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Full Power Short-circuit Tests of HVDC Circuit Breakers using AC Generators Operated with Reduced Power Frequency

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SUMMARY

This paper presents test results of an active current injection mechanical HVDC circuit breaker. The design, operating principle and two possible ways to realize extra high voltage (EHV) ratings using this type of HVDC circuit breaker are discussed. In addition, the practical implementation of a test circuit capable of testing the DC current interruption performance, not only of the mentioned HVDC circuit breaker topology but also of other proposed technologies of HVDC circuit breakers, is discussed. In order to demonstrate the performance of a HVDC circuit breaker, a test circuit needs to provide the necessary stresses: current, energy and voltage (both during and after interruption). A test circuit based on AC short-circuit generators operated at reduced power frequency, capable of providing the mentioned stresses, is designed and implemented. Special provisions on protection of the test-object and the test circuit are demonstrated.
A prototype of mechanical HVDC circuit breaker module (80 kV rated voltage) based on active current injection is tested. To demonstrate DC current interruption performance at different current magnitudes, test duties with bi-directional currents ranging from 2 kA to 16 kA are defined. The prototype mechanical HVDC circuit breaker with active current injection is then used to successfully interrupt the test current at each test duty.

KEYWORDS

HVDC Transmission, Multi-terminal, HVDC circuit breakers, active current injection, DC short-circuit tests, DC interruption, testing

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1. INTRODUCTION

HVDC circuit breakers (HVDC CBs) are expected to play an important role in the protection of future multi-terminal meshed HVDC grids. Several concepts of HVDC CBs have been proposed and realized into prototypes [1]-[5]. This paper presents, first, the design and operation of an active current injection HVDC CB. Two possible approaches towards realization of a full-pole (extra high-voltage (EHV)) active current injection HVDC CB are described. The merits and major challenges of each approach are discussed. Next, it focuses on the test results and the test circuit used for this purpose.

Before testing HVDC CBs, appropriate test requirements need to be defined. Since there are no international standards specifying test requirements of HVDC CBs, generic test requirements have been derived from system studies [6]-[9]. Because the performances of different technologies of HVDC CBs vary with the magnitude of interrupted current, four different test duties with the similar nomenclature as AC circuit breaker test duties have been defined and tests are conducted accordingly.

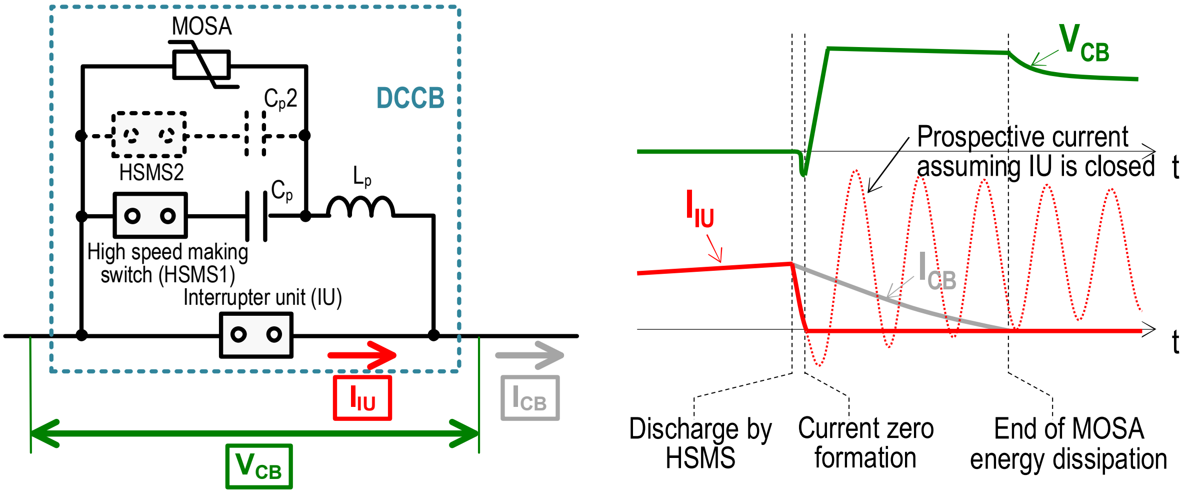
A test circuit using AC short-circuit generators operated at reduced power frequency has been proposed, which is especially suitable when the duration of the interruption process is shorter than the AC voltage half cycle [9]-[11]. AC short-circuit generators are already in use for AC equipment testing; therefore, without significant investment, these can readily be used for testing HVDC CBs. As such, the paper discusses a practical implementation of HVDC CB short-circuit test method and its procedure in detail using AC short-circuit generators operated at reduced power frequency. The DC current interruption performance of mechanical HVDC CB, composed of a vacuum interrupter with active counter current injection, is analyzed.

There are two major issues of using AC short-circuit generators for this application: overcurrent protection in case the test object (TO) does not clear the short-circuit current; and the application of dielectric stress after interruption. Methods to overcome these challenges are demonstrated. Finally, the paper discusses the challenges and requirements of a test installation for testing a full-pole HVDC CB. Prospective test results of example cases considering several modules of different technologies of HVDC CBs have been demonstrated in a test lab.

2. MECHANICAL HVDC CB WITH CURRENT INJECTION SCHEME

The mechanical HVDC CB with active current injection scheme is composed of a vacuum interrupter in the main current path and a parallel circuit which is used to inject high-frequency counter current, see Figure 1a. The current injection is controlled by a high-speed making switch which, when closed, results in a high-frequency (in the order of several kHz) as shown in Figure 1b. The oscillation frequency and magnitude is determined by choice of passive components (reactor and pre-charged capacitor). The inverse current generates a current zero within the main interrupter, which can typically be achieved within 8 ms from trip order from the dc relay.

