D10.8: Initiation of standardization activities for HVDC circuit breaker design, testing and application

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CONTENT

EXECUTIVE SUMMARY

This deliverable aims to contribute to the standardization of testing of HVDC circuit breakers. Its content is based on observations made during testing of experimental versions and prototypes of HVDC circuit breakers of the active current injection type (pre-charged capacitor discharge and VSC assisted resonant current technology) and hybrid technology in the PROMOTioN project.

An overview is presented of the international efforts (committees, working groups) of IEC and CIGRE that are starting/active and to which PROMOTioN is supplying input through active participation.

Electrical stresses on T&D equipment basically consists of two types: dielectrical and make-and break (switching) stresses:

- Dielectric stresses and testing: An inventory is provided of the status of (initiation of) standardization in China, where HVDC breakers are now being applied in projects. Test parameters are collected from Chinese national standards (in development) and various ongoing multi-terminal (MT) HVDC project specifications.
- Fault current breaking: In this deliverable, the focus is on the interruption of fault currents (breaking) since this is the key function of HVDC breakers and its verification is the aim of work package 5, 10. Through a simple analytical model, six essential stages of current interruption are defined together with their relevant electrical parameters. Based on that, a list of test-requirements is presented, agreed among the partners of the work package. The list contains basically four type of tests: low-current-, continuous current- and fault current tests and is supplemented by a test to verify the dynamic dielectric withstand of switching gaps during the fault current suppression period.

  The test-circuits and methods developed in PROMOTioN are designed to carry out verification of the correct functioning during all the six stages of fault current up 20 kA by circuit breakers of 350 kV (500 kV TIV) in an affordable test-program. This test-capability has been demonstrated in the project.

Non-electrical stresses that are being discussed are mainly the following:

- A strong argument is made to intensively verify the mechanical consistency, integrity, stability of the mechanical switching gaps that are common to all HVDC circuit breakers for reducing losses. All mechanical switching devices are built upon high-speed actuators that are new to the industry. In many cases unusual series combinations of up to ten switching gaps are needed for interruption/insulation.
- The Metal Oxide Surge Arresters (MOSA) energy absorption devices in HVDC circuit breakers are stressed thermally and proper design is needed to handle this adequately. The capability to absorb the thermal energy, released during the fault current suppression period has a key position in such a test and needs large testing power.

In HVDC circuit breakers, a whole class of new technologies (mechanically, electrically, thermally) are combined. Several (sub)components available for standard application, are being applied in a non-standard manner. A functional matrix is provided on the potential issues that may arise because of this.

Together with a critical analysis, the material will serve as hands-on input to standardization in IEC.

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1 INTRODUCTION

1.1 PURPOSE

The purpose of this document is to provide information regarding status of standardization of HVDC circuit breaker testing in various national (China) and international (IEC: International Electrotechnical Committee) and the input given to this process by PROMOTioN.

1.2 MOTIVATION

The main objective of this document is to contribute to standardization of testing of HVDC circuit breakers, based on the work carried out in WP10 considering the observations and lessons learned in the testing of three technologies of HVDC circuit breakers. Standardization is supported by:

- Collection of the relevant stresses to this equipment in service;
- Assessment of the sensitivities of sub-systems and sub-components to these stresses

Standardization should lead to:

- Drafting a set of test requirements in order to promote testing under equivalent conditions, thus creating a level playing field towards the market for equipment tested in accordance with these international standards.

1.3 DOCUMENT STRUCTURE

This document consists of the following parts:

- Chapter 2 gives an overview of the relevant international working committees in CIGRE (pre-standardization) and IEC (standardization) that are active and starting. An inventory is presented of the status of standardization of HVDC circuit breakers in China. Data from national standards (in development) and various MT HVDC projects are collected in tables.
- Chapter 3 lists the progress made within PROMOTioN on standardized test requirement. Key topic is a commonly agreed list of test requirements covering six critical stages of fault current interruption, together with a technical motivation and a calculation method to quantify stresses in testing. The clearly quantified list of test is transferred to the IEC standardization committee. A matrix of non-standard stresses on standard breaker (sub)components is provided as a guideline for future test-requirements.
- Chapter 4 lists a number of other stresses, that are not within the scope of this document. It contains a critical analysis to be submitted to standardization committees. The verification of withstand of these stresses (not yet in quantifiable test-requirements) will be transferred to the relevant IEC committee.

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2 STATUS OF STANDARDIZATION OF HVDC CIRCUIT BREAKERS

2.1 STANDARDIZATION COMMITTEES WORKING TOWARDS HVDC CB STANDARDS

2.1.1 LIST OF INTERNATIONAL COMMITTEES AND THEIR ACTIVITIES

The following lists the (pre-)standardization committees in CIGRE (International Council of Large Electric Systems) in recent years.
All committees had (a) member(s) active in PROMOTioN WP 5, 10.

- **CIGRE JWG A3B4.34 (2014-2017) on HVDC switchgear (incl. HVDC circuit breakers).**
  This working group (WG) made an inventory of HVDC switchgear, including HVDC circuit breakers. In 2017, CIGRE Technical Brochure 683 “Technical requirements and specifications of state-of-the-art HVDC Switching Equipment” [1] was issued. One of the most important result is the adoption of a standardized nomenclature, see Figure 1. Strong recommendation is expressed to use this nomenclature as commonly agreed in future discussions on standardization.
  The document gives an overview of testing of HVDC circuit breaker (concepts) based on capacitor discharge circuit (single- [2] and multiple frequency [3]) and based on LF AC short-circuit generator supply [4].

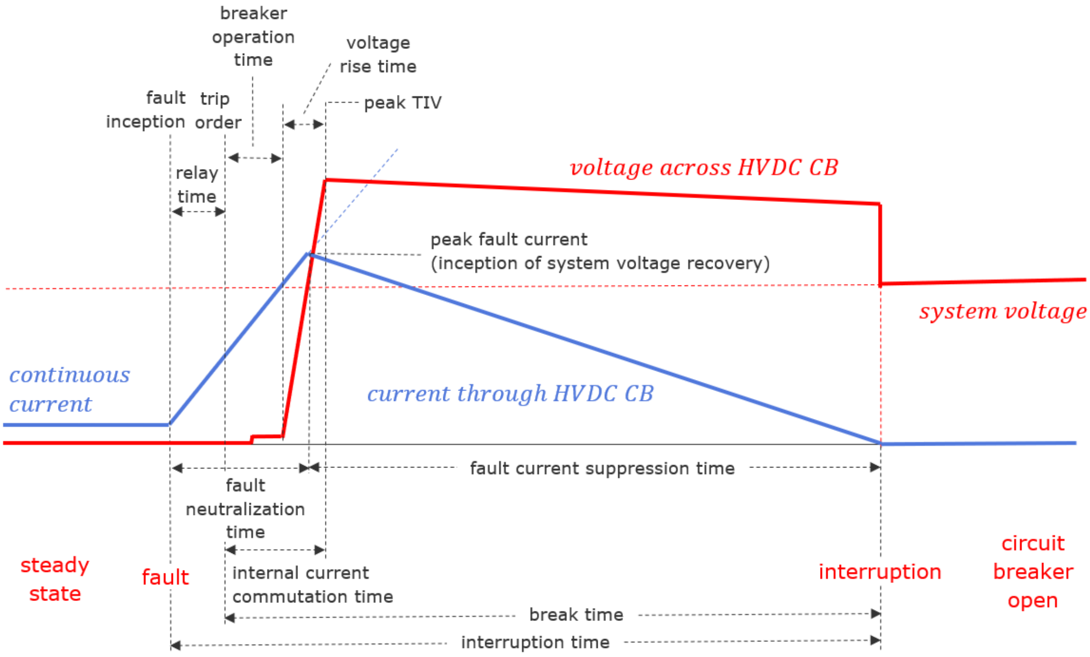

Figure 1: Standardized waveshapes of current and voltage during fault current interruption of HVDC circuit breakers (after [1]).

- **CIGRE WGA3.39 (2017-2020) on surge arresters (including those used in HVDC circuit breakers)**
  This WG focusses on the service experience of MOSA (Metal Oxide Surge Arresters) including those applied in HVDC circuit breakers. The latter application was included since MOSA in DC breakers will deal with significantly different stresses than in its standard application as overvoltage protection. Results, obtained from the work described in PROMOTioN deliverables D10.3 and D10.4 are included in the report of this WG. Moreover, failure modes of ZnO blocks after multiple energy injection in excess of the design specification has been been reported [5, 6].

- **CIGRE WG A3.40 (2018-2021) on MV DC systems and switchgear**
  This WG is dealing with medium voltage (MV) DC systems and circuit breakers. The WG is working to collect field experience, to make an inventory of state-of-the-art technology and to summarize technical requirements for MV DC breakers < 100 kV.

- **CIGRE JWG B4A3.80 (2019-2022) on HVDC circuit breaker requirements**
  This WG is set-up to propose test requirements for HVDC circuit breakers. Its tasks are:
  - Describe basic configurations and overview of the HVDC circuit technologies available in the market and under research / development, including different designs of HVDC circuit breakers investigated in PROMOTioN project and other research projects in different countries.
  - Describe possible applications of HVDC circuit breaker and define technical requirements of HVDC CBs for these different applications;
  - Study specific component stresses (relevant to testing) under continuous operation, load switching and fault current switching. Specific attention will be given to behaviours due to operation of mechanical or hybrid switches, current commutation as well as energy dissipating processes within the equipment.
  - Specify testing methods for component and equipment;

  Representative from several PROMOTioN work packages are joining this WG to bring in various aspects towards the targeted tasks as listed above.

- In 2018 PROMOTioN WP10 organized in conjunction with CIGRE Study Committee A3 (T&D equipment) during the Paris conference a workshop on HVDC circuit breakers in which various test experiences from three Chinese MT HVDC projects were shared. The workshop attracted 140+ participants.

The following lists the standardization committees in IEC (International Electrotechnical Committee) in recent years regarding HVDC switchgear and HVDC circuit breakers. All (except the two last) committees had (a) member(s) active in PROMOTioN WP 5, 10:

- **IEC AHG4 (2016-2017), on market relevance of HVDC switchgear**
  This ad-hoc IEC working group had the task to assess the relevance of starting standardization of HVDC switchgear, including HVDC circuit breakers and HVDC GIS. This covers all technical aspects of

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air and gas-insulated switchgear for indoor and outdoor applications with switchgear voltages above 1.5 kV DC. The findings of the AHG were presented at the IEC TC 17 meeting in 2017 [7].

- **IEC AHG60 (2017-2018), on existing standards of HVDC switchgear**
  This ad-hoc working group is a follow-up of IEC AHG4, once it was confirmed by IEC TC17/17A that there was a relevance of standardization. AHG 60 was formed with the task to further analyse document 17/1032/INF and make recommendations to IEC SC 17A. Its final report is presented in 2018 [8].

- **IEC 62271-316 (2020 ongoing), standardization on HVDC circuit breakers**
  This IEC working group will start (in 2020) standardization of HVDC circuit breakers (for fault current interruption). Major input from PROMOTioN, as detailed in chapter 3.7 will be provided.

- **IEC 62271-5 (proposed project number) (2020 ongoing)**
  This document will form the common basis of documents that will be developed for DC switchgear (above 1.5 kV) and DC switchgear assemblies in a similar manner as was done for AC switchgear and AC assemblies (IEC 62271-1).

