of 2600 A [2].

The extremely short opening time required is roughly 10 times lower than for typical available HVAC breakers and carries a number of design implications (Figure 7). The contact system is of a lightweight and compact design, based on multisegmented electrical contact elements (eC) being moved in a direction perpendicular to the current path (pL, pR). This allows for fast residual current interruption and dielectric insulation build-up. Two axisymmetric shield electrodes (sE) provide dielectric shielding of spring loaded contacts (fC) that compress the moving contacts (eC) which in closed position form two parallel contact stacks conducting the load current. The moving contact members (eC) are embedded in flat insulating rods (iR). These rods are in turn connected to actuators of repulsive force type based on the well-known Thomson coil (eddy current) principle (A, B). They provide fast response to the trip signal, a high acceleration up to 3000 g and dual motion of the contacts. The contact system including the drives are mounted inside a metallic enclosure of GIS type (eM) using a compressed insulating gas such as SF_6, the latter greatly reducing the required insulation distances and thus contact system weight.

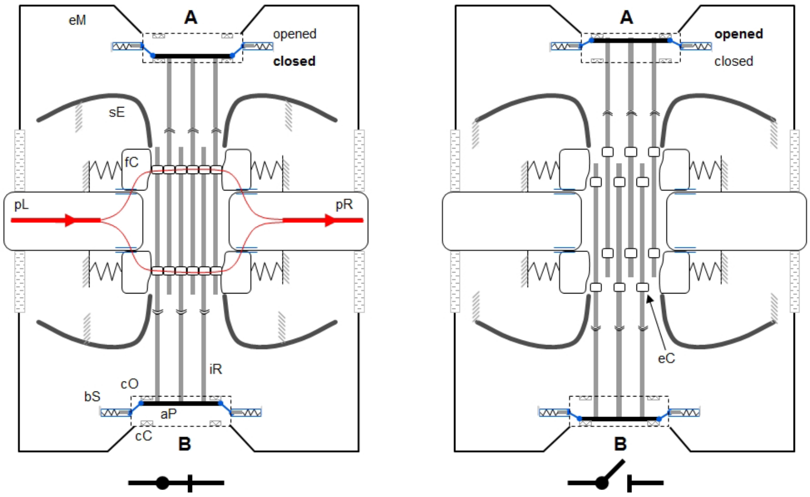


Figure 7. A principle cross-sectional view of the UFD and its contact system in closed (left) and opened (right) position

The external control and supervisional unit contains the pre-charged capacitors as energy storage for the actuators as well as all control and supervisory circuits. Fast electronics and the use of optical transmission links reduce the time delay for trip commands to negligible levels.

The use of a metallic enclosure allows for either grounded enclosure approach analogue to GIS and dead-tank breakers, or a live-tank variant where the enclosure is brought to the same electrical potential as one of the leads. For the live-tank, externally insulated variant, the insulation to ground is provided by the surrounding air and string insulators which also makes a cascaded arrangement (2,3…) feasible to reach higher rated voltage, e.g. above 500 kV_{DC}. To ensure a proper voltage grading between the individual UFD units, internal or external grading capacitors can be used. Series cascading is also feasible for the ground-potential (dead-tank) variant but requires a larger enclosure which carries internal design implications.

As no specific tests standards are available yet for the novel UFD device, existing AC breaker standards, DC insulation component standards as well as system simulations have been combined to form the first set of UFD test specifications including corresponding test descriptions. All technical aspects of the UFD including electrical, mechanical and thermal performance have been considered therein. In addition to individual tests of e.g. mechanical switching speed and endurance, HV insulation, and contact temperature rise, synthetic tests were conducted. This kind of testing is widely used for certification of high-voltage switchgear and re-creates typical operating and fault conditions, including full voltage, current, and mechanical (switching) stress on the UFD. Furthermore, the UFD has been installed and successfully tested in the hybrid HVDC breaker test circuit (see Section 2.1) to verify switching sequence and timing.

3. Hybrid HVDC-Breaker applications

Three different applications of HVDC breakers will here be discussed.

1. DC-breaker in point-to-point HVDC transmission
2. Free-standing HVDC-breaker for dc-grid enabling of a point-to-point or multi-terminal
3. Free-standing HVDC-breaker as a line breaker in meshed dc-grid.

Other sources of dc-grid application requirements are found in [3],[4] and[5].