The topology can perform multiple operations in rapid succession if required (e.g. auto-reclosing function). This can be achieved by parallel connection of a second making switch and pre-charged capacitor, as shown by the dotted lines in Figure 1a. After the first operation is performed, the first high-speed making switch (HSMS1) is left in the open position. HSMS2 and C_{p2} are then used to inject a second counter-current.



a) b)

Figure 1: Schematic of circuit and waveform of active injection current zero creation scheme

System simulations have been performed to demonstrate the fault clearing capability of the mechanical HVDC CB in a 320 kV, four terminal HVDC network [3],[7],[8]. In these studies, it was found that, when considering a tentative relay time of 2 ms, faults could be cleared using an active current injection mechanical HVDC CB with an operation time of 8 ms, with an interruption capability of 16 kA.

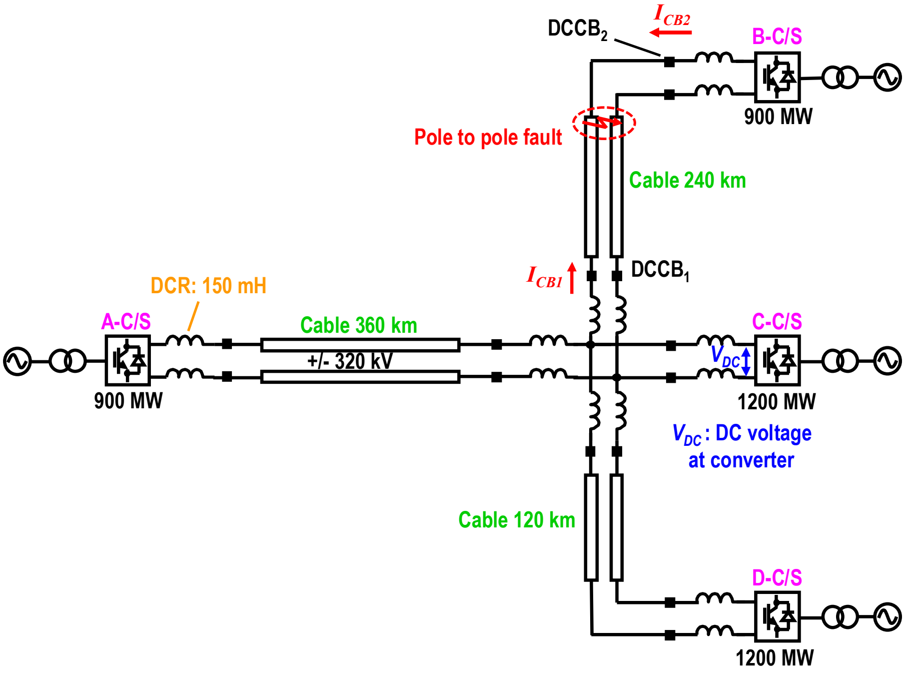


Figure 2: Four-terminal radial HVDC network model

These studies have been continued to assess the energy dissipation requirements of the breaker. It has been found that the breaker should be able to absorb up to 34.2 MJ, in some cases (see Table 1).

Table 1: Simulation result

Subject of the requirement	DCCB$_1$ (Central node side)	DCCB$_2$ (Converter side)
Interruption current [kA]	10.7	12.7
TIV amplitude [kV]	497	502
MOSA dissipation energy [MJ]	34.2	16.0

2.1 FULL-POLE CONFIGURATION FOR 320 kV HVDC CB (or EHV LEVEL)

In order to increase the voltage withstand ability of the HVDC CB (e.g. for EHV-HVDC applications) a number of vacuum interrupters are connected in series. Example topologies applicable for the active current injection HVDC CB, are shown in Figure 3 and Figure 4.

Figure 3 shows the schematic of configuration 1, referred to as common current injection type. In this configuration, the metal oxide surge arrester (MOSA), which clamps the transient interruption voltage (TIV) and dissipates energy is common to all breaker units. Therefore, the voltage stress per MOSA element is uniform irrespective of operation time of the high-speed switches. Current injection sequence for the charged capacitor is relatively simple (when compared to configuration 2).

Figure 4 shows the second configuration, referred to as module type. In this topology, each interrupter unit has their own current injection branch, and surge arrester bank. This results in a highly flexible design, in terms of voltage class. Allowance for the voltage sharing rates of each break must be considered. However, for example, with three 80 kV modules a 240 kV DCCB can be achieved; with four, 320 kV. Each capacitor C_p must be pre-charged, ready for operation, which is more challenging in this configuration (compared to configuration 1).

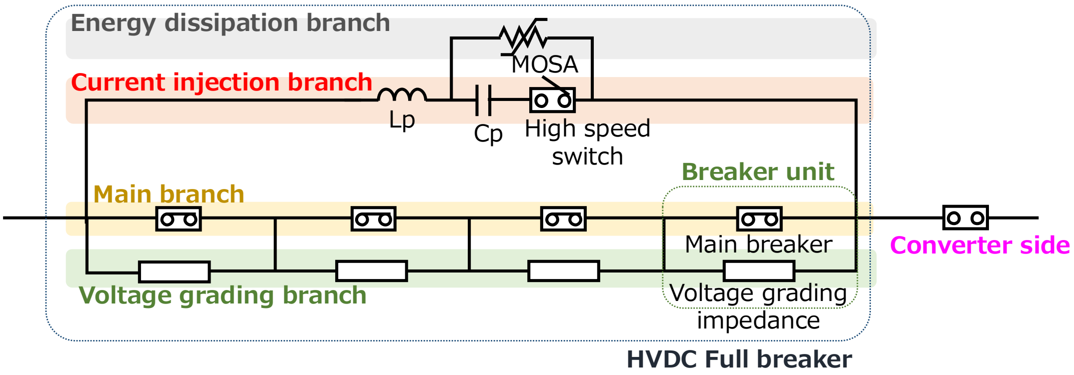


Figure 3: Schematic diagram of multi-break HVDC CB configuration 1 ”Combined”

