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Proactive Hybrid HVDC Breakers - A key innovation for reliable HVDC grids

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SUMMARY

Existing mechanical HVDC breakers which are capable of interrupting DC currents within several tens of ms are too slow to fulfil the requirement of a reliable DC grid. Semiconductor based DC breakers easily overcome the limitations in operation speed but generate large transfer losses typically in the range of 30% of the losses of a voltage source converter station.

To overcome these obstacles a hybrid HVDC breaker is proposed in this paper. The alternative design has negligible conduction losses while preserving fast current interrupting capability. By intelligent internal control, the same performance regarding clearing a DC fault can be obtained as with a pure IGBT DC breaker.

This paper presents a detailed description of the proposed hybrid DC Breaker, its design principles and proactive control with particular focus on the reliability of the concept. The modular design of the hybrid DC breaker for HVDC applications is described and results from prototype testing are presented. Furthermore, the application of the hybrid DC breaker associated with the design of a DC switchyard is discussed.

KEYWORDS

HVDC Grid; DC Breaker - Hybrid; Semiconductor Breaker

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1. INTRODUCTION

The advancement of the voltage source converter based high voltage direct current transmission system makes it possible to build a HVDC grid with many terminals. Comparing with the AC grid, the active power conduction losses are relatively low and the reactive power conduction losses are zero in a DC grid. This advantage makes the DC grid more and more attractive [1]. However, the relatively low impedance in DC grids is a challenge when a short-circuit fault occurs in the DC grid. The fault penetration is much faster and deeper in a DC grid. Because of that, it requires fast and reliable HVDC breakers to isolate faulted parts in order to avoid a collapse of the common DC voltage in large DC grids. Furthermore, keeping a reasonable level of the DC voltage is a precondition for the converter station to operate normally. In order to minimize disturbance on converter operation, particularly the operation of the converter stations which are not connected to the faulted line or cable, it is necessary to clear the fault within a few milliseconds.

Existing mechanical HVDC breakers which are capable of interrupting DC currents within several tens of ms [2] are too slow to fulfil the requirement of a reliable DC grid. Furthermore, the mechanical DC breakers require significant efforts, which include installing additional passive components to create the resonance circuit, to generate current zero crossing for the breaker to succeed in breaking the current once the contacts open. Development of very fast mechanical DC breakers is a demanding task [3]. Semiconductor based DC breakers easily overcome the limitations in operation speed but generate large transfer losses typically in the range of 30% of the losses of a voltage source converter station.

To overcome these obstacles a hybrid DC breaker for HVDC grid applications is proposed in this paper. The paper is organized as follows. At first, the performance requirement on the DC breakers is highlighted as the main apparatus which determines the system performance of the DC grid. Next, a detailed description including the design principle is given for the proposed hybrid DC breaker. Finally, some test results from a prototype of the main switch branch in the hybrid DC breaker are presented.

2. SYSTEM DESIGN REQUIREMENTS

A DC grid is formulized when more than two converter stations are interconnected on the DC side via DC cables or overhead lines in meshed or radial system. Each converter station of the DC grid couples the DC grid to an AC grid. To be able to maintain the active and reactive power control capability of the converter, it is normally requested that the DC voltage should be above at least 80% of the nominal DC voltage. If the converters lose the control capability due to the low DC voltage, the following consequences can be voltage collapse in the DC grid and high current or voltage stresses on the converter, in addition to affecting the coupled AC grid voltage. A DC short-circuit fault in the worst case can make the DC voltage suddenly reduced from nominal level to near zero at the fault location. The voltage reduction at other places of the DC grid depends mainly on the electrical distance to the fault location and DC reactors installed near the stations. For a DC grid connected by DC cables the fault has to be cleared typically within 5ms in order not to disturb converter stations as far as 200 km away from a DC short-circuit fault, which is a significant different requirement compared to AC fault clearing times.

It is not only the DC grid system performance that requires fast DC switches. From the DC breaker design point, it is also very crucial to realize a fast fault current breaking as will be shown in the following.