- **IEC 62271-314 (2020 ongoing), standardization of HVDC transfer switches**
  This IEC working group will start (in 2020) standardization of HVDC transfer switches (for load, earth transfer, metallic earth return, commutation etc.).
  In separate projects, also standardisation committees dealing with DC earthing- and disconnecting switches (IEC 62271-313), DC bypass switches (IEC 62271-315) and DC gas-insulated switchgear assemblies (IEC 62271-317) are established in 2019.

- **IEC/TS 63014-1, 2018: High-voltage direct current (HVDC) power transmission – System requirements for DC-side equipment - Part 1: Using line-commutated converters.**
  This technical specification (TS) lists test requirements for HVDC switchgear applied in HVDC switchyards of LCC based projects. Although this document includes requirements for DC disconnectors and certain types of specialised DC switching devices (such as the Metallic Return Transfer Switch (MRTS)), it excludes any type of DC circuit breaker designed to interrupt fault currents. DC-side equipment for HVDC systems based on voltage-sourced converter (VSC) technology is excluded from this document and will be covered in a future Part 2 of IEC 63014.

In the Appendix chapter 6, Figure 14, Figure 15 are reproduced as published in CIGRE Green Book [9]. The figures show in more detail the basic interruption processes in the main HVDC circuit breaker technologies: active current injection and hybrid technology.

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2.1.2 DEFINITIONS PROPOSED BY CIGRE AND THE PROMOTION PROJECT

The PROMOTioN project proposes to follow the technology definitions from CIGRE TB 683 [1]:

- Active current injection DC circuit breakers.
  Breaker technology of MEU (active current injection of decreasing amplitude initiated by a pre-charged capacitor [10]) and SciBreak (active current injection with increasing amplitude initiated by a VSC converter [11]). The common denominator of this technology is counter current injection from an auxiliary circuitry into an arcing device (vacuum circuit breaker) to create current zero and interruption.
- Power electronic DC circuit breakers.
  Since this type of breaker has not reached a sufficient TRL level for HV applications (mainly because of unacceptable losses in HV applications), this technology is not considered in PROMOTioN WP5, 10.
- Mechanical and power electronic hybrid HVDC circuit breakers.
  In the PROMOTioN project WP5, 6 and 10 the circuit breaker of ABB [2] falls within this category. In the following, the term "hybrid HVDC circuit breaker" will be used for convenience.

In general, use of the term "mechanical" HVDC circuit breaker should be avoided, since all practical HVDC circuit breaker technologies rely on mechanical switching devices, either for interruption and/or for insulation. Since the full system power in normal operation is flowing through this subsystem, reliability of this mechanical subsystem is required to be high.

The naming of the three functional branches (see Figure 2) of HVDC circuit breakers is not harmonized internationally. Various names are in use, see table 1. The function of the various branches is discussed in section 3.4.

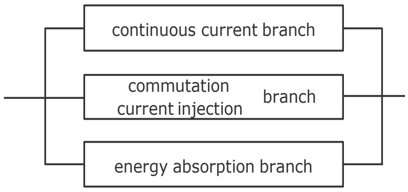

Figure 2: Basic HVDC circuit breaker branches as functional lay-out

Table 1: Different naming conventions of the functional branches/paths/devices of HVDC circuit breakers

Source	CIGRE TB 683 and [12]	CIGRE WGB4/A3.80 -2020	GB/T 38328-2019 [13]
1[1]	nominal current path	main current branch	main conduct device
2	commutation path or current injection path	commutation branch (hybrid) or current injection branch (active current inject.)	current transfer device
3	energy absorption path	energy absorption branch	energy absorption device

2.1.3 CHINESE STANDARDS RELATED TO TESTING OF HVDC CIRCUIT BREAKERS

The following Chinese standards exist covering DC switchgear:

- GB/T 25309, 2010: Chinese standard for current transfer switches;
- GB/T 25091, 2010: Chinese standard for DC disconnectors and earthing switches;
- GB/T 25307, 2010: Chinese standard for DC by-pass switches;

[1] The term adopted by IEC is "continuous current".

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The following documents are (at the time of writing) being drafted at the time of writing

- NB/T 42107: Chinese draft standard for DC circuit-breakers. This standard will have a separate document on hybrid and on active current injection type of circuit breakers [13];
- GB/T 38328: Chinese draft Common specifications of high-voltage direct current circuit-breakers for high-voltage direct current transmission using voltage sourced converters.

In the list of documents given here GB means National standard of China, NB means the standard by National Energy administration of China. The additional “T” means recommended standard.

The Chinese standards are a result of the work done in the year 2010, when two 800 kV point-to-point HVDC projects (Yunnan-Guangdong, Xiangjiaba-Shanghai) were put into operation. The standardization of equipment is a part of the construction of these projects.

It must be noted that the Chinese standard for DC circuit breaker is not officially published.

Of the standards on HVDC circuit breakers AC standards [14, 15] are widely quoted, most of the terminology, test items, test procedures are directly used. Special structures, special duties are described in the DC standards, obvious differences can be found in the DC switchgear standards compared to the AC equipment. The DC standards form a basis for projects in China, the parameters, ratings, descriptions of duties, test items and test procedures were summarized based on the existing HVDC projects.

The standards of HVDC switchgear, not dealing with fault currents were published in 2010, and not revised till present days, many new projects were built after 2010, and the new ratings, requirements were not mentioned in the standards.

CIGRE WG B4A3.80 monitors the Chinese standardization status and will report in its Technical Brochure to be finalized in 2021.

In the following, key points are summarized regarding HVDC circuit breakers. All italicized texts are quotations from the document [13] (English translation not authorized).

SCOPE

“This standard applies to all high voltage direct current circuit breaker (including mechanical DC circuit breaker, power electronic DC circuit breaker and hybrid DC circuit breaker) for indoor and outdoor installed in flexible DC systems of DC 6 kV and above”.

DEFINITIONS

HVDC circuit breaker and its branches (“*devices”):*

“A switching device, capable of making, carrying and breaking direct current under normal circuit condition and also making, carrying and breaking direct current under specified abnormal circuit conditions such as those of short circuit within a specified time.

NOTE 1: The high-voltage direct current circuit breaker generally includes: main conduct device, current transfer device and energy absorption device. The main conduct device is used for carrying direct current and has the capability of breaking the current of the main circuit in cooperation with the current transfer device. The

current transfer device is used for transferring the current of the main conduct device to the energy absorption device. The energy absorption device is used for absorbing the energy stored in the system.
NOTE 2: The high-voltage direct current circuit breaker can be divided into mechanical DC circuit breaker, power electronic DC circuit breakers and hybrid DC circuit-breaker according to the types of interrupting device. The high-voltage direct current circuit-breaker can be divided into unidirectional DC circuit -breaker and bidirectional DC circuit-breaker according to the direction (of current) *flowing in the main circuit"*

In the Chinese document, three types of interruption devices are distinguished: "*mechanical DC circuit breaker, power electronic DC circuit-breakers and hybrid DC circuit-breaker".*

RATINGS

The following main rating values have been defined in [13]:

– *Rated direct voltage:*
  Standard values of rated direct voltage (kV) are given below.
  6, 10, 25, 35, 50, 100, 160, 200, 320, 400, 535, 800.
– *Rated insulation level:*
  The rated insulation level of the high-voltage direct current circuit breaker shall be provided by the flexible DC transmission projects.
  Insulation level shall include DC withstand voltage (1 min DC withstand voltage, 3 h DC withstand voltage, 1 h DC withstand voltage), rated lightning impulse withstand voltage and rated operating impulse withstand voltage. Among them, the withstand voltage applies at the standardized reference atmosphere (temperature (20 °C), pressure (101.3 kPa) and humidity (11 g/m^3)) specified in GB/T 311.1-2012 (IEC 60071-1).
– *Rated direct current:*
  The rated direct current in ampere (A) of the high-voltage direct current circuit breaker is the r.m.s. value of current which the HVDC circuit breaker shall be able to carry continuously under specified conditions of use and behavior.
  Standard values of rated direct current (A) are given below.
  156, 250, 500, 625, 750, 1 000, 1 250, 1 560, 2 000, 2 500, 3 000.
– *Rated prospective short-circuit current* (in TB 683 this is defined as "Prospective fault current")
  The rated prospective short-circuit current in kilo-ampere (kA) is the steady-state value of prospective current being located between the terminals of the high-voltage direct current circuit breaker under specified conditions of use and behavior.
  Standard values of rated prospective short-circuit current (kA) are given below.
  8, 10, 12.5, 16, 20, 25, 31.5, 40, 50, 63.
– *Rated cut-off current* (in TB 683 this is defined as "Peak fault current")
  The rated cut-off current in kilo-amperes (kA) is the maximum instantaneous value of current interrupted by the high-voltage direct current circuit breaker during the breaking the rated prospective short-circuit current under specified conditions of use and behavior.

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Standard values of rated cut-off current (kA) are given below.

4， 5， 6.3， 8， 10， 12.5， 16， 20， 25， 31.5

– *Rated absorbed energy*

The value of the energy absorbed by the energy absorption device, the DC circuit breaker being interrupt the rated cut-off current.

TYPE TESTS

In the Chinese document GB/T 38328-2019 , the following type test requirements have been detailed:

Table 2: Type test of HVDC circuit breakers in GB/T 38328-2019

Type test	*Test specimens*
Dielectric tests	*The completely assembled, as in service*
Radio interference voltage (RIV) test	*The completely assembled, as in service*
Measurement of resistance of the main circuit	*Main conduct device* (see table 1)
Maximum continuous operating voltage test	*Main conduct device* (see table 1)
Short-time withstand current and peak withstand current tests	*Main conduct device* (see table 1)
Verification of the protection	*Components*
Tightness tests	*Components*
Electromagnetic compatibility (EMC) test	*Components*
Mechanical operation test at normal temperature	*Mechanical breaking device (if any)*
Terminal static load test	*Components*
Making and breaking tests	*The completely assembled, as in service*
X-ray Test Procedure for Vacuum Interrupter	*Vacuum interrupter (if any)*
Seismic qualification tests	*The completely assembled, as in service*
Communication conformance test	*Control equipment*
Cooling equipment test	*Cooling equipment (if any)*

Since dielectric tests and making and breaking tests are required on the complete device, as in service, some details are added below, also taken from GB/T 38328-2019 [13].

– Dielectric tests

For the dielectric test requirement the following applies:

1) Lightning impulse tests: Reference is made to IEC 62271-1 [15] and IEC 60060-1 [16]

2) Switching impulse tests: Reference is made to IEC 62271-1 and IEC 60060-1

3) DC voltage withstand tests: Starting from a voltage not higher than 50% of the test voltage U_{d1min}, the voltage shall be raised to the specified 1 min test voltage U_{d1min} within approximately 10 s, kept constant for 1 min, reduced to the specified 1 h test voltage U_{d1h}, kept constant for 3 h and then reduce to zero.

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Dielectric tests shall be between the two terminals of the circuit breaker and between one terminal and earth. For voltage application between terminals, the energy absorption branch shall be disconnected.