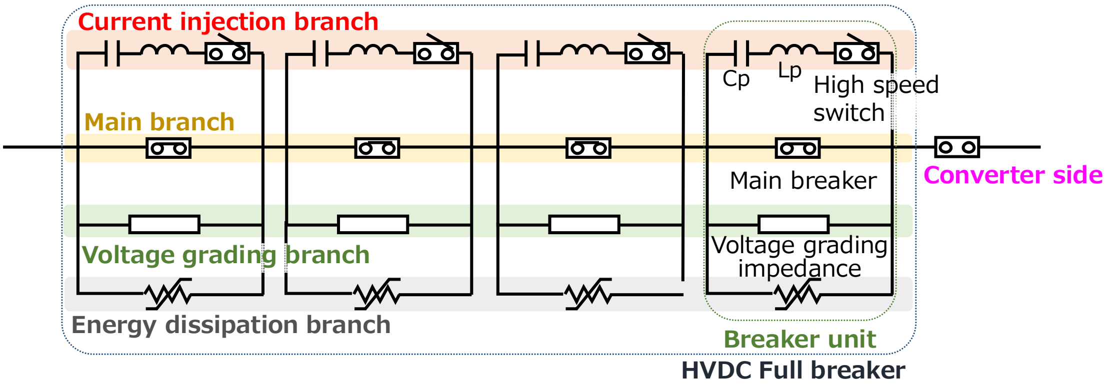


Figure 4: Schematic diagram of multi-break HVDC CB configuration 2 ”Module”

Table 2: Comparison of multi-break HVDC CB configuration

Item	Configuration 1 "Combined"	Configuration 2 "Module"
Capacitor charging	**<Simple>** C_p can be charged in the same way as that for single break HVDC CB basically.	**<Complicated>** It's challenging in this configuration that each capacitor C_p must be pre-charged, ready for operation.
Voltage class flexibility	**<Low>** Current injection branch should be designed for each system voltage.	**<High>** The rated voltage of the HVDC CB can be flexible for various system voltage by just adjusting the number of the series of the module.
Impact of mechanical switch operation variation	**<Small>** Scatter of operation time of high speed switches doesn't have to be considered.	**<Large>** Impact of uneven operation time of high speed switches on the evenness of energy dissipation in each MOSA can be large.

2.2 REQUIREMENTS FOR A SINGLE EHV DCCB UNIT

As described in section 2.1, all simulations were performed at full system voltage – i.e. 320 kV. Whereas, EHV class HVDC CBs typically consist of multiple breaks, by connecting modules in series. In this case, a single EHVDC CB unit test, like that being applied for ACCB, is applicable. This is acceptable as long as the stresses in the unit test are equivalent to those of corresponding to one unit of the HVDC CB in a real HVDC system. This test method is a practical solution in order to perform economical and reasonable tests. For example, considering a 320 kV HVDC CB which consists of for series of 80 kV modules, the current through series connected modules is the same, and hence the test current requirement for a unit test is the same as that for a full pole HVDC CB. The voltage across the modules is determined by the MOSAs and typically distributed equally among the modules. Hence the test voltage requirement for a unit test is equal to the full pole voltage rating divided by the number of modules plus a margin. Special care must be taken in case the HVDC CB contains any common full pole components, such as the current injection circuit in case of configuration 1 in Figure 3. Full pole components must be separately tested at the full pole test voltage requirements. In addition, parasitic elements such as stray inductance in full pole configuration must be carefully considered during unit testing to ensure adequate verification of current commutation between parallel branches. Lastly, the energy absorption is shared among the modules. Hence the test energy requirement for a unit test is equal to the full pole energy absorption rating divided by the number of modules. A test factor may have to be added to cover for slight variations in energy absorption between modules caused by small timing differences in the moment of arc extinguishing in the different modules.

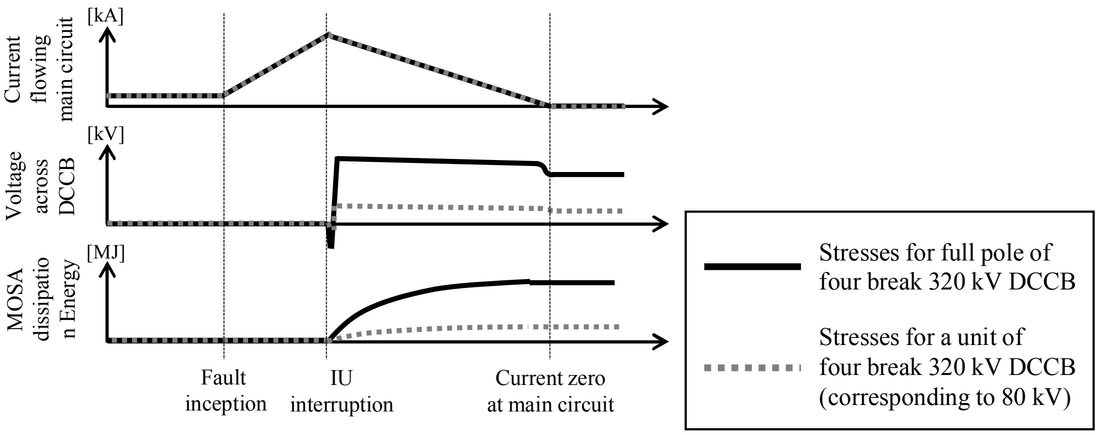


Figure 5: Stresses on full pole 320 kV HVDC CB (black line) compared with those for one unit of 80 kV HVDC CB (Gray dotted line)

Figure 5 shows the stresses for one unit of 320 kV full pole HVDC CB, and the prorated test stresses for one module. Current stress for each module is same as that for the full pole. On the other hand, voltage and MOSA energy dissipation stress corresponds to 1/4 of those for full pole.

3. TEST CIRCUIT FOR HVDC CIRCUIT BREAKER USING AC SHORT-CIRCUIT GENERATORS

A diagram of the test circuit based on AC short-circuit generators is shown in Figure 6. The test circuit is composed of four parts, namely; power source, over-current protection, dielectric and/or charging source and arcing time prolongation in the auxiliary breaker, each of which indicated in separate dotted boxes. The purposes of each part are described in this section.