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

Figure 1(b) shows the electromagnetic transients around the instant of current breaking. The current starts to rise when the fault occurs. When the switch opens, the current starts to decrease by commutating the current to the arrester. The fault current in the arrester bank establish a counter voltage across the DC reactor which reduces the fault current to zero by dissipating the fault energy stored in the DC reactor and fault current path of the DC grid. The voltage level of the arrester bank must exceed the DC voltage capabilities in the DC grid.

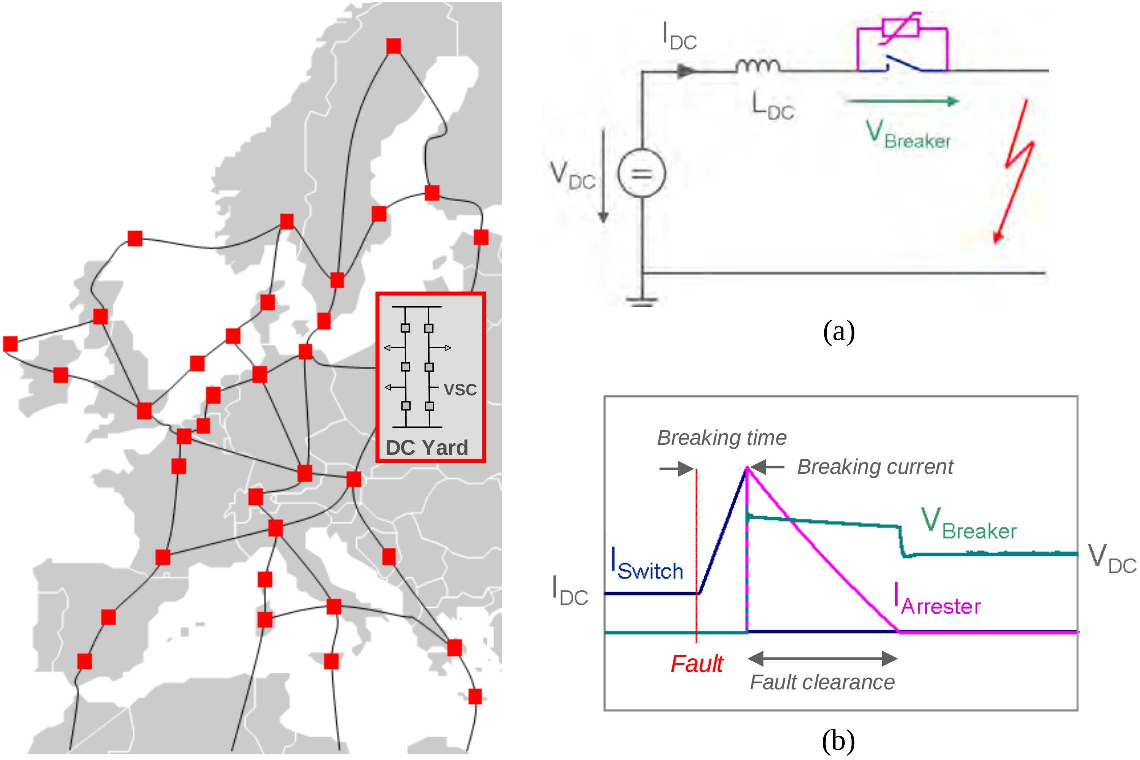

Figure 1: Representation of DC breaker in DC grid

The total fault clearing time consists of two parts: the breaking time corresponds to the current rising period and the fault clearance corresponds to the current decreasing period. Both time durations are decisive for the design and cost of DC breaker as well as the reactor.

In practice, the breaking time is given by the response time of the protection and the action time of the DC switch. A longer time to break will demand an increased maximum current breaking capability of the DC switch and increase the energy handled by the arrester, thereby a higher cost for the DC breaker. Therefore, it is crucial to keep the breaking time as short as possible. Under the condition when the breaking time is given and the maximum breaking current capability is also given, the only adjustable parameter is the inductance of the DC reactor, as it decides the current rising rate. The DC reactor has to be selected such that within the breaking time, the current should not reach a level higher than the maximum breaking current capability of the DC breaker. However, the size of the DC reactor may be limited due to not only the cost but also the stability of the DC grid system.