- Making and breaking tests

  The following breaking test requirements have been defined in GB/T 38328-2019, table 3:

Table 3: Breaking current requirements for HVDC circuit breakers in GB/T 38328-2019

Test-duty	*Testing current*	*Operating sequence*	*Number of operating sequences* [a]
1	*short-time overload direct current*	*C*	*6*
2	*Small current* [b]	*O*	*6*
3	*Rated direct current*	*O*	*6*
4	*30% rated cut-off current*	*O*	*6*
5	*60% rated cut-off current*	*O*	*6*
6	*100% rated cut-off current*	*O*	*6*
7	*100% rated cut-off current*	*O-CO* [c]	*2*
NOTE: Since the capacity of the laboratory cannot simulate the energy absorbed by the high voltage direct current circuit breaker when breaking the short-circuit current of the actual system, the rated absorbed energy of the MOV is tested by the method of the sampling inspections, and are subject to agreement between manufacturer and user.			
[a] *For bi-directional DC circuit breaker, test-duty of 1 to 6 shall comprise 3 tests in each direction and test -duty 7 shall comprise 1 test in each direction.* [b] *The value of small current is recommended to be the 5% value of the rated direct current.* [c] *The auto-reclosing duty is defined as O-t-C-t'-O, where O is the opening operation and C is the closing operation, t is the opening-closing time, it is recommended to be no more than 300 ms. t' Is the closing-opening time, subjected to agreement between manufacturer and user. The first O operation of the cut-off current is 100% of the rated cut-off current, and the second O operation of the cut-off current can be subject to agreement between manufacturer and user.*			

- Voltage test as condition check:

  When the insulating properties across the terminals of the high voltage direct current circuit breaker after the making breaking and/or mechanical/electrical endurance tests cannot be verified by visual inspection with sufficient reliability, and there are no specified product standard, a direct voltage withstand test applied in dry condition across the two terminals of the high voltage circuit breaker may be appropriate. The 80% of the value of the test voltage during 1 min shall be applied, and kept constant for 1 min. Any methods of measurements are subject to agreement between manufacturer and user.

2.1.4 MAIN TECHNICAL PARAMETERS OF HVDC CIRCUIT BREAKERS IN CHINA.

As an example of test parameters of a HVDC circuit breakers for a ±160 kV and ±500 kV VSC-HVDC system is China, the following table is informative.

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Table 4: Main technical parameters of HVDC circuit breakers in Chinese projects

Parameters	***Units***	***Values***	
Rated DC voltage	*kV*	*160*	*535*
Rated DC current	*A*	*1000*	*3000*
Maximum continuous DC current in operation	*A*		*3300*
Short-time overload DC current in operation	*A*		*4500 (1 min)*
Cut-off current [2]	*kA*	*9*	*25*
Cut-off time [3]	*ms*	*≤ 5*	*< 3*
Rated absorbed energy (hybrid DC circuit breaker)	*MJ*		*> 125*
Rated absorbed energy (mechanical DC circuit breaker)	*MJ*		*> 155*
Rated DC voltage withstand (to earth)	*kV*	*252*	*856 (1 min)* *588.5 (3 h)*
Rated switching impulse voltage (to earth)	*kV*	*450*	*1175*
Rated lightning impulse voltage (to earth)	*kV*	*550*	*1425*
Rated DC voltage withstand (between terminals)	*kV*	*252*	*856 (1 min)* *588.5 (3 h)*
Rated switching impulse voltage (between terminals)	*kV*	*350*	*920*
Rated lightning impulse voltage (between terminals)	*kV*	*450*	*1104*

[2] In CIGRE TB 683 this quantity is called “peak fault current”
[3] In GB/T 38328 this time is defined as “*interval time between the DC circuit breaker receives the opening command and the peak value of the transient interruption voltage is reached*”. In CIGRE TB 683 this quantity is called “internal current commutation time”.

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2.1.5 CHINESE PROJECT SPECIFICATION OF TEST REQUIREMENTS FOR 500 KV HVDC CIRCUIT BREAKERS

The realization of the ±500 kV Zhangbei meshed HVDC onshore grid [17,18] a project in China, will initially include 16 HVDC circuit breakers of five different Chinese suppliers offering three designs of current injection and hybrid circuit breakers [19,20]. For these circuit breakers, project specifications are issued by SGCC (State Grid Company of China).

Table 5: (partial) List of test requirements for HVDC circuit breakers for Zhangbei 500 kV project

Test type	***Test duty***		***Value***	
			***Document SGCC* [21]**	***Manufacturer [22]***
Dielectric test	*On DC CB support structure*	*DC voltage test and partial discharge test*	*941.6 kV (535 kV × 1.1 × 1.6 / 3 h)*	*856 kV / 1 min 589 kV / 3 h*
		switching impulse test	*1175 kV × Kt Kt: atmospheric correction factor*	*1300 kV*
		lightning impulse test	*1425 kV × Kt Kt: atmospheric correction factor*	*1550 kV*
		Short-time DC voltage test	*1010 kV / 50 ms*	*1010 kV / 1 min*
	between DC CB terminals	*DC. voltage test*	*588 kV (535 kV × 1.1) / 1 h 856 kV (535 kV × 1.6) / 1 min*	*589 kV / 1 h 856 kV / 1 min*
		switching impulse test	*920 kV (800 kV × 1.15)*	
		lightning impulse test	*1104 kV (800 kV × 1.38)*	
		DC voltage wet test [4]	*588 kV (535 kV × 1.1) / 5 min*	
Operation test	*Main branch Maximum continuous running current test*		*In × K1 / 1 h In: rated continuous current K1: test factor*	
	Main branch Overload current test		*4.7 kA (4.5 kA × 1.05) / 10 min*	
	Main branch Short-time current test		*According to the waveform*	
	Transfer branch Short-time current test		*According to the waveform*	
	Current breaking test		*10 A, 50 A, 200 A, 500 A, 1500 A*	*4.5 kA / 2.7 ms*
	Closing test		*4.5 kA*	
	Fault current breaking test		*7.5 kA, 15 kA, 25 kA*	*25 kA / 2.7 ms*
	Closing test		*4.5 kA*	
	Reclosing test		*(refers to relevant techn. clause)*	*25 kA / 0.3 s / 6.8 kA*

For other test requirements the document [21] refers to the relevant technical project specifications. These include: EMI test duties for the complete equipment during operation, as well as for individual components (IGCT as making switch for active current injection breakers, disconnector, power supply transformers etc.), including electrostatic discharge tests, RF electromagnetic field radiation immunity tests, electrical fast transient pulse immunity tests, conducted RF disturbances immunity test, power frequency & impulse magnetic field immunity tests and damped oscillation immunity tests.
Mechanical, seismic tests, shock immunity and components, control tests are also left to the project.

[4] This test is not necessary for active current injection breakers

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3 MAKING AND BREAKING REQUIREMENTS FOR HVDC CIRCUIT BREAKERS - PROMOTION RESULTS

3.1 BACKGROUND

This chapter describes the efforts within PROMOTioN to generate and collect knowledge on the impact of (electrical) stresses on HVDC circuit breakers and its subcomponents. Since standards need to cover verification of withstand against such stresses, it is of importance to have a good understanding on how (sub-) systems interact with other (sub-)systems and the power system.

Figure 3: Staged line-to-earth fault in a three-terminal 160 kV HVDC system [28]

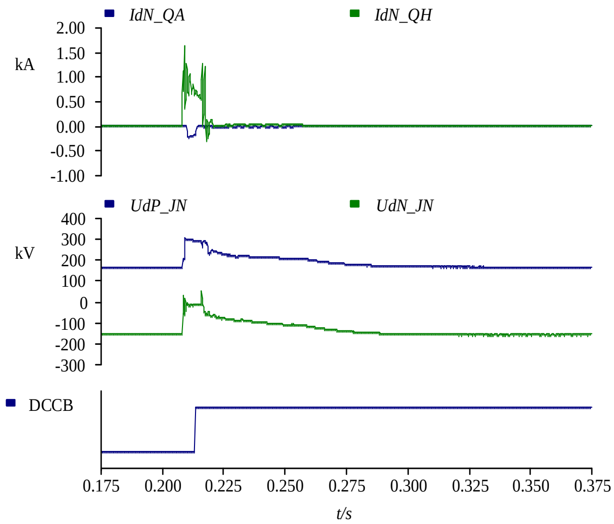

Figure 4: Response of HVDC CB on a system fault of 1.4 kA in 160 kV system [28].

One issue is the lack of operational experience of MT HVDC grids and even what is more lacking is the occurrence of faults in such systems, that was put into operation recently in China.
HVDC circuit breakers are in service at the time of writing in two radial MT HVDC projects. First, hybrid HVDC breakers were installed in the ±200 kV Zhoushan five terminal island link (2014) [23, 24, 25] from State Grid Co. of China. The other is in the ±160 kV three terminal Nan'ao project (2013) [26], operated by China Southern Power Grid, where active current injection HVDC circuit breakers are installed [27].
The only documented fault case [28] is a staged fault test in the Nan'ao 160 kV project, where a line-to-earth fault is on purpose initiated. An active current injection HVDC breaker cleared the fault of 1.4 kA with a breaker operation time of 3.5 ms. The fault was artificially introduced to verify not only the operation of HVDC circuit breaker but also to verify the overall coordination of control and protection systems. Note that prior to the installation of the HVDC circuit breaker, the system was protected from AC side using conventional AC circuit

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breakers where the whole DC side is shutdown in case of such a fault. In this exercise, this protection strategy is used as backup in case the HVDC circuit breaker/dc side protection fails to clear/detect the fault.

The absence of real grids has led to a large number of fault simulation studies in modelled grids. Many DC fault studies have been presented on model HVDC grids [29, 30], the most prominent, but also the most complicated one being the CIGRE B4.58 benchmark system [31]. As a simplification, also in PROMOTioN, models were designed of 4 to 5 terminal systems (see deliverable 5.1, [30]).

3.2 PROMOTION CONTRIBUTIONS

The following PROMOTioN deliverables were produced in PROMOTioN dealing with electrical stresses imposed on the HVDC circuit breaker components from faulted HVDC systems:

D.4.2: Broad comparison of fault clearing strategies for DC grids
Benchmarking of fault clearing strategies. Broad address fault clearing strategies in a generic way. Certain choices have been made to avoid overly detailed studies or conclusions, which also implies that not all cases for each fault clearing strategy have been covered. A common set of metrics to compare the fault clearing strategies has been defined.
An in-depth analysis of a 4 terminal system has been performed.

D 5.1: HVDC network fault analysis.
Definition of a benchmark HVDC meshed grid model for simulation of fault transients (current, voltage) regarding stresses to switching devices and system during a fault. For this system, the standard simulation EMTDC/PSCAD software and detailed equivalent model, which is accurately sufficient for system fault studies, is adapted to include fault situations. The main achievement in this deliverable is finding the worst-case fault condition in a multi-terminal HVDC system in a generic manner. The worst-case condition being evaluated with respect to the rate-of-rise and peak value of fault current as well as the speed of propagation of voltage collapse during a fault.

D 5.2: HVDC circuit breaker modelling and analysis.
Definition of electrical models of each circuit breaker technology in order to characterize the interaction between circuit breaker and system. Sufficiently accurate models (for the purpose of system simulation study) of various technologies of HVDC circuit breaker were developed as an output of this deliverable. Functional data of the various technologies serve as input for the model. The focus here will be on the electrical features for which functional input data were provided by the manufacturing partners. The physical stresses (electrical, thermal, mechanical) of the subcomponents (interrupters, semi-conductors, energy storage components, energy absorbers etc.) were characterized in detail in WP 6.