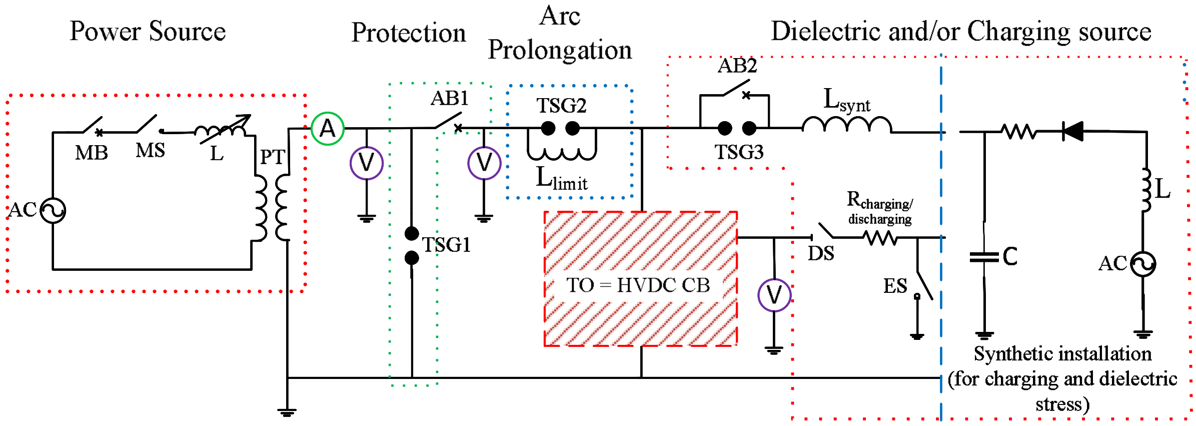
3.1 Power source

This is the short-circuit power source supplying the necessary current, voltage and energy stresses during current interruption. It consists of short-circuit generators and power transformers capable of operating at reduced power frequency. The short-circuit generators have a master breaker (MB) and a making switch (MS) in each phase, see Figure 6. For testing HVDC CBs, only half a cycle of AC current is needed. The making switches (MS) are used to control the desired point on the voltage wave at which the current rises. The master breakers (MB) will clear the power source after approximately half a cycle.

When operating short-circuit generators at reduced power frequency, the generated voltage and hence power is reduced proportionally. Therefore, multiple series power transformers are needed to step-up the test voltage to a desired level and several short-circuit generators are connected in parallel to compensate for the reduced power. The sub-transient reactance and the transformer leakage reactance plus adjustable reactors constitute the total inductance in the circuit needed to realize the rate of rise of current and energy to be absorbed by the HVDC CB.

3.2 Over-current Protection

If the test object (TO) for any reason does not operate or clear, it will be subjected to the full prospective half cycle current from the power source, which could result in damage to the TO in some cases. To mitigate this risk additional circuitry has been implemented – see the dashed box labeled 'protection' in Figure 6. It consists of a plasma triggered spark gap (TSG1) and an auxiliary SF_6 AC breaker (AB1) acting as a crowbar circuit.



Key

MB= Master Breaker
MS= Making Switch
L= adjustable reactor
PT= Power Transformer(s)
AB= Auxiliary AC breaker

L_{synt} = inductance in the synthetic circuit
TSG=Triggered Spark Gap (Triggered make gap)
$R_{charging/discharging}$ = charging and discharging resistor
L_{limit} = initial current limiting reactor

DS= Disconnector switch
ES= Earthing Switch
Ⓐ= Current measurement
Ⓥ= Voltage measurement

Figure 6: Schematic diagram of a complete test circuit for HVDC CB based on AC short-circuit generators

The triggered spark gap (TSG1) is controlled by a real-time current level detector which sends trigger signal if the pre-set threshold value is reached. The arc voltage of the auxiliary circuit breaker AB1 enhances current commutation from the TO to the TSG1. This is demonstrated in a test lab as shown Figure 7. In the results shown, the generator produces a current with a prospective peak of 33.5 kA. TSG1 is triggered at a threshold of 20 kA, at which point current begins to commutate, preventing overcurrent which may result in possible damage to the TO.

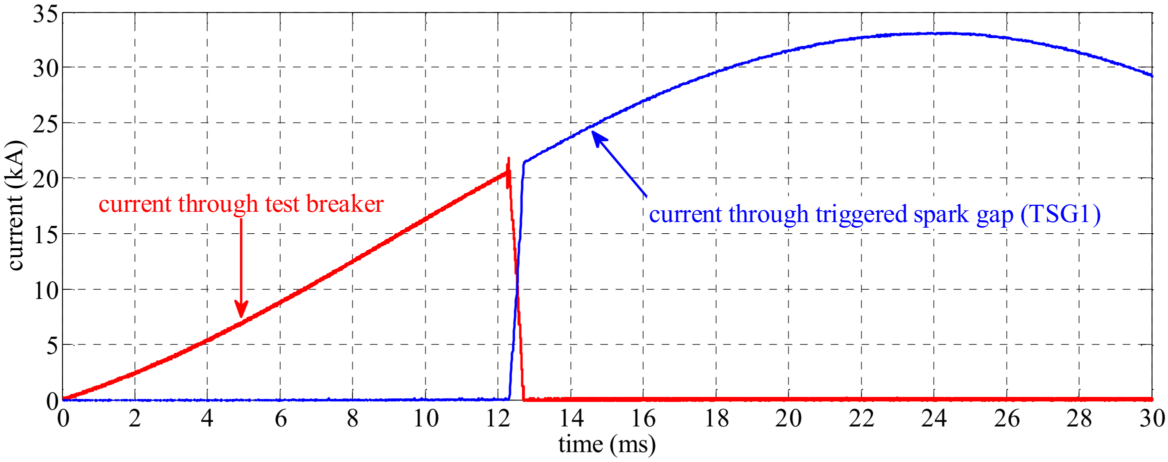


Figure 7: Successful demonstration of over-current protection by triggered spark gap in parallel with the test object. The spark gap TSG1 received a triggering signal when a current level of 20 kA was exceeded.