The time duration for fault clearance will affect the voltage dimensioning for 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 higher pole to pole voltage rating and thus costs of the DC breaker.

In order to give a rough idea about the relation of the above discussed parameters, the following example is given. Assuming a breaking time of 2ms, which is possible for semiconductor based DC switches, and a DC line fault close to the DC switchyard, the maximum rise of the fault current will be

3.5kA/ms for a DC reactor of 100mH in a 320kV DC grid with 10% maximum overvoltage. For a given rated line current of 2kA, the minimum required breaking capability of the DC breaker is 9kA.

It should be pointed out that a reactor of 100mH is already several times higher than the reactor which is normally installed in the point-to-point DC transmission system based on voltage source converters. It seems that it is unrealistic to allow an even larger reactor. As a consequence, the action time for the DC breaker is expected to be lower than 2ms, since it is also necessary to reserve a certain time for the protection to make a correct decision.

3. PROPOSED HYBRID IGBT DC BREAKER

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

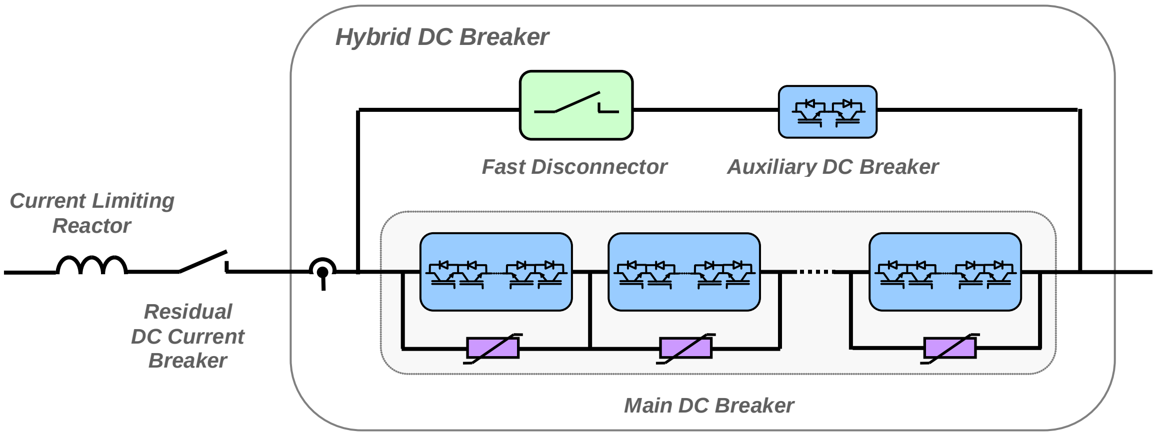

Figure 2: Modular Hybrid IGBT DC Breaker

During the normal operation, the current will only flow through the bypass and the current in the main breaker is zero. When a DC fault occurs, the auxiliary DC Breaker immediately commutates the current to the main DC Breaker and the fast disconnector opens. With the mechanical switch in open position, the main DC breaker breaks the current.

The mechanical switch isolates the auxiliary DC breaker from the primary voltage across the main DC Breaker during current breaking. Thus the required voltage rating of the auxiliary DC breaker is significantly reduced. A successful commutation of the line current into the main DC breaker path requires a voltage rating of the auxiliary DC breaker exceeding the on-state voltage of the main DC breaker, which is typically in the kV range for a 320kV DC breaker. This results in typical on-state voltages of the auxiliary DC breaker in the range of several volts only. The transfer losses of the hybrid DC Breaker concept are thus significantly reduced to a percentage of the losses of a pure semiconductor breaker.