3.1. HVDC-breaker for fast dc-fault handling capability in point-to-point transmission

A half-bridge modular multi-level converter (HB-MMC) will respond to dc-side faults with short circuit current limited by the inherent impedance of the converter as given by the arm reactors and the transformer in combination with the short circuit current level of the connected ac-grid. The state of the art for dc-cable transmission is to use the ac-side breakers to interrupt fault current, followed by dc-side disconnection of the faulty cable prior to reconnection of the converter by reclosing ac breakers. Such protection strategy gives adequate availability due to the relatively low probability for cable failures, although reactive power support by the converter is lost during the cable isolation sequence. For dc-overhead line transmission, or when very high availability of reactive power support is required, a fast HVDC-breaker as shown by Figure 8 will facilitate interruption of dc-fault current allowing continuous reactive power support by the converter. This system is a bipolar transmission with a metallic return conductor based on asymmetrical monopoles for the positive and negative dc-poles, respectively. Based on the requirement to limit the short circuit current during dc-side faults a unidirectional HVDC-breaker will be sufficient.

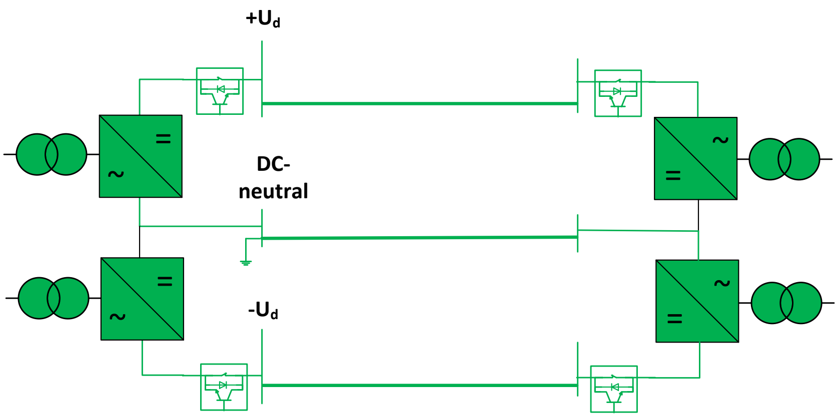


Figure 8. Ponit to point asymmetric HVDC system

The short circuit current from the converters during a DC-fault is cleared by the HVDC breakers, allowing reactive power support to persist with a minimum disturbance, as shown in Figure 9. Clearance of a dc-side fault involves deionization of the arc which would be established at a lightning strike on an over-head line. Successful deionization of a dc-fault is achieved through the counter voltage provided by the dc-breaker arresters. Since the arrester protective voltage is 1.5 times the dc-pole voltage level a fast reduction of the fault current is obtained. Typically dc-fault deionization has a duration of 100 to 200 ms.