3.3 Dielectric and/or charging source

When in service, the HVDC CB is subjected to system voltage (DC) immediately after current interruption. In a test circuit supplied by AC short-circuit generators, this cannot be provided. However, with a similar principle as synthetic testing of HVAC CBs, DC recovery voltage can be applied from a separate source, for example from a charged capacitor bank. However, unlike for HVAC CBs where the moment of current zero is determined from power frequency, for HVDC CBs the instant at which the DC dielectric voltage is applied cannot be precisely determined in advance. Thus, a real-time current zero detection is required. For precise timing, the voltage is injected first by triggering spark gap TSG3, see Figure 6. However, to maintain conduction in a spark gap there must always be current flowing. Thus, to ensure dielectric stress when current ceases to flow, another auxiliary breaker AB2 in parallel with the TSG3 is closed shortly after triggering TSG3.

3.4 Arcing time prolongation in the auxiliary breaker

For the auxiliary breaker AB1 to provide galvanic isolation between power source and test object, it must have already gained sufficient dielectric strength by the time the HVDC CB interrupts the short-circuit current. AB1 has a duty to interrupt a residual current or in some cases an oscillating current that remains after the short-circuit current is suppressed by the HVDC CB. However, since AB1 is an AC CB it can only interrupt once current is suppressed by the HVDC CB. After interruption AB1 is subjected to differential voltage between the two sources, the AC generators and the DC voltage applied to the test object after current interruption.

If an HVDC CB operates before the auxiliary breaker gains sufficient dielectric strength, the auxiliary breaker’s arcing time must be prolonged artificially. Therefore, for a certain duration an additional reactor is inserted to let the AC CB reach its minimum arcing time at low current level. This current level can be in the order of magnitude of normal load current of the HVDC CB. Then, this reactor is bypassed by a triggered spark gap TSG2 (see the dashed box labeled arc prolongation in Figure 6) and the actual short-circuit stress is produced.

4. PERFORMANCE DEMONSTRATION OF THE TEST CIRCUIT

4.1 Test set-up

The test set-up with a prototype of active current injection HVDC CB is shown in Figure 8. The parts of the HVDC CB include a high-voltage vacuum interrupter and a high-speed making switch contained in the same tank, current injection capacitor banks, current injection reactors, stacks of metal oxide surge arrester (MOSA) and the HVDC CB control panel. The breaker is rated for 80 kV DC system and operates with principle described in Section 2.

The triggered spark gap and the auxiliary AC CB shown in Figure 8 are part of a test circuit as described in 3.2 Over-current protection.

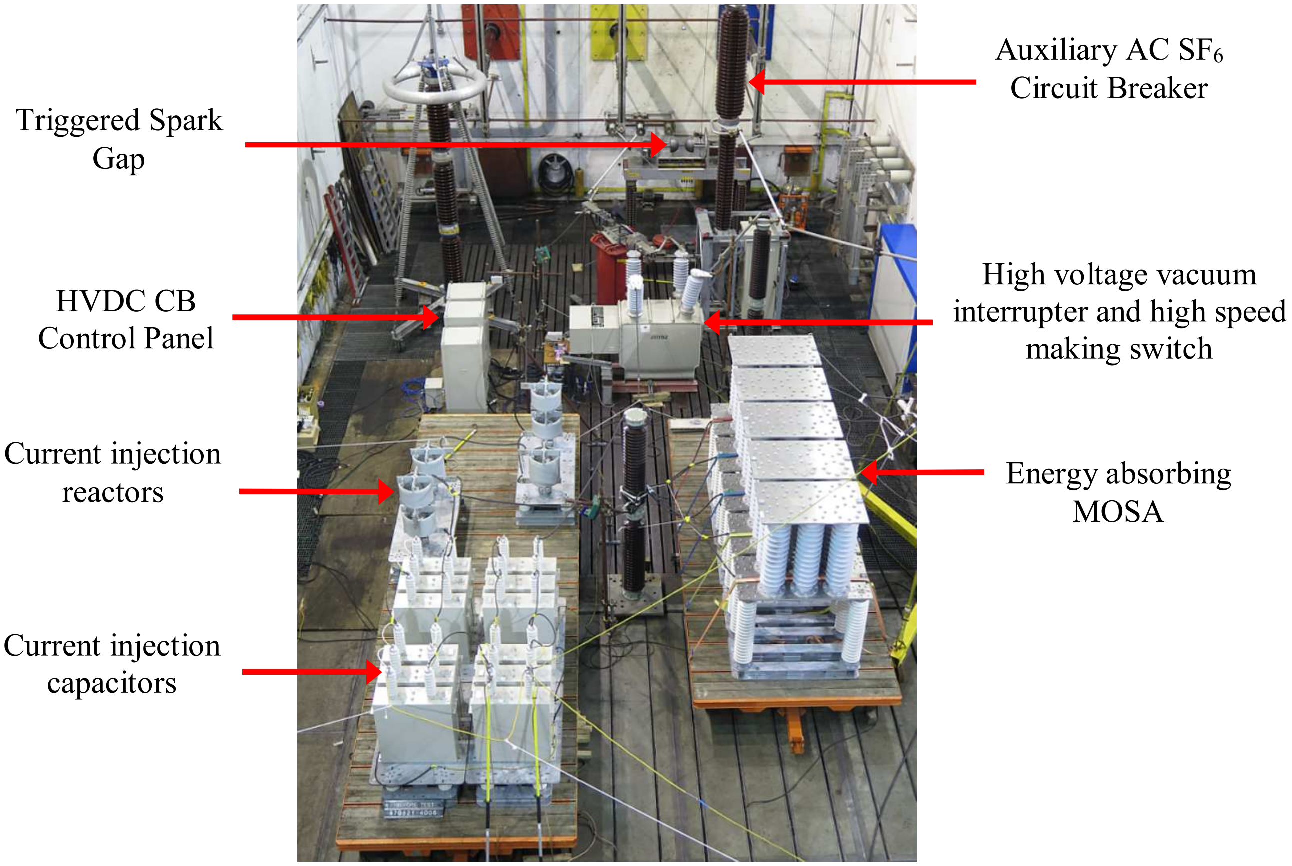


Figure 8: Test set-up of prototype active current injection mechanical HVDC CB tested at DNV GL's KEMA Laboratories

4.2 Test procedure

To verify the performance of the HVDC CB when interrupting different current magnitudes, four test duties named T100, T60, T30 and T10, shown in Table 3 are defined. Before the actual test of the HVDC CB, the test circuit components are set for specific test duty, as noted in Table 3.