The mechanical switch opens with zero current and low voltage stress and can thus be realised as a disconnector. The fast disconnector will be exposed to the recovery voltage defined by the protective level of the arrester banks first after being in open position while the main DC breaker opens. Series connection of several mechanical switching elements resulting in opening times below 2ms is thus possible without grading capacitors to control the dynamic voltage distribution.

Proactive control of the hybrid DC breaker allows to compensate for the time delay of the mechanical switch if the opening time of the multiple internal disconnectors is less than the time required for selective protection. As shown in Figure 3, proactive current commutation is initiated by a built-in overcurrent protection of the hybrid DC breaker as soon as the DC line current exceeds a certain overcurrent level. Current breaking of the main DC breaker is delayed until a trip signal of the selective protection is received or the faulty line current is close to the maximum breaking current capability of the main DC breaker.

To extend the time instance until the self-protection of the main DC breaker trips the hybrid DC breaker, the main DC breaker may operate in current limitation mode prior to current breaking. The main DC breaker controls the voltage drop across the DC reactor to zero to prevent a further rise of the line current. Pulse mode operation of the main DC breaker or sectionalizing of the main DC breaker as shown in Figure 2 will allow to adapt the voltage across the main DC breaker to the instantaneous DC voltage level of the DC grid [4]. The maximum duration of the current limiting mode depends on the energy dissipation capability of the arrester banks.

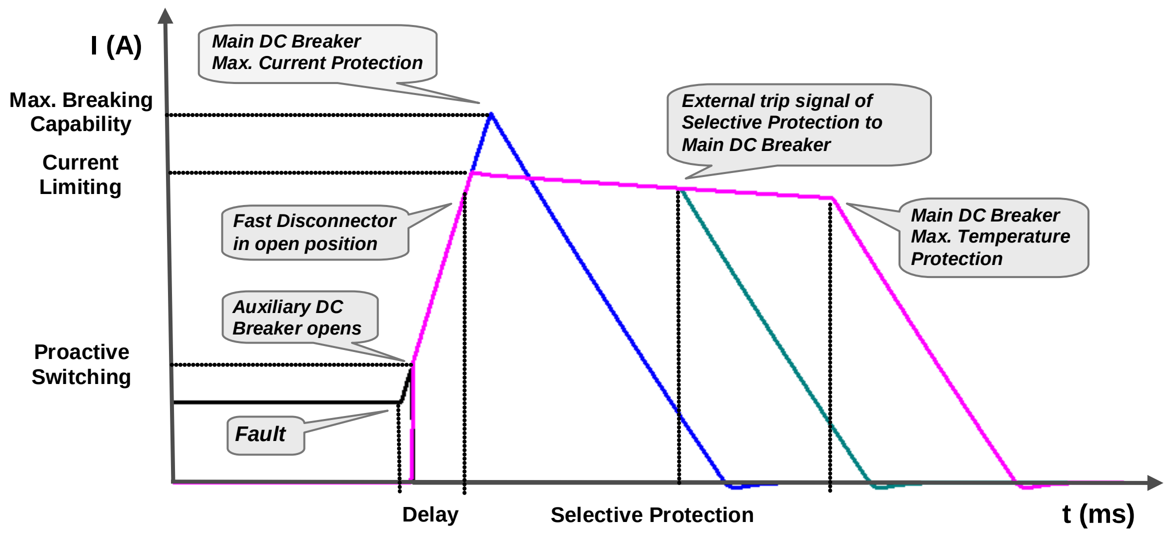

Figure 3: Proactive control of Hybrid DC Breaker

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

Fast backup protection similar to pure semiconductor breakers is possible for hybrid DC breakers applied to DC switchyards. Due to the proactive mode, overcurrents in the line or a superior switchyard protection will activate the current transfer from the bypass into the main DC breaker of 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 then 0.2ms. This will avoid major disturbances in the DC grid and keep the required current breaking capability of the backup breaker at reasonable values. If not utilised for backup protection, the hybrid DC breakers automatically return to normal operation mode after the fault is cleared.