D 5.3: Fault stress analysis of HVDC circuit breakers

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This deliverable combines the results of D 5.1 and D 5.2 in which the benchmark grid developed in D 5.1 is simulated by including simulation models of HVDC circuit breakers in such a grid. In this case the models of the HVDC circuit breakers are operated according to the operational parameters provided by respective parameters. The ultimate goal of this deliverable is identification of stresses on HVDC circuit breakers of different technologies based on realistic input data from the manufacturers. Evaluation of the most severe conditions, depending on the technology applied, are performed. This has led to the proposal of a technology independent “black-box” set of test requirements.

D 5.4: Documents on test requirements

The studies in D 5.3 quantified different stresses (current, voltage and energy) on the various technologies of HVDC circuit breakers. Since the specific values are system dependent (configuration, control, etc.) generic test requirements have been defined based on parameters extracted for system simulation studies in D 5.3. Hence specification of test requirements under specific conditions and circuit topologies (TSO requirements): close/remote fault, high current/voltage derivatives, oscillations on DC variables, space charging of insulators by steady state DC operation, etc.

D 5.5: Documents on test procedures

Analysis and development of potential HVDC circuit breaker test procedures and protocols.

D 10.2: Evaluation of the interaction of circuit breaker sub-components with the test-circuit during the interruption process

The specific stresses on the various key-components of the test-objects (interrupters, electronic switches, mechanical switches, protection- and snubber circuitry, commutation and energy absorption) are identified. This deliverable describes the design of an experimental active current injection circuit aimed at studying experimentally the stresses on the vacuum circuit breaker (in the continuous current branch) and the MOSA energy absorber branch. This deliverable provides knowledge on the design of MOSA for HVDC circuit breaker application with practical test results. The main issues associated with application of MOSA as a combination of a number of parallel columns each consisting of a large number of non-linear metal oxide varistors have been identified.

D 10.3: Acquisition of input data for characterization of stress withstand of breaker sub-components

Digital data of specialized measurements are acquired for input in the characterization studies and analysis. A database is provided to be used for the validation of the models regarding thermal and electrical stresses to electronic switches and surge arresters. Critical information has been extracted by investigating the test results obtained from experimental DC circuit breaker.

D 10.4: Document on test result analysis.

Detailed data and analysis is giving insight in the interruption process of arc based HVDC CB technologies. Digital data is acquired during the stress experiments in the circuit breaker performance assessment. Results are summarized in [33].

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D 10.5: Failure mode and effect analysis of DC circuit breakers
Possible modes of failures of circuit breaker (sub-components) are analysed and classified. Failure modes of subcomponents of three HVDC circuit breaker technologies are considered, and their impact on the required functions of the HVDC circuit breaker.

A summary of the knowledge collected in these deliverables can be found in a series of (PROMOTioN initiated) publications in IEEE Trans. on Power Delivery [4, 30, 32, 33].

3.3 STRESSES ON HVDC CIRCUIT BREAKER SUBCOMPONENTS

All designs of HVDC circuit breakers have components that are used in a non-conventional way, or they include new types of components. In order to reduce the risk of failures in the application of HVDC circuit breakers, standardization committees need to analyse the new stresses, typical for HVDC circuit breakers, that these components face.
Table 6 lists the 'standards' components applied in a 'non-standard' way.

Table 6: HVDC circuit breaker components facing "non-standard" stresses and possible issue

Subcomponent		In standard operation	Operation in HVDC CB application	Potential issue(s)
mechanical switching devices	(Multiple) actuator(s) for mechanical switching device	Speed 1 – few m/s	Ultra-high speed High impact forces Control electronics on board	Mechanical reliability Compatibility with equipment attached EMI sensitivity
	Power supply to actuator	At earth potential	At high potential	Non-galvanic power supply
	Vacuum interrupters for interruption	Power frequency AC current interruption	High frequency current interruption at very high *di/dt* and recovery at small gap length against very high *du/dt*	Interruption of high-frequency current Very high *du/dt* recovery
	Vacuum interrupters for insulation	AC voltage insulation	DC voltage applied after interruption	DC voltage withstand capability
	High-speed making switches (vacuum, power electronics, triggered gap)	Capacitor bank inrush current making	Injection current making above highest IEC standardized value	Contact welding by pre-strike arc Mechanical synchronicity

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	Multiple vacuum breakers in series [5]	Usually single break	Multiple switching gaps in series	Grading for transients and DC Redundancy Mechanical synchronicity
	SF_6 gap(s) for insulation (ultra-fast disconnector)	Very low opening speed in GIS AC application	Ultra-high contact separation speed	Switch very low current DC voltage dynamic withstand capability Extreme mechanical consistency over time
semiconductor switching devices	Semiconductors in continuous current branch (load commutation switch function)	Power electronics switch with high frequency	Conduct continuously and switch only occasionally	Thermal stability. Unequal thermal distribution
semiconductor switching devices	Semiconductors in commutation branch (main breaker function)	Power electronics switch with high frequency[6]	Never/hardly conduct and switch only occasionally	Reliability after long idle time
MOSA	MOSA consisting of multiple columns	Overvoltage protection	Significant energy absorption (similar application in series capacitor bank protection)	Thermal overload, runaway Current sharing between columns
MOSA	MOSA columns	Always under (AC) voltage	Occasionally stressed by voltage	Conditioning Stability of U-I characteristic

3.3.1 MECHANICAL SWITCHING DEVICES

Every practical HVDC circuit breaker is equipped with a mechanical switching device, the function of which is to enable low losses in continuous operation and to alleviate (when in open state) dielectric stresses on the power electronic components. In HVDC breakers, these mechanical switching device has to achieve contact separation very fast, which is achieved by novel electromagnetic repulsion drives. Such drives are electronically controlled, which means a certain susceptibility exists to EM interference from transients from the primary sources (arcing, re-ignition, fast switching, high-di/dt current, high-du/dt voltage etc.).

In most designs a number of mechanical switching devices are put in series. This implies that power to the individual drives cannot be supplied through galvanic connections. Usually, transformers are used, that need to have sufficient insulation capability. For example, several isolation transformers are stacked in series to achieve sufficient insulation from earth for 500 kV HVDC circuit breakers. Figure 5 displays an insulation transformer for application in a 500 kV HVDC breaker [22].

Figure 5: Power supply to actuators at high potential: 5 insulation trans-formers in series [22]

[5] Some HVDC CB designs (incl. hybrid) have up to 10-12 vacuum switching gaps in series
[6] In certain applications, like DC choppers, infrequent switching by semiconductors is applied

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Such drives, and their power supply, have not been used before in power equipment and service experience is very limited or even non-existent. In formulating test requirements, due attention needs to be paid to the verification of the mechanical endurance of the total kinematic chain.

In addition, the proper functioning of a stack of a larger number of smaller vacuum interrupters needs a well synchronized contact separation, and a built-in redundancy to overcome the functional loss of one or more individual interrupter. Differences of ±0.1 ms in switch opening times are reported in a stack of 10 vacuum disconnecting switches isolating 1000 kV in 2 ms [22].
The special ultra-fast drives cause huge impact forces on the contact systems of vacuum/ SF_6 interrupters. Care must be taken to apply standard AC vacuum interrupters in combination with fast EM drives. Especially the bellows of vacuum interrupters must be designed to withstand a certain number of high impact force opening operations [34].

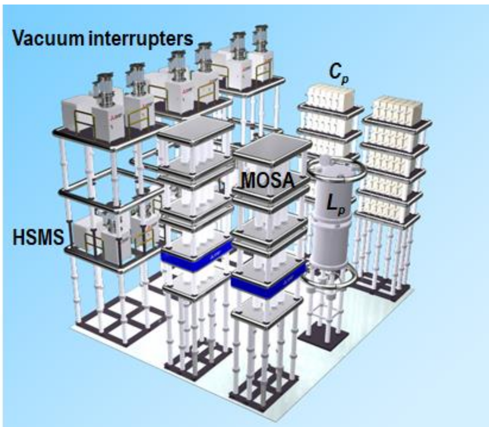

Figure 6: Conceptual design of a 525/600 kV active current injection HVDC circuit breaker. HSMS: high-speed making switch [35].

The series combination of many interrupters has its challenges, not only mechanically but also electrically. Sharing (grading) of voltage needs to be considered properly, not only regarding DC voltage but also transients. For AC applications, niche products like capacitor bank switches consisting of up to 9 series vacuum interrupters do exist, however these have a poor service record. For AC, high-voltage vacuum circuit breakers are developed with as few as possible series interrupters [34], not more than two at present. Figure 6 shows a conceptual design of a 525/600 kV active current injection HVDC circuit breaker with 6 ultra-fast HV vacuum circuit breakers in series [35]. Figure 7 shows a schematic of a 160 kV active current injection circuit breaker with 4 vacuum circuit breakers in series [28].

Vacuum is a very good “medium” regarding interruption of HF current and very fast recovery of the gap against steep rising recovery voltage. Nevertheless, the application of vacuum interruption in active current injection type of HVDC circuit breakers can approach performance limits, and measures might be necessary to mitigate high *di/dt* stress, such as by saturable reactors and high *du/dt* stress e.g. by snubber capacitors. The *di/dt* can be kept within the range of interruption limitation of the vacuum breaker by adjusting the parameter of the injection circuit.

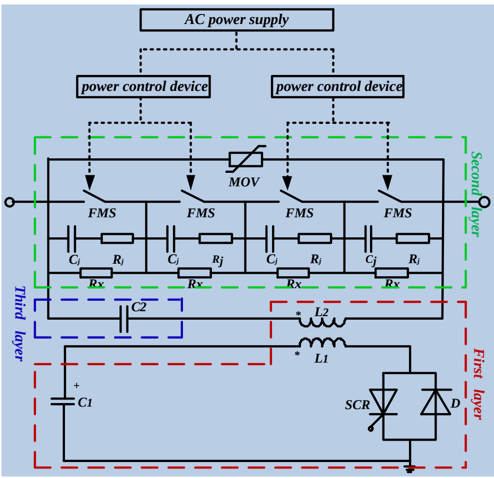

Figure 7: Schematic drawing of the 160 kV HVDC with 4 vacuum circuit breakers (FMS) in series [28].

Mechanical gaps (vacuum/SF_6) break down when they are not able to withstand voltage. Most critical is the fault current suppression phase, where the overvoltage is around 1.5 pu whereas at the same time the gaps are recovering from interruption and/or switching. After fault current suppression, depending on the timing of the residual current switch, there is a much longer exposure to the recovering system voltage and its transients, until the residual current switch takes over that voltage stress.

Breakdown of (a) vacuum gap(s) is less critical than of an SF_6 gap, since vacuum is able to restore its insulation state very fast (see [33]), while SF_6 disconnectors cannot interrupt current.

In hybrid HVDC circuit breakers, SF_6 disconnectors need to open with very low current and with very low voltage in order to avoid arcing. Once current (at contact separation) exceeds a certain threshold, the arc will persist during a time, depending on the voltage across the disconnector.