Table 3: Test circuit components and corresponding parameter values for various test duties. Power frequency of test circuit is 16^{2}/$_{3}$ Hz

Test duty	Circuit inductance **(mH)**	Test parameters		Number of tests per current direction
		Interruption current **(kA)**	Energy**(MJ)**	
T100	20.5	16	4.0	1 (tested once only positive direction)
T100	10.4	16	1.5	2
T60	16.7	10	1.0	1
T30	33.4	5	0.5	1
T10	167.2	2	0.5	2

For each test duty, a prospective current is demonstrated with the HVDC circuit breaker remaining in a closed position. The aim is to verify the desired making angle as well as the rate of rise of a test duty current. In addition, initially the test circuit parameters are designed to supply energy not exceeding 1.5 MJ. For each test duty, a prospective current is demonstrated with the HVDC circuit breaker remaining in a closed position. The aim is to verify the desired making angle as well as the rate of rise of a test duty current. To control (and limit) the energy dissipated in the breaker, the source voltage magnitude adjusted*. For low energy tests (1.5 MJ) a source voltage of 19 kV is used, and for 4 MJ tests 40 kV is used.

*It should be noted that the TIV generated by the breaker governed by the internal MOSA, rather than the source voltage. Therefore, the source voltage can be almost freely selected, in order to control energy dissipation, within a reasonable range (i.e. cannot be larger than peak TIV).

4.3 Test results

For each test duty, bidirectional current interruption tests were conducted. Figure 9 shows test results of a test duty T100 (16 kA) current interruption both in the forward and reverse direction. The prospective current, with a peak of 33.5 kA is superimposed for comparison. In both tests, the current injection capacitor of the HVDC CB is charged with the same polarity. Local current interruption in the vacuum interrupter of the HVDC CB is added to the graphs as well. After the current is suppressed, there is an oscillation of a few hundreds of Hz. This is due to the interaction between the charged capacitor of the HVDC CB and the inductance in the circuit. During these tests auxiliary breaker AB1 (which isolates the power source after interruption) was intentionally not operated. In a practical operation in HVDC grid, this is prevented by residual current breaker connected in series with HVDC CB.

The traces in Figure 9b) and d) show the TIV generated by HVDC CB during energy absorption period.

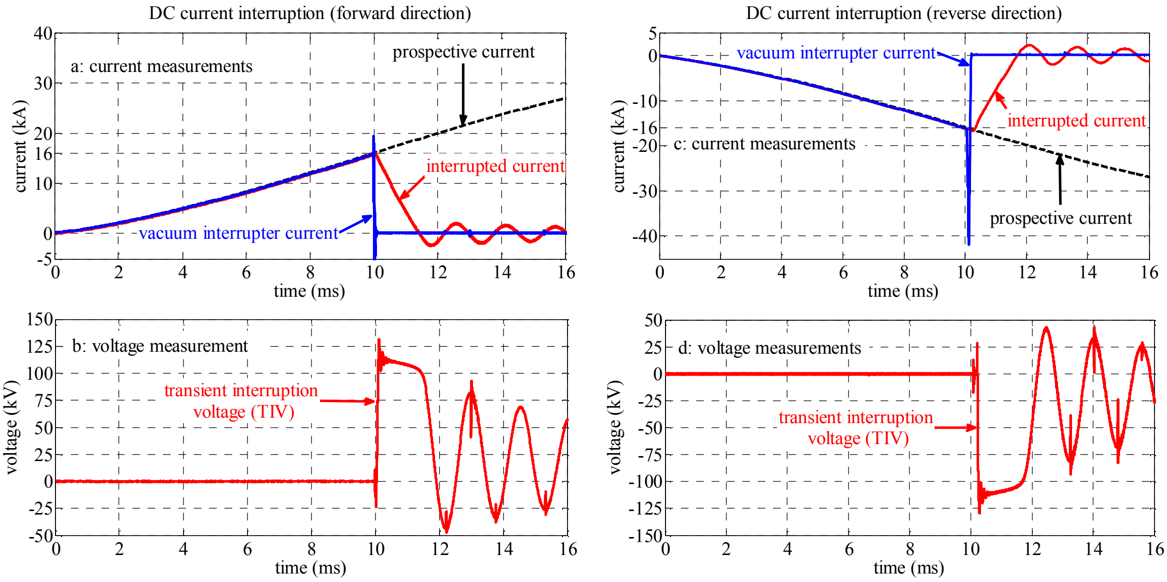


Figure 9: T100 (16 kA) bidirectional DC current interruption test results and prospective current of active current injection HVDC CB in a test circuit supplied by short-circuit generators at $16^2/_3$ Hz.

4.4 Test results at power frequency of 30 Hz and application of dielectric stress after current interruption

Test circuits supplied by AC short-circuit generators can be operated at different frequencies depending on the breaker operation time and the energy rating of the test object. Typically, for large energy absorption, the operation frequency is chosen so that half a cycle of the source voltage is longer than twice the breaker operation time. In any case, the entire current interruption process has to be completed while sufficient source voltage is maintained.

Figure 10 shows test results of forward and reverse current interruption of active current injection HVDC CB in a test circuit supplied by short-circuit generators operated at 30 Hz. In this case AB1 (see Figure 6) is tripped simultaneously with the test object. After the current is suppressed, AB1 clears the small post-suppression oscillating current observed in Figure 9. In such a way, AB1 provides galvanic isolation between the power source and the test object; thus, readying the test object for DC voltage application (although post-interruption dielectric stress from a separate source was not applied in the tests shown in Figure 10). The continuous DC voltage observed across the HVDC CB (see Figure 10b) and d)) after current interruption is due to trapped charge across HVDC CB's injection capacitor at the moment the current is suppressed to zero. Initially, this is considered to provide dielectric stress after current interruption; however, it decays rapidly as can be observed from the graphs.