4. PROTOTYPE DESIGN OF THE HYBRID DC BREAKER

The present goal of the hybrid DC breaker is aimed to achieve a current breaking capability of 9kA in a DC grid with rated voltage of 320kV and rated DC transmission current of 2kA. The maximum current breaking capability is independent from the current rating and depends on the design of the main DC Breaker only. The fast disconnector and main DC Breaker are designed for switching voltages exceeding 1.5 pu under consideration of fast voltage transients during current breaking.

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

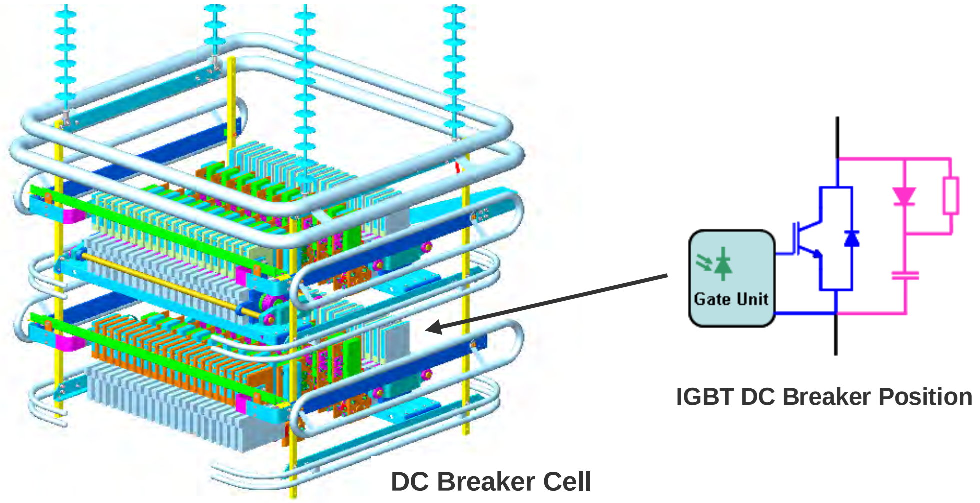

Figure 4: Design of 80kV Main DC Breaker Cell

Each stack is composed of up to 20 series connected IGBT DC 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 4.5kV voltage rating [5] enable a compact stack design and ensure a stable short circuit failure mode in the case of individual component failure. Individual RCD turn-off snubbers across each IGBT position ensure equal voltage distribution during current breaking. Optically powered gate units allow to operate the IGBT DC breaker independent from current and voltage conditions in the DC grid. A cooling system is not required for the IGBT stacks since the main DC Breaker cells are not exposed to the line current during normal operation.

For the design of the auxiliary DC breaker, one IGBT DC breaker position for each current direction is sufficient to fulfil the requirements on the voltage rating. Parallel connection of IGBT modules increases the rated current of the hybrid DC breaker. Series connected, redundant IGBT DC breaker positions improve the reliability of the auxiliary DC breaker. A matrix of 3 x 3 IGBT positions for each current direction is chosen for the present design. Since the auxiliary DC breaker is continuously exposed to the line current, a cooling system is required. Besides water cooling, air-forced cooling is applicable due to the relatively low losses in the range of several tens of kW only.

5. TEST RESULTS

During the design of the hybrid DC breaker prototype, different tests have been performed in order to verify the expected performance, and some more tests are still ongoing. The first test setup mainly focused on the control of semiconductor devices and their current breaking capability. The second test setup verifies both the voltage and current capability of one DC breaker cell of the main DC breaker. The ongoing extension of this test setup will focus on the overall performance of the hybrid DC breaker.

A downscaled prototype of the IGBT DC Breaker cell with three series connected IGBT modules and a common arrester bank has been used to verify the current breaking capability of 4.5kV StakPak IGBTs [5] in the first test circuit according to 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 DC grid. The DC voltage level prior to the fault and after fault clearance is less critical since the voltage stress across the IGBT DC breaker positions during current breaking depends on the applied arrester bank only.