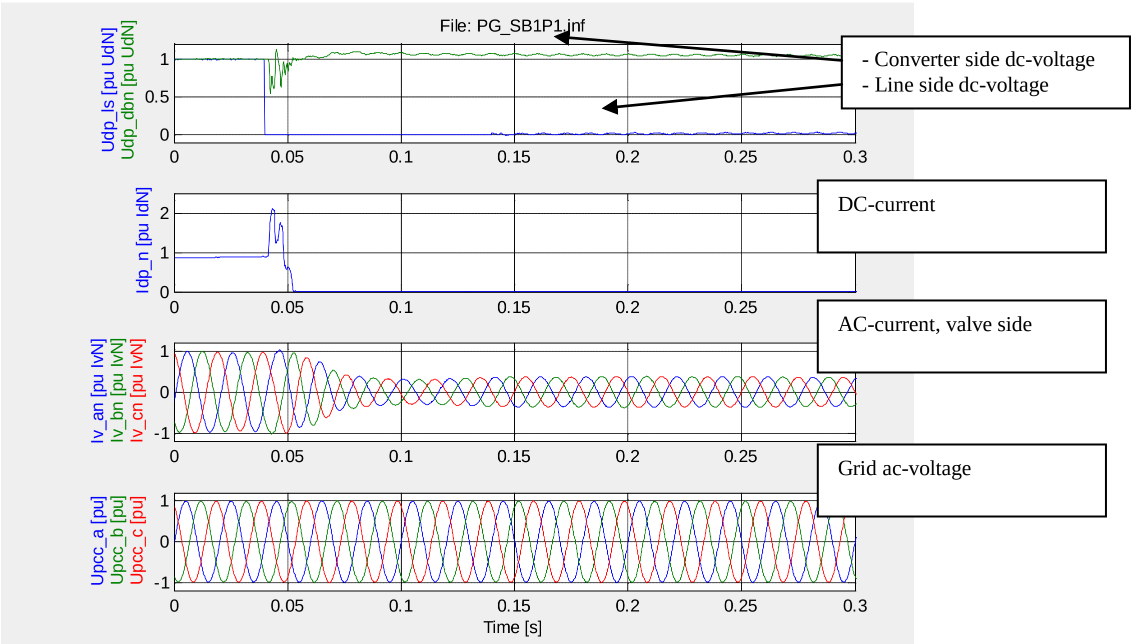


Figure 9. DC-fault handling in OHL point-to-point transmission

In Figure 10 a fault clearing sequence of two restart attempts is presented followed by a final successful recovery to normal voltage. An unsuccessful voltage recovery, due to failure to deionize the arc will result in a repeated HVDC-breaker protection actions and deionization intervals. Typically the HVDC-breaker will be designed to handle three restart attempts, where one of the major decisive factors is the energy capability of the arresters across the HVDC-breaker cells. The case presented relates to a dc-breaker having 7 main breaker cells. The first trace shows the status of each of the breaker cells, showing all cells opening at the fault instant. At the first and second restart attempt, the HVDC-breaker cells are closed sequentially giving a smooth rise of current due to the line fault not being successfully cleared at this stage. In the fourth trace the individual HVDC-breaker cell voltages are seen related to the sequential operation. After successful fault clearing the dc-side voltage is gradually established through sectionalized switching of the HVDC-breaker cells as shown by Figure 10.

In some critical applications where degraded insulation withstand capability of overhead lines can be expected, for example in highly polluted or coastal areas, a reduced dc-voltage restart could be included. In order to achieve a capability to quickly restore operation at a reduced dc-voltage level, a HB-MMC must be somewhat overrated since the ac-voltage level obtained at the converter bus (valve side of converter transformer) is defined by the modulation index and the dc-voltage level according to the equation below.

$$\overline{U}_v = m_a U_d - jx_v \overline{I}_v$$

In order to obtain a design where the same level of converter bus voltage can be maintained both at normal and reduced dc-voltage, the nominal converter bus voltage level must be reduced accordingly. An example is presented below related to the following operating conditions:

1. $U_{d1}=U_{dN}$
2. $U_{d2}=0.8U_{dN}$

$$\left.\begin{aligned}\overline{U}_{v1} &= m_{a1}U_{d1} - jx_v\overline{I}_v;\\ \overline{U}_{v2} &= m_{a2}U_{d2} - jx_v\overline{I}_v\end{aligned}\right\}\overline{U}_{v1} = \overline{U}_{v2} = 0.8\overline{U}_{vN} \Rightarrow \begin{cases} m_{a1} = 0.8m_{aN}; U_{d1} = U_{dN} \\ m_{a2} = m_{aN}; U_{d2} = 0.8U_{dN}\end{cases}$$