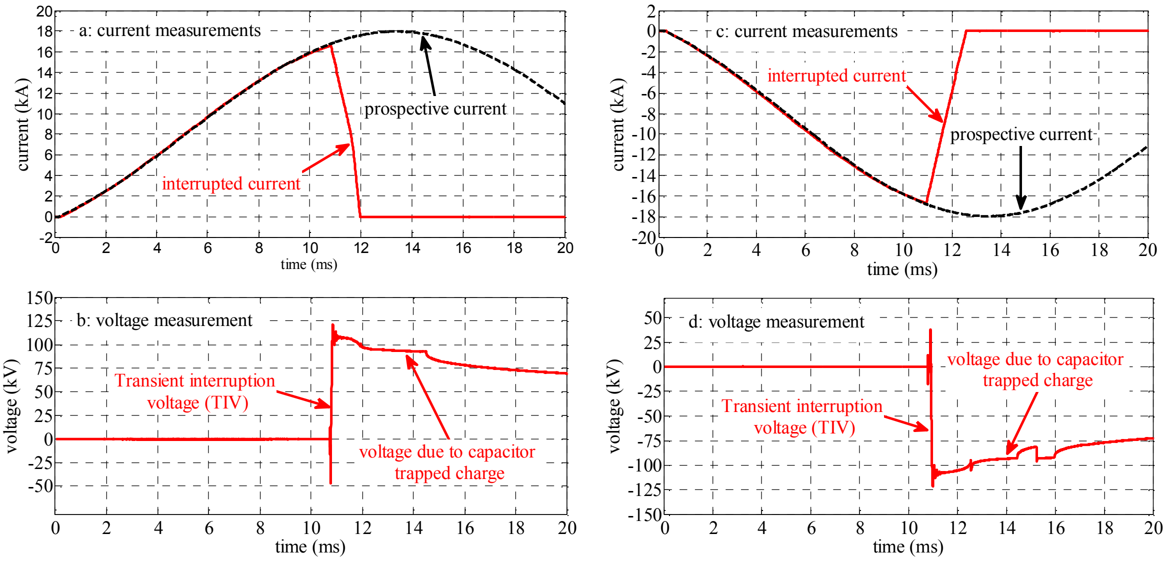


Figure 10: T100 forward and reverse current interruption by active current injection mechanical HVDC CB in a test circuit supplied by AC short-circuit generators operated at 30 Hz.

In these tests, the energy dissipation is quite small (1.5 MJ). If larger energy is needed to be applied, the sufficient supply voltage needs to be present longer and hence, frequency of the supply needs to be reduced.

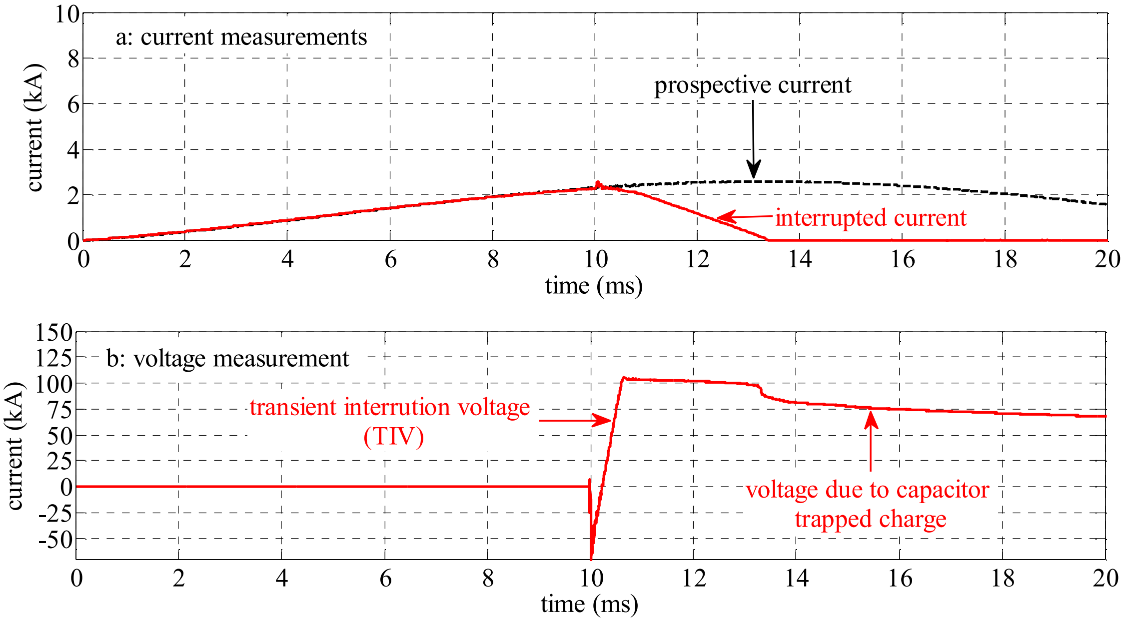


Figure 11: T10 forward current interruption by active current injection mechanical HVDC CB. The short-circuit generators are operated at 30 Hz.

Figure 11 shows test results T10 (2 kA) forward current interruption. Like the T100 test shown in Figure 10, AB1 is tripped simultaneously with the test object, resulting in trapped charge across the capacitor of the test object. It is clear from this figure that the HVDC CB successfully interrupted the low duty current as well.

5. CAPABILITY AND CHALLENGES OF TESTING A FULL-POLE HVDC CIRCUIT BREAKER

The test results of prototyped HVDC CB reported in the literature are mainly performance demonstrations of local current zero creation by single module breakers rated for 80-120 kV. However, it is essential to verify the complete interruption process of full-scale equipment. To test a full-pole HVDC CB, a test environment with sufficient power is necessary.