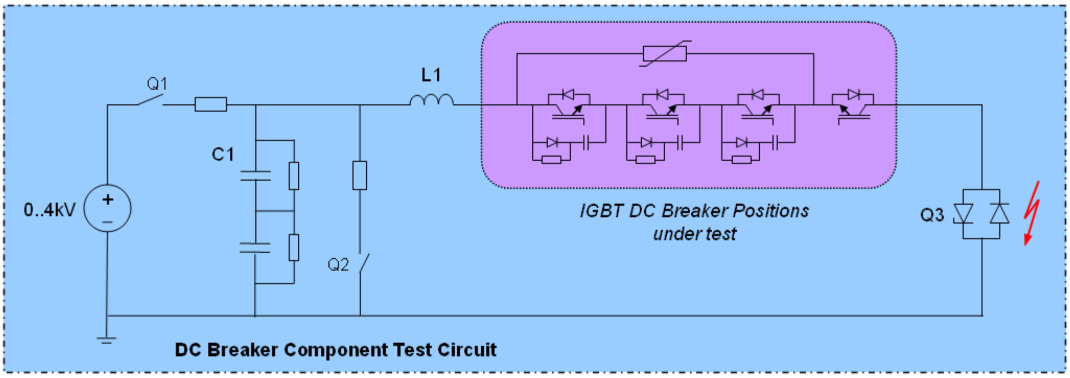

Figure 5: DC Breaker Component Test Circuit

As shown in Figure 6, the maximum breaking current capability of the IGBT DC breaker cell is given by the saturation current of the applied IGBT modules rather than the safe operation area (SOA) as typical for voltage source converter applications. The series connected DC breaker IGBT positions commutate the line current within 2µs into the RCD snubber circuits, which limits the rate of rise of the voltage across the positions to 300V/µs. Zero voltage switching reduces the instantaneous switching losses and ensures a equal voltage distribution independent of the 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 DC breaker positions reaches the protective level of the arrester bank.