Current at contact separation is determined by the leakage current though the snubbers/grading elements of the series (semiconductor) switches in the continuous current branch (up to a few amperes). The voltage against which the disconnector is opening is determined by the on-state voltage of the semiconductors in the commutation branch (load commutation switch), which can be several hundreds of volts to a few kilovolts. The latter could be sufficient to keep current conduction in the disconnector if opened before current is fully commutated.

Therefore, the design of (ultra-)fast disconnectors is very critical. Opening of the disconnector needs to be synchronized carefully, after decay of current transients in the continuous current branch.

After the main breaker has interrupted the fault current, the full MOSA voltage appears across the opened continuous current path and the switching gap which must be sufficiently open to isolate. Breakdown of this gap would lead to the full voltage of the main breaker being applied across the load commutation switch, which might not be designed to handle. Therefore, dielectric coordination of this disconnector is very critical, which calls for only a very small variation in its opening time over service life. Requirements for mechanical stability are more severe than for controlled (capacitor bank) SF_6 circuit breakers for HVAC applications [36].

Figure 8 shows examples of various mechanical switching devices in HVDC circuit breakers [37].

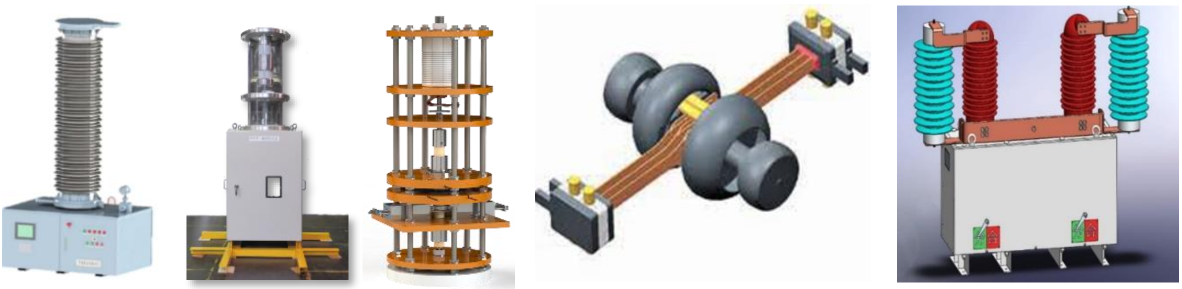

Figure 8: Examples of mechanical switching devices in HVDC circuit breakers. Left to right: one unit (of two) of SF_6 ultra-fast disconnector for 500 kV HVDC circuit breaker [37]; 100 kV vacuum circuit breaker with high-speed actuator [35]; vacuum interrupter in VSC assisted resonant current design with Thompson drive [11]; 350 kV ultra-fast SF_6 disconnector [52]; series combination of two 40.5 kV vacuum disconnectors with Thomson coil actuators (one third of the complete disconnector in a 200 kV HVDC breaker) [40].

In several cases, standard AC vacuum circuit breakers are used as ultra-fast disconnector. Such devices are not optimized for DC voltage withstand, so proper verification is necessary. Moreover, standard vacuum breakers contain arc control devices (axial or radial magnetic field arc control devices), which add unnecessary

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weight to the interrupters and additional stress to the drive. In addition, the standard contact material, CuCr, may not be the optimum choice for DC conduction and insulation. From dedicated studies it was found that different designs of commercially available 36-38 kV AC vacuum circuit breakers acted very different regarding the interruption of HF counter current and TIV withstand capability [33].

In the active current injection schemes using the capacitor discharge as the counter current source, an ultra-fast switching device must be used to start the discharge. This may be a mechanical switch (vacuum making switch, triggered spark gap) or a semiconductor stack (IGCTs, thyristors, see Figure 7). In both applications, the very large di/dt and peak current need to be evaluated as being a non-standard stress. In the case of vacuum, provisions must be made to avoid contact welding, originating from the pre-strike arc that is comparable to the back-to-back capacitor bank making function in AC application. For EHV applications several of these switches need to be connected in series. Synchronous operation of these making devices is essential to avoid premature current injection as a result of pre-strike. In case of semiconductor making switches, *di/dt* and short-time thermal and dynamic stresses can be extreme and far from standard.

During normal operation the making devices are subjected to continuous DC voltage stress in open position from a pre-charged capacitor.

3.3.2 SEMICONDUCTOR SWITCHING DEVICES

The application of large stacks of semiconductors is not new and can be found in AC/DC converters.

In the load commutation switch, that needs to commutate the current into the commutation (main breaker) branch, fault current is ramped down to zero with a very high di/dt. This switch consists of a limited number of semiconductors, in a series-parallel matrix to ensure low enough continuous losses, voltage withstand and has built-in redundancy being a crucial component in continuous supply [38]. The proper choice of the number of elements is critical from thermal point of view. Continuous cooling is necessary.

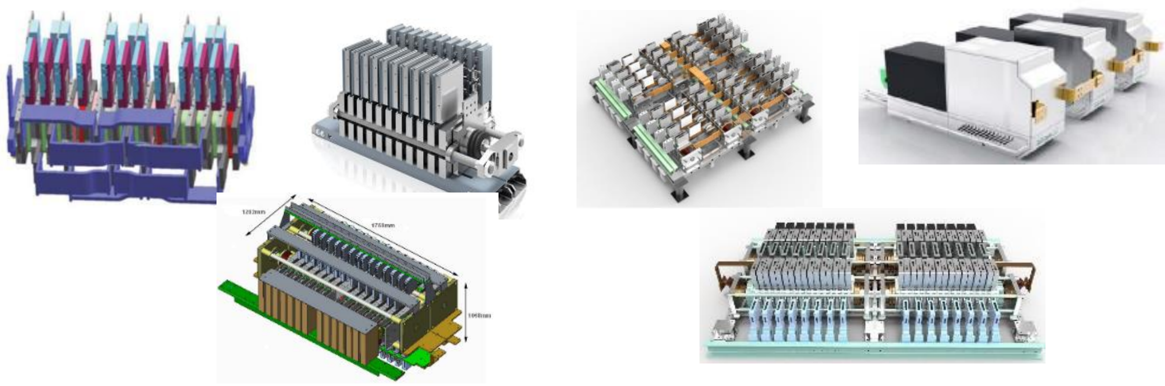

Figure 9: Various examples of sections of semiconductor switching devices of HVDC circuit breakers. Source: from left to right [38], [22], [39], [20], [40], [24].

Figure 9 displays examples of semiconductor switching devices in HVDC circuit breakers [39, 40].

Load commutation switches are mostly made from the state-of-the-art PressPack IGBTs which consist of IGBTs and diodes at different sections of the semiconductor volume. These PressPack IGBTs have IGBT and diodes

to be able to conduct current in reverse direction. Since the load commutation switch is conducting DC current continuously in normal operation only the IGBT parts of the semiconductor volume are heated by on-state loss. Since both components are thermally relative separated, this results in unequal heating and thermal gradients which do not get sufficient attention due to lack of operational experiences. During functional tests of HVDC circuit breakers which focus on the proof of concept, steady-state effects like unequal heating cannot be observed. The latest developments of IGBTs, known as BIGTs (Bi-mode Insulated Gate Transistor), which use the same package for both IGBT and diode operations [41] are not susceptible to this situation.
Hybrid breakers, being modularly constructed, can control the switching off of various modules of the main breaker components. Thus, rate-of-rise of TIV can be controlled and adapted to the dynamic dielectric withstand of the disconnector.
By activating only a limited number of cells in the main breaker semiconductor stack, certain designs of hybrid HVDC circuit breakers can operate in fault current limiting mode [42].

In hybrid HVDC breakers, the load commutation switch is conducting current continuously (the main breaker may be as well, but at very low current) without switching. This is a different operation than in “normal” operation, (like in converters) where semiconductors are switching continuously. In such a way semiconductors conduct during on-state while diodes might conduct during off-state. This results in a lower thermal gradient across the package volume. On the other hand, the breaker in the commutation branch is idle, or conducting small current, while under “standard operational conditions” its semiconductors are operating continuously. It is not known how the “one time only” activation to switch off all semiconductors might have an impact on a possible conditioning of the semiconductor junction and/or package.

3.3.3 ENERGY ABSOPTION

A combination of a large number of MOSA arresters needs to take care of providing the counter voltage and absorbing the energy from the faulted system. It cannot be avoided that several stacks (columns) need to be applied in parallel. Many columns are connected in parallel to deal with significant amount of energy in the

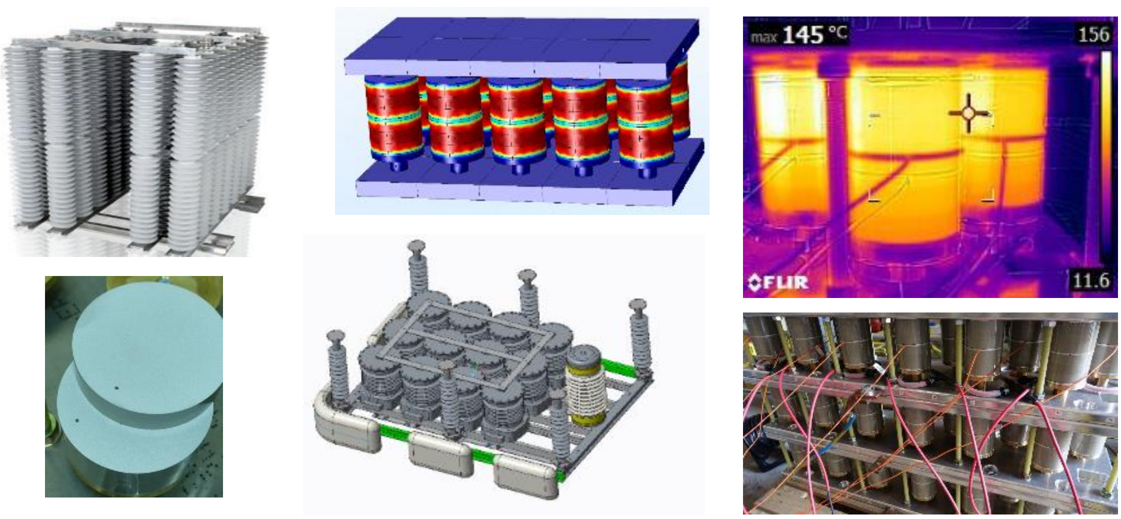

Figure 10: Impression of MOSA applied in HVDC circuit breakers. Centre top and right: experiments to study the impact of thermal overloading of arrester discs and -columns [33]. Lower left: Puncture of ZnO material after electrical overload.

system [22]. This means the individual ZnO varistor discs composing each column need to be carefully selected to have an equal current flowing through each. Given the high non-linearity of the U-I characteristic, a small mismatch of voltage would lead to a large current difference. This, in turn, would heat the column and change its characteristic unfavourably or could lead to a complete failure of the MOSA due to unequal heating [5, 43]. Therefore, very careful matching of the MOSA columns is essential, like for some other energy absorption applications, like in protection circuits of series capacitor banks. This procedure is described in D 10.2 in the design of a 18 MJ MOSA bank for an experimental DC circuit breaker [44]. Figure 10 shows some visual impressions of (experimental) MOSA for energy absorption.