There are two main challenges which must be addressed before testing a full-pole HVDC CB. First, sufficient power to supply the rated stresses at full-pole: current, energy and voltage (both during and after interruption). Second, the test installation should be able to withstand the TIV generated by a full-pole HVDC CB during the entire energy absorption period.

Although the first challenge can be addressed by availability of short-circuit power for testing, a lot depends on the parameters of the HVDC CB, for example the breaker operation time and the energy rating of the HVDC CB application. The breaker operation time along with the maximum current to be interrupted dictate the rate of rise of current (di/dt) of the prospective current whereas the energy rating of the breaker application dictates the magnitude of source voltage and frequency.

Tests demonstrating the capability of KEMA Laboratories to supply adequate stresses to multi-unit HVDC CBs of various technology are performed. Some of the test results showing prospective short-circuit current and the source voltage are depicted in Figure 12. The graphs in part a) and b) of Figure 12 show results obtained by operating six short-circuit generators (of 2250 MVA each) at 30 Hz in parallel. The test in part a) is performed considering a fast HVDC CB, having breaker operation time of 2-3 ms, rated for 200 kV and above. Prospective current with a rate of rise of 5 kA/ms is achieved in this case. Assuming a relay time of 1 ms after short-circuit making and breaker operation time of 2 ms, a breaker needs to interrupt about 15 kA. In doing so, for example, if a HVDC breaker rated for 240 kV (three 80 kV breaker modules) is tested with this test set-up and 16 kA is interrupted, energy of about 10 MJ need to be dissipated by the breaker. HVDC CB rated for higher voltages can still be tested with the same test circuit, however, in the latter case less energy is absorbed due to reduced current suppression time.

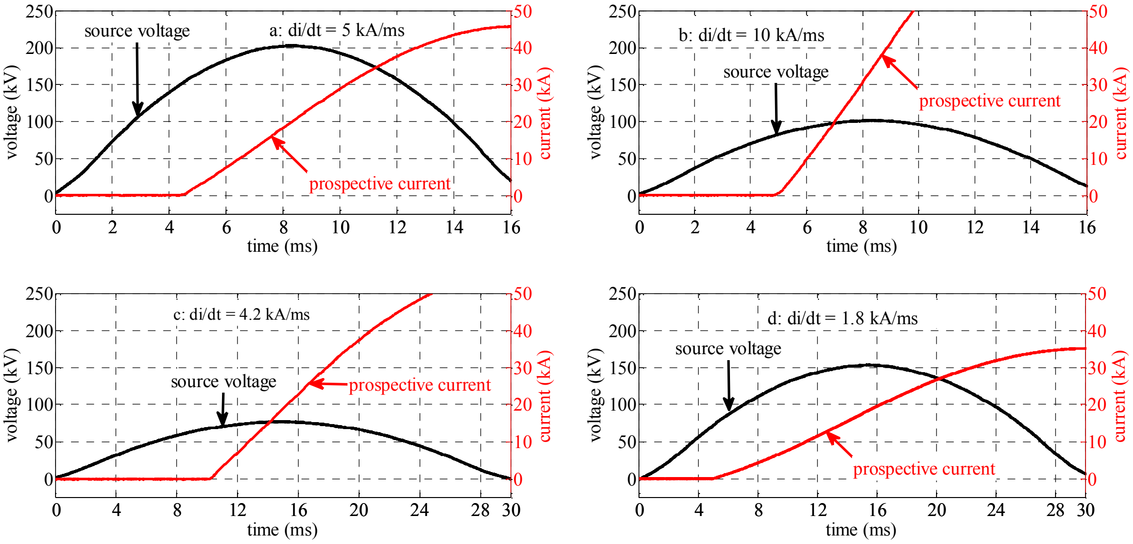


Figure 12: Demonstration of prospective current at different voltage considering various technologies of HVDC CBs having different breaker operation times.

Similarly, the experimental results in part b) of Figure 12 show that short-circuit current with rate of rise of 10 kA/ms at 100 kV obtained. This can be used to test HVDC CB rated for 100 kV and above. It must be noted that additional current limiting reactors can be used to reduce the rate of rise of current as needed.

The graphs in Figure 12 part c) and d) are obtained by operating six short-circuit generators at $16^2/_3$Hz. In part c) prospective current with a rate of rise 4.2 kA/ms is obtained at source voltage of 80 kV. The demonstration in part d) is conducted for HVDC CBs having breaker operation times in the range of 8-10 ms. The prospective current having di/dt of 1.8 kA/ms is obtained at source voltage of 155 kV. This means, at least two HVDC CB modules each rated for 80 kV can be tested with the test set-up used in the demonstration. For example, assuming HVDC CB rated for a 160 kV system, 20 MJ need to be absorbed by the breaker after interrupting 16 kA. If the same HVDC CB rated for 240 kV is tested with the same circuit, 15 MJ needs to absorbed by the breaker.

6. CONCLUSION

The paper presented DC fault current interruption test results of an active current injection mechanical HVDC CB prototype of 80 kV level. Guidelines for deriving test requirements for an 80 kV unit test from different methods of full pole HVDC CB configurations are provided. A test circuit based on AC short-circuit generators operated at reduced power frequency is designed and implemented in a high-power laboratory. It is demonstrated that with sufficient available short-circuit power, a test circuit supplied by AC short-circuit generators can supply the necessary stresses to the HVDC CB. The performance of the HVDC CB when interrupting four different test duties with currents in the range of 2-16 kA is demonstrated.

The HVDC CB successfully interrupted bidirectional current for each test duty with energy absorbed up to 4 MJ.

A method for preventing over-current in a test object in case it does not clear the short-circuit current is experimentally verified. Finally, the paper discussed practical demonstration of capability of a test laboratory considering different technologies of HVDC CBs. It is shown that multi-unit HVDC CBs, with breaker operation times in the range of 1-10 ms, can be tested with the proposed test circuits.

7. ACKNOWLEDGEMENT

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