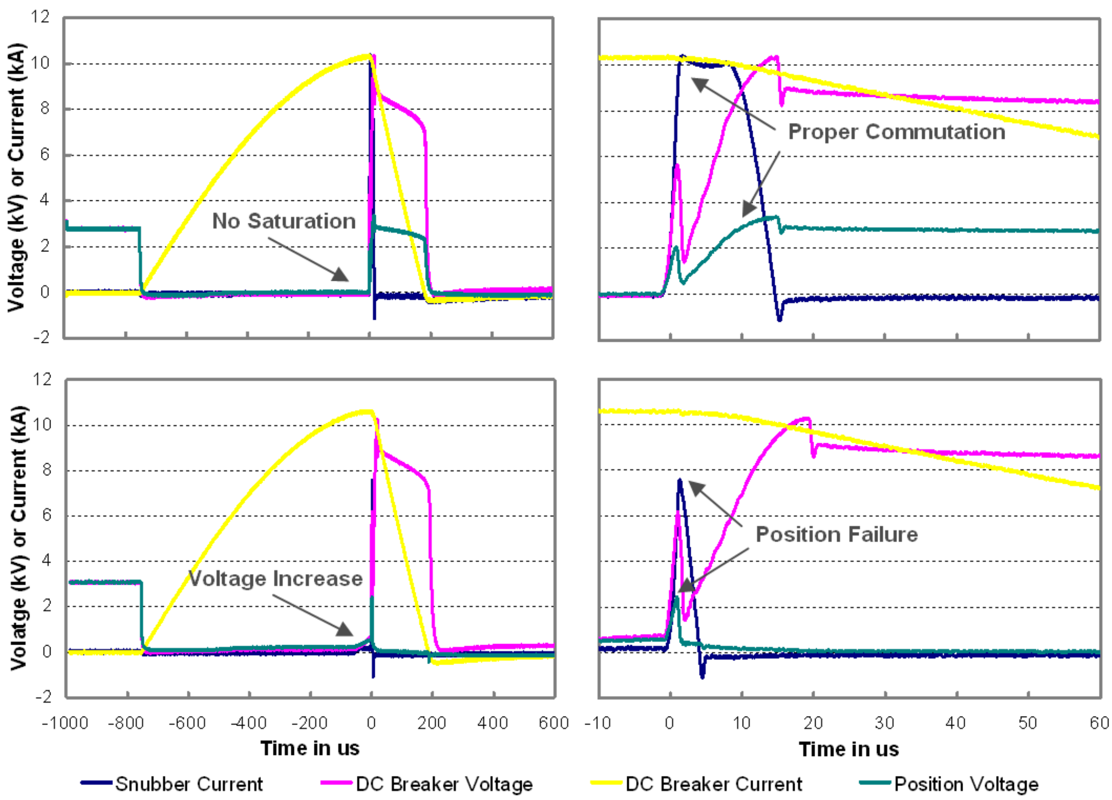

Figure 6: Maximum stress tests on IGBT DC Breaker positions (right: Zoom)

The IGBT DC breaker positions passed the stress tests for breaking currents below 10kA. For higher currents, internal current limitation of the DC breaker positions to saturation current level of the IGBT modules occurs and the voltage drop across the IGBT modules rises suddenly. 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 established. Since only one of the IGBT modules failed during the test, the fault was still cleared by the two other modules.

The nominal DC voltage per IGBT DC Breaker cell is 80kV for the prototype under test. Due to the high voltage level, the second test setup requires a significant large space. In Figure 7, the test circuit for the hybrid DC breaker concept is shown. A ±150kV DC switchyard supplies the containerized test equipment to verify the functionality of the main IGBT DC Breaker represented by two series connected IGBT DC Breaker stacks and a common arrester bank. The desired DC voltage level is built up by charging the capacitor bank C1. The reactor L1 is selected to give the expected di/dt during a short-circuit fault. The short-circuit fault is initiated by the triggerable spark gap Q5.