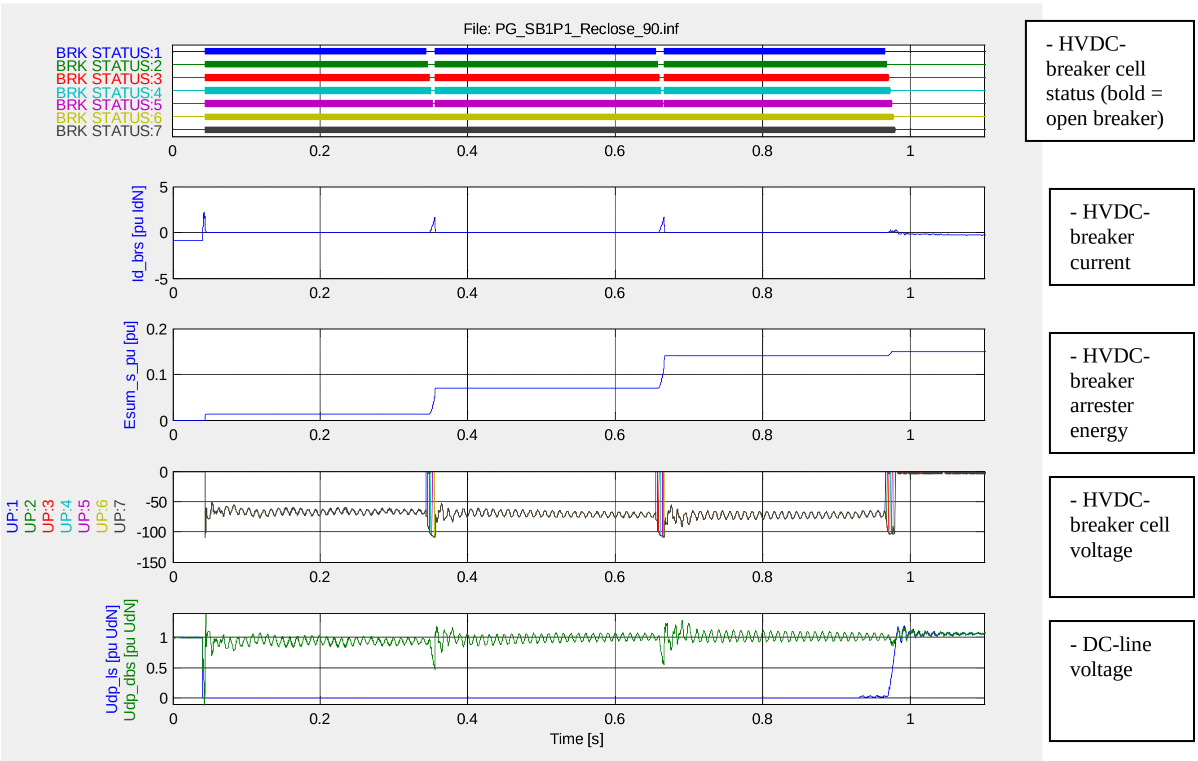


Figure 10. Post fault dc-voltage recovery

Consequently, in order to obtain rated power at nominal dc-voltage, for a design prepared for reduced dc-voltage the valve ac-current level must be increased by 25%. In conclusion, a HB-MMC design ready for a fast transition to reduced dc-voltage of 80% must be overrated by 25% in terms of ac-current. The actual valve arm current being a combination of ac- and dc- current is therefore only increased by about 17% due to the dc-current being the same as in the normal design.

3.2. DC-grid enabling through HVDC-breaker current limitation

As shown in Figure 11 below, an original point-to-point transmission (shown in green) is extended to 3-terminals or more as shown in red. The dc-line that is used to connect the new converter stations to the original transmission circuit is connected through bidirectional HVDC-breakers in each end.

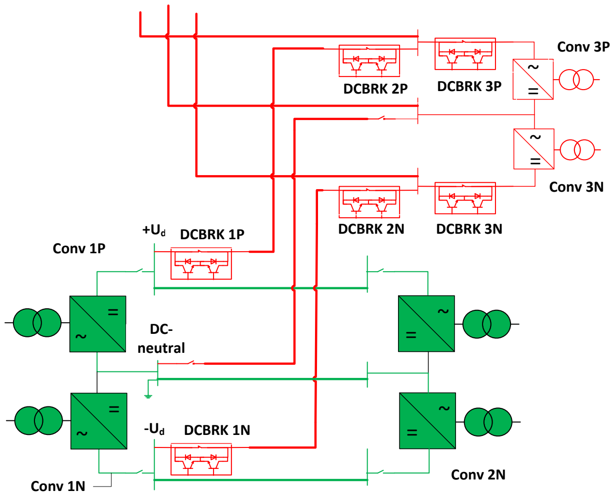


Figure 91 Multi-terminal extension of point-to-point dc-cable transmission

The HVDC-breakers will serve two main objectives:

1. The first HVDC-breakers (DCBRK1P, DCBRK1N) would serve as current limiters or current interrupters in order to maintain fault current levels of the original system below the original ratings. Consequently, the original system can be designed without any consideration to short circuit current contribution related to an extended grid including additional converters.
2. The first and the second HVDC (DCBRK1P, DCBRK1N, DCBRK2P, DCBRK2N) breakers will together ensure isolation of faults in the first transmission line.

The first objective relates to faults occurring in the original transmission system, e.g. internal converter faults. During an internal fault in one of the converters 1 or 2, depending on the possibility to isolate the fault, the HVDC-breakers (DCBRK1P, DCBRK1N) will either open to interrupt current and isolate the faulty system or operate in current limitation mode to prevent rated current levels of the original system to be exceeded. In Figure 12, current limiting action by sequential operation of the HVDC-breaker cells is presented. As can be seen by the cell status, only four cells are opened in this case giving a total arrester voltage of close to the normal dc-line voltage in order to maintain a limited current. After the interval of current limiting action the dc-voltage is gradually recovered by sequential closing of the four HVDC-breaker cells.