The total mass of ZnO material in HVDC circuit breakers can be over one thousand kilograms, which implies that cooling down (after interruption of a significant fault current) is very time consuming. In testing, it is recommended to have cooling down times of a few hours depending on the amount of the energy dissipated by the MOSA. Note that in order to conduct the interruption test economically, testing is normally conducted with lower energy capacity than the maximum MOSA requirements.
When one re-opening function is required, the design should be able to absorb up to double the energy that is associated with one interruption (and proportionally more when more than one re-opening operations are expected). Moreover, the other functions of the breaker (local current zero creation, counter voltage creation etc.) should be accommodated for quickly repeated operation. Multi re-opening of HVDC breakers is required in overhead line (OHL) systems. As a result, Chinese circuit breakers for the Zhangbei (OHL) project have been specified to deal with total energy absorption exceeding 150 MJ [45]. OHL arcing faults most often disappear after a single opening operation of the breaker. When the actual short-circuit with the large fault current is removed, in many cases a secondary arc to earth (carrying a current of hundreds of amperes) persists, which is fed through the stray impedances of the transmission system. Reclosure should then be delayed until the secondary arc ceases, mostly by natural reasons, like wind or be thermal elongation. CIGRE studies have indicated that in HVAC overhead line systems, after a single open-close action the fault is removed in the vast majority of the cases [46]. Further study needs to reveal the persistence of secondary arcs in HVDC OHL systems.
In cable systems, reclosure does not seem to be a suitable action, since faults in cable systems are normally destructive and need repair.

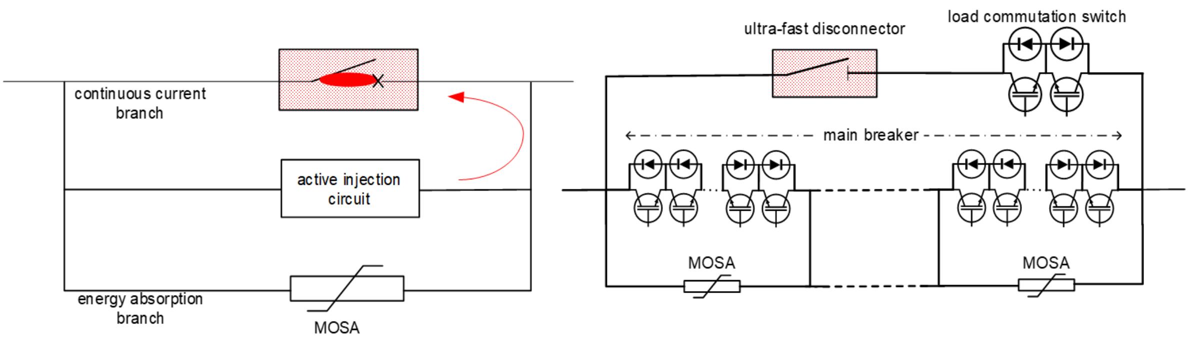

Figure 11: Principle schematic of HVDC circuit breakers. Left: active current injection technology; right: hybrid technology

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3.4 THE CURRENT INTERRUPTION PROCESS

When a DC breaker (see Figure 11), operating in a system with system voltage U_s is called upon to operate, the following sequence of events unfolds:

1. At first, current is interrupted/blocked in the continuous (main) current branch on the rising edge of fault current with rate of rise *di/dt*, by power electronics or by mechanical switchgear with an auxiliary circuit (active injection circuit) or by a combination of both to create local (internal in the breaker) current interruption. DC breakers basically differ in the way local current interruption is created and what mechanical switching element is used for interruption and/or insulation. In every design, mechanical switchgear is present to interrupt and/or to isolate. This can be vacuum or SF_6 insulated switchgear, but the one common key requirement is that it must be very fast acting (few milliseconds of contact separation) and therefore differs from AC switchgear that never achieves contact separation on the first rising edge of the fault current.
2. After the continuous current branch is blocked for current conduction, current is forced to commutate into the commutation (or current injection) branch, a parallel path in which the current is charging a (lumped or stray-)capacitance, either immediately upon commutation (active current interruption), or delayed after interruption by semiconductors (hybrid). The current charges the capacitance by which a fast-rising voltage, termed as transient interruption voltage (TIV), will develop. This voltage stresses the insulating vacuum / SF_6 gap in the continuous current branch.
3. The TIV rise continues until the protection level of a metal-oxide surge arrester (MOSA) bank in the third parallel branch is reached. From that moment on, current starts to flow through this branch. Because MOSA protection voltage (U_{MOSA}) is higher than the system voltage ($U_{MOSA} > U_s$), now the current through the MOSA will steadily decline to zero. When the current is suppressed to (near) zero after the fault current suppression time ΔT_{fs}, the very small residual current can be interrupted by another switch (residual current switch) and system voltage re-appears across the open DC breaker. Note that the system voltage in the healthy part of the system starts to recover as soon as counter voltage has been fully developed, reducing the impact of the fault on the system basically to the relay time (ΔT_{relay}) + internal current commutation time (ΔT_{ic}), the sum of which is called fault neutralization time. After this time, the fault(current) is not yet removed from the system, but its impact is reduced.

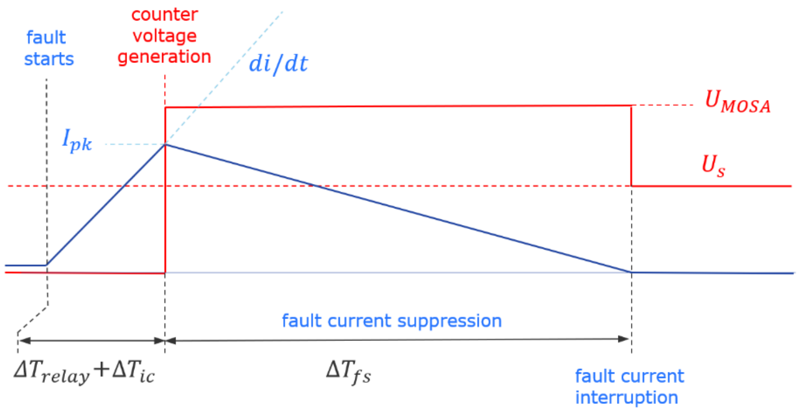

Figure 12: Simplified outline of HVDC current interruption. Red: Voltage across circuit breaker, blue: System current

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The detail interruption process for each type of the HVDC CB can be found in the appendix Figure 14, Figure 15. This process is schematically outlined in Figure 12.

3.5 CURRENT INTERRUPTION PARAMETERS

The current interruption process in DC systems can be easily understood and formulated using a simple analytical model which is used for estimation of test-circuit stresses and for drafting test requirements. For full understanding of interruption phenomena detailed modelling an electrical transient analysis tools are necessary. In the model, the following parameters are relevant and serve as input variables when determining test-parameters:

- System parameters:
  Rated system voltage: U_s;
- Protection parameter:
  Relay time: $\Delta T_{relay;}$
- Circuit breaker parameters:
  Internal current commutation time: ΔT_{ic},
  Peak value of fault current to be interrupted: I_{pk};
  Counter voltage developed and maintained by MOSA: U_{MOSA}.

From these input parameters (in the left box below), stresses and circuit elements (output parameters, right box below) can be easily estimated following the equations below.

$$\boxed{U_s,\ U_{MOSA},\ I_{pk},\ \Delta T_{relay},\ \Delta T_{ic}} \longrightarrow \boxed{di/dt,\ L,\ \Delta T_{fs},\ E}$$

The inductance L of the circuit causing the rate-of-rise, the required breaker operation time ΔT_{ic} (this is the time between trip of the breaker and the generation of counter voltage) and the fault current suppression time (ΔT_{fs}) and the energy to be absorbed by MOSA are derived using the basic equations below:

$$\frac{di}{dt} = \frac{I_{pk}}{\Delta T_{ic} + \Delta T_{relay}};\ L = \frac{U_s}{\frac{di}{dt}}$$

$$\frac{I_{pk}}{\Delta T_{fs}} = \frac{1}{L}(U_{MOSA} - U_s) \rightarrow\ \Delta T_{fs} = \frac{I_{pk}L}{U_{MOSA} - U_s}$$

$$E = \frac{1}{2}U_{MOSA}I_{pk}\Delta T_{fs} = \frac{1}{2}\frac{U_{MOSA}I_{pk}^2 L}{U_{MOSA} - U_s} = \frac{1}{2}LI_{pk}^2\frac{1}{1 - \frac{U_s}{U_{MOSA}}} > \frac{1}{2}LI_{pk}^2$$

This basic and simple set of equations is sufficient to estimate the main parameters of HVDC circuit breakers. Of critical importance is the energy that is to be absorbed by the MOSA. This subcomponent must be designed to be able to deal with this. The energy consists of two components: one is the energy stored in the system inductance at the moment of peak current ($\frac{1}{2}LI_{pk}^2$) and the other is the energy that is supplied by the system during the fault current suppression time:

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$$E = \int_{\Delta T_{fs}} U_{cb} i \, dt = \frac{1}{2} L I_{pk}^2 + \int_{\Delta T_{fs}} U_s i dt$$

In order to get an example of the practical value of parameters, the data of a 320 kV HVDC circuit breaker is used as shown in table 7. Note that the energy absorption requirement (*E*) refers to a single breaking operation. In cases where faults are non-persistent, like when faults are followed by secondary arcs in overhead line systems, two or more opening operations may be required, basically doubling the energy dissipation, since the cooldown time of the large MOSA bank is much longer than the time between successive opening operations (in AC applications usually 300 ms).

Table 7: Example parameters of a 320 kV HVDC circuit breaker

Name (per CIGRE TB683 [1])	symbol	breaker	unit
Input parameters			
System voltage	U_s	320	kV
Peak fault current	I_{pk}	16	kA
Internal commutation time	ΔT_{ic}	3	ms
Relay time	ΔT_{relay}	2	ms
MOSA voltage	U_{MOSA}	480	kV
Derived parameters			
Fault current rate of rise	di/dt	3.2	kA/ms
Inductance	L	100.0	mH
Fault current suppression time	ΔT_{fs}	10.0	ms
Energy supplied to MOSA	E	38.4	MJ
Stored energy	$½LI_{pk}^2$	12.8	MJ

3.6 CRITICAL STAGES OF FAULT CURRENT INTERRUPTION

Test schemes and powerful circuits are developed and demonstrated that can verify performance and withstand during all critical stages of DC fault interruption.

The following six critical stages of interruption can be defined:

1. Rise of fault current → breaker needs to act very fast;
2. Local current interruption in continuous current branch;
3. Internal commutation → counter voltage generation;
4. Maintenance of TIV → fault current suppression;
5. Energy absorption;
6. System recovery voltage withstand.

In table 8 these stages are schematically outlined, and the critical parameter is identified.

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Table 8: Stages of interruption and critical parameters

Process		Breaker action	Components mainly stressed	Critical parameter
1	Rise of fault current	activates and trips very fast	mechanical actuators continuous current branch	ΔT_{ic} di/dt
2	Local current interruption	blocks the continuous current branch	interrupting device (vacuum interrupter, load commutation switch)	I_{pk}
3	Internal commutation	generates counter voltage disconnector insulates	active current injection circuit switch in continuous current branch breaker in commutation branch	U_{MOSA}
4	TIV maintenance	withstands short duration overvoltage (≈ 1.5 pu) fault current suppression	mechanical switching gap breaker in commutation branch insulation to earth	U_{MOSA} ΔT_{fs}
5	Energy absorption	absorbs energy	MOSA	E
6	System voltage recovery	withstands long duration dielectrical stress	mechanical switching gap (residual current switch)	U_s

3.7 RECOMMENDED FAULT CURRENT BREAKING TESTING

In the recent past, several tests on prototype HVDC breakers were carried out as part of the development process. In all cases, capacitor bank discharge circuits are used that produce an oscillating current with a single [19, 20, 24, 47, 48] or two frequencies [3]. In this way, a proper rate-of-rise of DC fault current can be realized, and the capability of current zero creation in the continuous current branch and commutation followed by counter voltage creation can be verified. However, TIV withstand and energy absorption cannot be practically verified in such an approach, because capacitor circuits cannot provide the energy to sustain the TIV voltage to supply sufficient energy [4]. As an example, the very large capacitor banks used in synthetic test circuits of high-power laboratories cannot be charged to an energy level above a few megajoules.