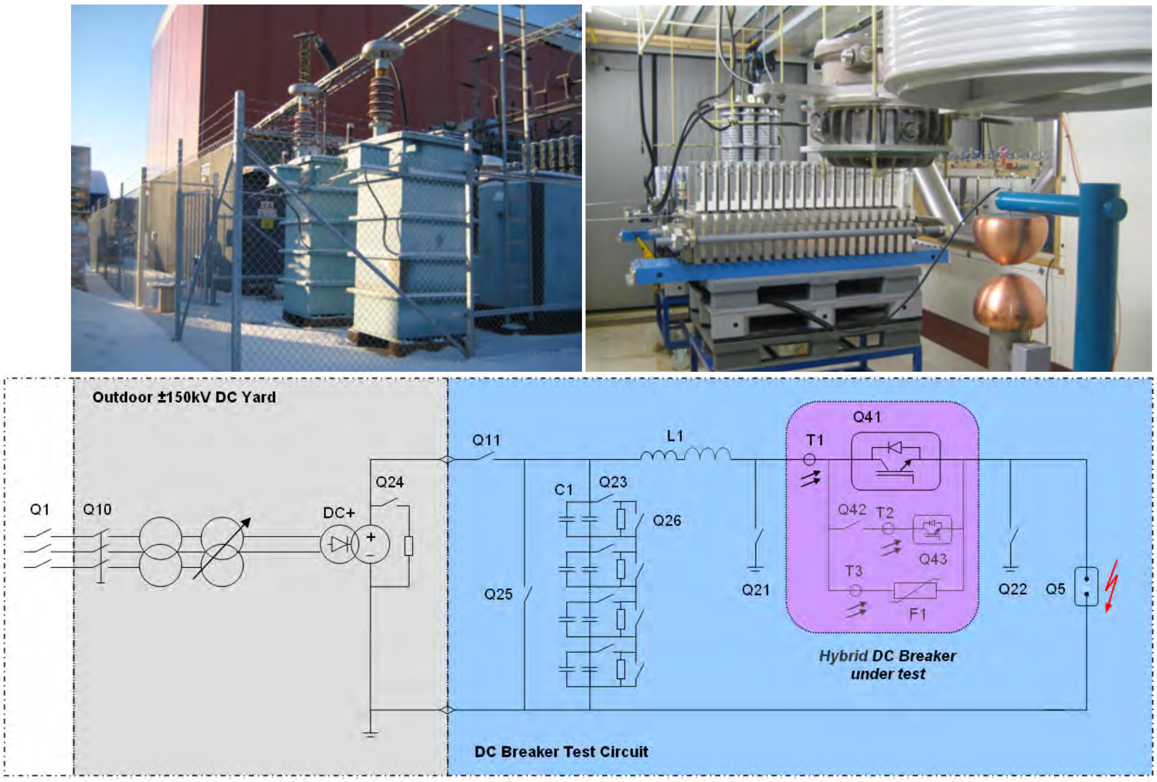

Figure 7: Containerized DC Breaker Test Circuit at ABB Ludvika, Sweden

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

The test setup will be expanded to verify the complete hybrid DC breaker concept including the proactive control. A second capacitor bank and large reactors will be installed to limit the rate of rise of the line current to typical values of the DC grid. The fast disconnector and auxiliary DC breaker under test will be designed for a 320kV DC application.

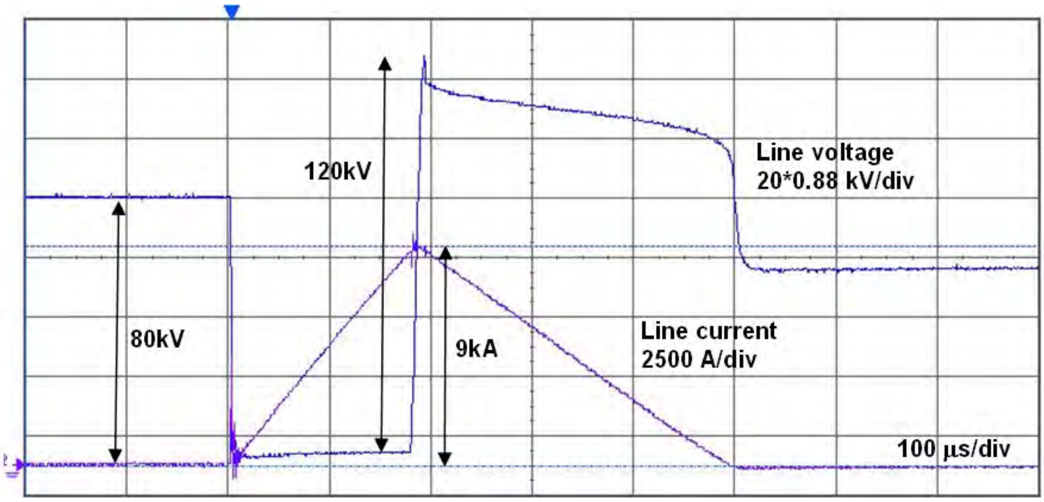

Figure 8: Verification of modular IGBT DC Breaker cell

6. OUTLOOK AND CONCLUSIONS

The rating of the proposed modular hybrid DC Breaker is easily adapted to different voltage and current requirements. Introduction of BiGT technologies [6] 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 up to 16kA and operating times within 2ms including the time delay of the protection system, proactive hybrid DC breakers are well suited for DC switchyards preventing a collapse of multiterminal HVDC systems due to DC line faults.

The proactive control allow for almost immediate backup protection in DC switchyards and thus reduces the size of the required switchyard equipment. The modular design enables current limitation mode for reliable self-protection of the hybrid DC breaker. Other advantages of the current limiting design are current redirection to other lines with low transient voltage stress, application as insertion resistor during energising of the DC grid and sectionalisation of DC grids during faults while maintaining the DC power transfer.

Fast, reliable and almost lossless DC breakers and current limiters based on the proposed hybrid DC breaker concept are soon commercially available for DC voltages up to 320kV and rated currents of 2.6kA. Thus DC breakers are no longer a showstopper for large DC grids.

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