3.3. DC-line fault clearing in dc-grid applications

As shown in Figure 11 the line between Conv 1P/1N and Conv 3P/3N has HVDC-breakers in each end. Thereby, fault isolation is possible for faults occurring on this line in order to minimize the impact on the remaining dc-grid. The dc-voltages of the healthy parts of the grid are maintained while the faulty line is isolated. After deionization, the dc-voltage is re-established on the faulty line through sectionalized closing of the breaker-cells of the two line breakers.

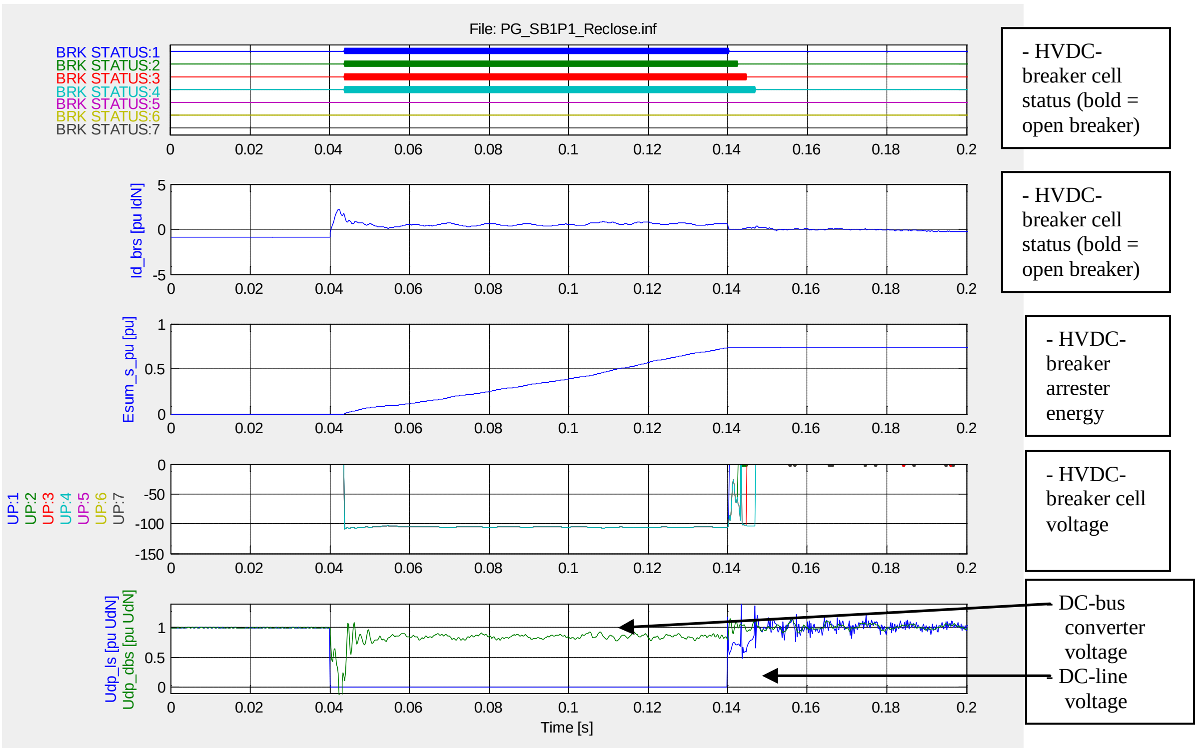


Figure 12 Current limiting action by the HVDC-breaker

4. Conclusion

The technology and implementation of a hybrid HVDC breaker have been demonstrated in detail. The hybrid HVDC breaker provides very fast dc-fault current interruption at negligible losses in normal operation through a combination of a mechanical ultra-fast disconnector, semiconductors and arresters. Measurement results from verification tests of the HVDC breaker are presented. The rating of the hybrid HVDC breaker is applicable to different system voltage levels and depends on the individual project specifications. The arrester bank can be designed to meet the requirements of different applications

Through a sectionalized design using breaker-cells a controlled current limitation as well as dc-voltage post-fault recovery is demonstrated. The handling of dc-faults in point-to-point dc-overhead line transmission is discussed enabling fast fault clearing action while providing continuous reactive power support. The HVDC-breaker thereby significantly boosts the capability and functionality of dc-circuit protection in order to enable a flexible future expansion of point-to-point transmission into multi-terminal or meshed configuration.

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