The main motivation of also including the stages 4-6 in interruption tests is the following:
Mechanical switches are key components of all HVDC circuit breakers. In some applications (active current injection) they switch high current, in other (hybrid) they isolate high voltage, or both. Short-time dynamic (stage 5) overvoltage withstand and long duration static dielectric withstand (stage 6) shall be an essential part of a verification program. Testing under static, cold conditions is technically inadequate, but separate tests are possible.
Surge arresters in HVDC circuit breakers are used in a different application than for overvoltage protection, the usual application. The unusual amount of energy to be absorbed requires a large number of parallel arrester

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columns and an equal current sharing between the non-linear ZnO elements. CIGRE WG A3.39 is studying the specific HVDC breaker MOSA application.

An obstacle in testing larger HVDC circuit breakers is that the “synthetic” test methods, commonly applied in AC breaker testing up to the highest voltages, cannot work for HVDC breakers. For HVDC breaker testing, sources providing real power, megawatts, are needed to prove the breaker’s energy dissipation capability.

A suitable ‘one shot’ method of applying all stresses as outlined above is covered by the application of AC short-circuit generators running in low-frequency mode (15-30 Hz) [10, 32, 49]. Because of the short duration of the interruption process (order 10-20 ms), the duration of a low-frequency AC voltage waveshape (several tens of milliseconds) is long enough to mimic the DC system voltage and power during the entire process.

Only for stage 6, system recovery voltage has to applied in a “synthetic” way, i.e. DC voltage application from a separate voltage source, like a pre-charged capacitor bank.

In PROMOTioN adequate circuits up to 350 kV rated DC voltage have been designed and demonstrated (deliverable D10.7) using six short-circuit generators and up to ten step-up transformers.

The advantage of the low-frequency AC method is that such sources are widely available in major high-power laboratories around the world. In many tests in the PROMOTioN project a frequency of 16⅔ Hz is chosen because several countries apply this frequency in traction applications and test-laboratories have experience with such equipment.

3.8 TEST-REQUIREMENTS AS APPLIED IN PROMOTION DEMO TESTS

Based on the considerations, discussed and motivated in this document, test requirements regarding the main function of HVDC circuit breakers were formulated by the members of WP10 of the PROMOTioN project, a high-power test laboratory and three manufacturers of HVDC circuit breakers.

Table 9 shows the breaking test requirements, as agreed among three HVDC circuit breaker manufacturers within the PROMOTioN project.

Table 9: HVDC circuit breaker fault current interruption test requirements as agreed in PROMOTioN

Name	Current	Breaking test	Number of tests
TC10+	10% of rated continuous current	tests in positive current direction	2
TC10-	10% of rated continuous current	tests in negative current direction	2
TC100+	100% of rated continuous current	tests in positive current direction	2
TC100-	100% of rated continuous current	tests in negative current direction	2
TF100+	100% of peak fault current	test at specified energy absorption [a], positive current direction	2
TF100-	100% of peak fault current	test at specified energy absorption [a], negative current direction	2
TDT+	To be estimated [c]	test at rated fault current suppression time [b] positive current direction	2

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TDT-	To be estimated [c]	test at rated fault current suppression time [b] negative current direction	2
In all tests, a constant DC voltage U_s (considering 10-15 % overvoltage) will be supplied during 300 ms after main current interruption			
All tests are single opening operations			
Notes	[a]: Specified energy absorption based on specified value of energy absorption (MJ) of the test-object delivered [b]: Rated fault current suppression time based on U_s, U_{MOSA}, ΔT_{ic}, I_{pk}, as would be present in service condition [c]: To be estimated with equations in chapter 3.5, see example below		

Motivation:

- TC10+, TC10-

  Small current switching may be more onerous for current injection type of breakers that generate counter current from a pre-charged capacitor.

  For small current interruption, the conditions at current zero are the following:

  - the arc carries only small current, this is positive for the interruption process;

  - the HF counter current crosses zero with a very high *di/dt* this is a more onerous factor for interruption;

  - when the HF current is interrupted, the remaining capacitor voltage (which is close to the charging voltage) stresses the switching gap with a very high *du/dt* and peak. This is challenging for the interruption process.

  It is observed in tests [33] that for such interruptions, multiple zero crossings are necessary and acceptable before interruption can take place.

  The associated multiple reignition voltage may not cause unacceptable transients or EM incompatibility. These tests need to verify interruption capability assuming a timing error of convertor start up until it reaches the continuous current.

  When current is to be interrupted below the chopping current (a few Amperes), no arc will develop.

- TC100+, TC100-

  These tests need to verify interruption capability of continuous current.

  Here, an issue may arise related to the voltage to earth. In case the HVDC circuit breaker produces 1.5 pu of voltage across its terminals, the voltage to earth in continuous current switching situations could reach close to 2.5 pu at supply side. This (dielectrical) stress is not replicated in this test-duty.

- TF100+, TF100-

  These tests need to verify interruption capability of fault current up to the rated peak fault current (I_{pk}). Since energy absorption requirements can be very large for the EHV type of HVDC breakers, it is impractical to install the volume of MOSA as required in service in the test laboratory, depending on the capability of the laboratory. Therefore, it is accepted that a smaller volume of MOSA is brought for testing.

- TDT+, TDT-

  These tests need to verify the dynamic dielectric withstand capability of the mechanical switching

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device during fault current suppression. Since the mechanical switching device may not be completely "stabilized" electrically, mechanically, thermally immediately after local current interruption, it is relevant to offer a realistic duration of MOSA (over)voltage stress. Since test-duty TF100 is allowed to be carried out with lower energy than in service, also the duration of the MOSA (over)voltage stress (ΔT_{fs}) is lower than in service. Therefore, a proper condition must be created (e.g. by lowering the peak fault current) to match the fault current suppression time with the rated energy.

Example: The HVDC circuit breaker, witch characteristics outlined in table 7, should in service be equipped to deal with a "rated energy" E = 38.4 MJ. In extreme cases, it would be impractical to install this MOSA volume in the test laboratory or the test laboratory is not capable of supplying this energy. Let's assume a practical volume of MOSA, installed in the laboratory, would by one dealing with E_{test} = 10 MJ. Then this energy limitation at peak fault current I_{pk} = 16 kA can be achieved by reducing the test voltage from the full system voltage U_s = 320 kV to $U_{s,test}$ = 165 kV. This would be the setting for test-duty TF100, replicating the correct peak fault current and energy absorption for the test object. However, under this condition, the fault current suppression time would be $\Delta T_{fs,test}$ = 2.6 ms, which would be much shorter than under service condition: ΔT_{fs} = 10 ms. In order to create this fault current suppression time, while keeping the energy absorption $E_{test} \leq$ 10 MJ, the supply voltage can be raised to $U_{s,test} = U_s$ = 320 kV, while decreasing peak current from I_{pk} = 16 kA to I_{pk} = 4.3 kA, which leads to $\Delta T_{fs,test}$ = 10 ms and E_{test} = 10 MJ.
These settings would satisfy the TDT test-duty. The reasoning above is summarized in the table 10.

Table 10: Summary of rationale of test-duties TF100 and TDT

parameters	symbol	rated values	test-duty TF100	TDT	unit
System voltage	U_s	320	165	320	kV
Peak fault current	I_{pk}	16	**16** →	4.3	kA
Internal commutation time	ΔT_{ic}	3	3	3	ms
Relay time	ΔT_{relay}	2	2	2	ms
MOSA voltage	U_{MOSA}	480	480	480	kV
Fault current rate of rise	di/dt	3.2	3.2	0.9	kA/ms
Inductance	L	100.0	51.6	372.1	mH
Fault current suppression time	ΔT_{fs}	10.0	2.6 →	**10.0**	ms
Energy supplied to MOSA	E	38.4	**10.1**	10.3	MJ
Stored energy	$\frac{1}{2}LI_{pk}^2$	12.8	6.6	3.4	MJ

In reality, voltage waveshapes of low-frequency AC short circuit generators are not constant and more refined analyses are necessary to achieve proper settings of the test-circuit components, see deliverable D10.7.

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The test program of table 9 is taken as a guideline in the testing of three HVDC circuit breakers rated 80 kV 16 kA (VSC assisted resonant current type), 160-200 kV 16 kA (active current injection type with capacitor discharge) and 350 kV 20 kA (hybrid type).

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4 OTHER TEST REQUIREMENT CONSIDERATIONS

4.1 TRANSIENT CURRENT SWITCHING

Cable charging current switching may lead to special situations. Switching of unloaded long cables (discharge current) may lead to transient currents determined by $I_{cable} = U_s/Z_0$ with Z_0 the characteristic cable impedance, having a value around $Z_0 = 30\ \Omega$ [50]. This would imply cable discharge currents up to several tens of kilo-amperes with a duration of around 1 ms / 100 km length, which is significantly shorter than the duration of the fault current interruption process. The energy, stored in a cable, however, is an order of magnitude smaller than the energy stored in the stray inductance of the system, for which the energy absorption branch is designed. Semiconductor elements must be able to deal with high discharge current peaks, whereas mechanical switches can more easily deal with these. Especially discharge currents from lumped capacitors located nearby the HVDC breakers (having a characteristic impedance of only a few ohms) can lead to high outrush currents.

4.2 MAKING OPERATION

Switching devices have the function to energize a load and to make a fault current. The latter situation occurs when the breaker closes while a fault is (still) present in the system. In such a case, the breaker experiences a fault current during the closing operation. This requires a complicated control scheme to synchronize the closing and subsequent opening of the various switching subcomponents to clear the fault current.
In active current injection breakers, the closing element are the vacuum breakers, that need to be designed for short-circuit making operation. In AC fault current making, irreversible contact welding is a failure mechanism. In this case, the pre-strike arc between the approaching contacts leads to local contact melting and when compressing the butt-type contacts, irreversible welding may occur when the design of the contact system is inadequate.
In hybrid breakers, it might be expected that making is achieved with the semiconductor load break switch (after closing the disconnector). In this case, it must be made sure the maximum current through the semiconductors must not be exceeded.
Test requirements yet need to be developed.

4.3 ELECTRICAL ENDURANCE

Electrical endurance is a term introduced to quantify the endurance of the arcing system in mechanical switchgear against the detrimental effects of switching arcs. The concept of electrical endurance was introduced for HV circuit breaker because arcing by multiple fault interruptions during a lifetime in arcing chambers (vacuum, SF_6) can cause degradation and wear leading to loss of functionality of the switching device. Electrical endurance testing is quantified in the relevant circuit breaker standard IEC 62271-100 (MV) and IEC TR 62271-310 (HV AC breakers)
In HVDC breakers, arcing is limited to the devices using vacuum interrupters for interruption (and initiation) of

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HF injection current. Disconnectors do not suffer electrical wear.
Generally, the resistance to wear by arcing of vacuum interrupter contact systems (effectively loss of contact material) is much higher than SF_6 contact systems in SF_6 circuit breakers. In addition, arc duration in HVDC circuit breakers is very short compared to AC breakers. In HVDC grid operation it seems unlikely that HVDC breakers will be used for frequent switching operations, especially under current making and breaking conditions. Therefore it could be argued that electrical endurance verification is not an issue for HVDC circuit breakers for the design under development so far.

4.4 MECHANICAL ENDURANCE

Mechanical endurance testing is common for HVAC circuit breakers, with test procedures describing (in IEC 62271-100) 2000 mechanical tests (standard mechanical endurance) and 10.000 mechanical operations (extended mechanical endurance). From CIGRE enquiries, it is known that around 50% of the major failures of HVAC breakers are due to mechanical components, mostly drive systems [51]. Mechanical failure likelihood might turn out to become critical when multiple ultra-fast switches are in use.
Since in most designs some or many mechanical switching gaps and new type of high-speed actuators are applied, mechanical abnormalities (mis-synchronization, contact welding, insufficient opening speed, etc.) might be an issue. High-speed actuator have not been applied before in commercial applications. What is also new is that the power for the series actuators needs to be supplied to potential, bringing additional design challenges. Together with the fact that multiple of such actuators need to operate in a very coordinated time-synchronized way, verification of the mechanical performance is a very relevant requirement.
It is recommended to follow the extended mechanical endurance as defined in IEC 62271-100, this means 10.000 mechanical operations under no (electrical)-load condition.
Mechanical stresses need to be considered with highest attention, since every HVDC circuit breaker has ultra-fast switching mechanical components, often in cascade on board. Given the fact that the vast majority of major failures in HVAC switchgear is related to failures in the mechanical, kinematic chain, a thorough verification of the mechanical operation of HVDC breakers and its reliability over time is necessary.

4.5 CONTINUOUS CURRENT CONDUCTION

Since HVDC circuit breakers are part of the continuous power chain, they have a key role in providing continuous power supply and therefore availability of their continuous current path is of key importance. Fast bypass switches might be considered to be able to bypass faulty HVDC circuit breakers. All other HVDC switchgear in the DC switchyards that conduct current continuously are based on single devices in which contact systems are applied based on proven AC technology having pin-tulip contacts of very low resistance. In HVDC circuit breakers, however, in most cases multiple mechanical contact systems in series are used, having multiple contact resistances in series. The ultra-fast opening requirements do not allow friction-based contact systems that are inherent contracting on high-current passage. Such contact systems are common in AC breakers where the electrical forces at short-circuit current tend to contract fingers onto the solid counter contact. Such a contact system is difficult to be applied in combination with a high-speed actuator.
Vacuum circuit breakers are available for current passage up to 4500 A continuous AC current, but contact

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systems tend to be heavy and need adaptation to be equipped with high-speed actuators. Series combination of many of such breakers is a serious challenge. (Ultra-)Fast disconnectors need specially designed contact systems, since AC disconnector contact systems cannot be applied, see Figure 13 [52].
Therefore, tests with continuous current, temperature rise and short-time current tests are important and criteria of contact resistance increase limits should be formulated.
Also, passage of full short-circuit current (when HVDC breaker remains closed for any reason) needs to be considered, especially in case power electronics are part of the continuous current branch.
For the latter technology, also continuity of the cooling system must be verified, as with converters.

Tests to be defined (as part of type test):

- Measurement of the resistance of the continuous current branch circuit;
- Temperature-rise tests;
- Short-time withstand current;
- Peak current withstand tests.

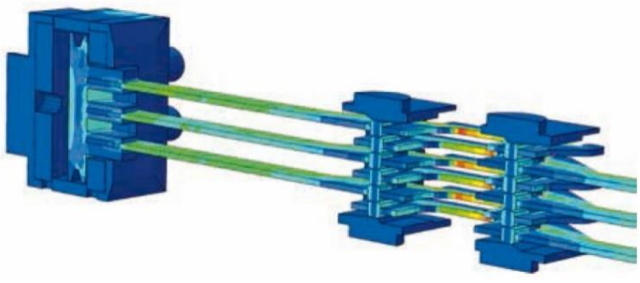

Figure 13: Contact system of an SF_6 ultra-fast disconnector [52]

4.6 RESIDUAL CURRENT SWITCHING

Interruption of residual current, flowing through the stray elements of the breaker system is necessary. This current can be in the 0.1 - 1 A range and flows as residual current through the MOSA columns and the grading resistors/arresters in the semiconductor stack in the commutation branch. Depending on whether residual current has zero crossings or not, AC type of load break switches or DC transfer type of switches with passive oscillation may be considered. The residual current waveshape may be project specific.
Residual current switches need to be included as an integral part of the HVDC circuit breaker system. It might be tested separately with a synthesized waveshape that is similar to the one produced by the open circuit breaker. When tested in combination with the circuit breaker, it must be considered whether the test-circuit generates a current waveshape representative for the actual service condition.

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5 DISCUSSION

This document serves as input to standardization of HVDC circuit breakers. It uses the observations collected in the research and testing of various technologies.
HVDC circuit breakers are crucial for interruption of fault currents, which most likely will take place in submarine HVDC cable links. Failures in HVDC cables do exist and can be quantified as follows. The average annual failure rate of submarine HVDC cables with some form of installation protection was calculated to be 0.096 per 100 km [53]. Using data from CIGRE and other sources, it was estimated that the annual failure of a submarine cable is 0.07 failures per 100 km [54]. More recent data suggests a value of 0.05 – 0.2 failures / 100 km [55] for HVDC cables. It is estimated that by 2030, 10 – 40 large submarine cable repairs will be ongoing per year [55].

Test parameters for HVDC circuit breakers are lacking in the international standardization literature, and even Chinese national documents are not finalized yet, in spite of the fact that various large scale MT HVDC projects are underway. Manufacturers use project specific specifications. Among these documents, no harmonization is achieved yet, and even separate documents for each technology exist. Considerable differences of test requirements in the various projects is reported.

Premature standardization of equipment specification can have unintended side effects, so there is no need to rush for standardization. Products are not mature enough and experience is missing. This might lead “misjudgements” to enter standards due to insufficient knowledge and also to blocking out innovative technologies that are not directly covered by the standard.
Also for HVDC, manufacturers use project specific specifications. What is new is that for the HVDC circuit breakers, specifications are written without proper knowledge of products and requirements from e.g. AC breakers are taken, completely irrelevant for HVDC breakers and for that reason are unacceptable in a tender. Standardization of test-requirements, however, will benefit the industry by creating an equal playing field for products, making no distinction between different device technologies.

There is a tendency, to consider HVDC circuit breakers as mainly power electronic devices and apply test-requirements based on this type of equipment (as defined in IEC TC 115 and discussed in CIGRE SC B4). However, it can be argued that the most critical components of a HVDC circuit breaker are the mechanical switching devices for interruption and/or insulation. In closed position they are crucial to system availability and in opening operation their dynamic dielectric coordination is very critical regarding current interruption. In contrast to power electronics, these devices are not easily scalable, and the standard electrical simulation tools fail to quantify the essential phenomena. Critical stresses are related to physical phenomena such as electrical breakdown, plasma physics, thermo- and fluid dynamical phenomena, that require multi-physics simulation tools supplemented by development testing. A strong involvement from IEC 17/17A (switching devices) and CIGRE SC A3 (T&D equipment) is essential.

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The test requirements defined in this document do include the stresses to the mechanical switchgear close to reality. Test methods and test-circuits have been designed and demonstrated that include all critical stresses of the fault current interruption process. These stresses are applied to the demonstrated HVDC circuit breakers in the PROMOTioN project.

Finally it must be realized that unlike HVAC breakers HVDC circuit breakers are not off-the-shelf devices having a standardized design, and their operation parameters, as well as their system interaction will be project specific.

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6 APPENDIX

In this appendix figures are reproduced as published in CIGRE Green Book [9]. It shows in more detail the basic interruption processes in active current injection and hybrid technology. The captions are from the original source and may use different nomenclature from this document.

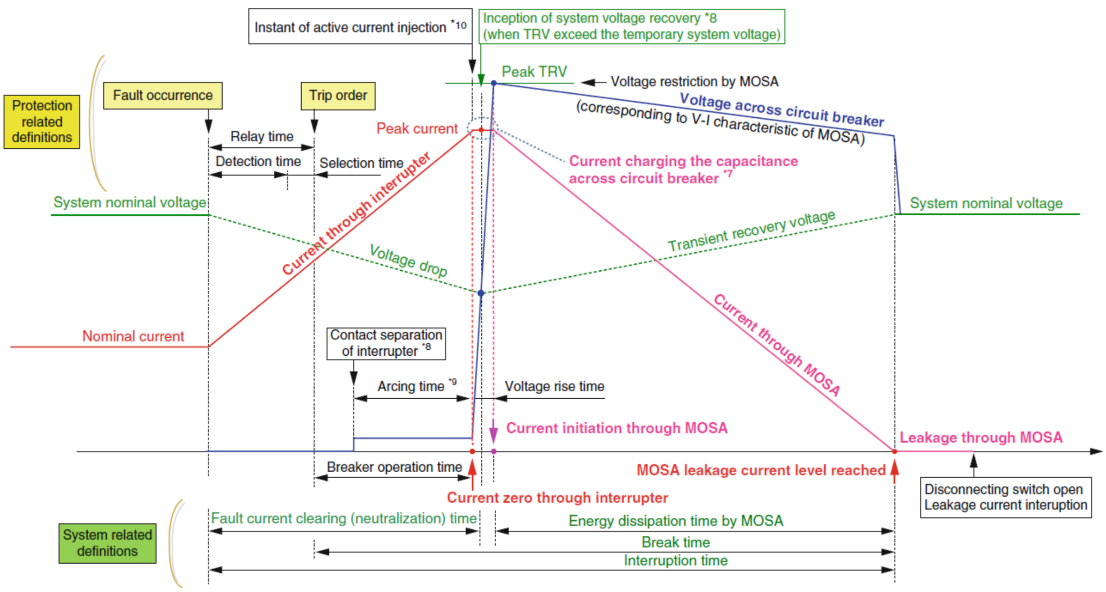

Figure 14: Voltage and current during DC current interruption with mechanical DC circuit breaker with active current injection scheme .
Note *8: A mechanical DC breaker with special design needs a few milliseconds to open electrodes (or separate contacts) after receiving a trip order.
Note *9: The arc voltage across the vacuum interrupter is almost constant after a contact separation irrelevant to the contact gap.
Note *10: The fault current through a vacuum interrupter is forced to make a current zero at the instant of active current injection, and the vacuum interrupter can immediately interrupt this high-frequency current.
Note *6: The voltage recovery is initiated when the voltage across the breaker (TRV) exceeds the temporary system voltage. The current through MOSA is initiated when the TRV is clipped by the restriction voltage by MOSA.
Note *7: The duration to charge the capacitance across the DC circuit breaker. The capacitance required for active current injection of mechanical DC circuit breaker is on the order of microfarads.

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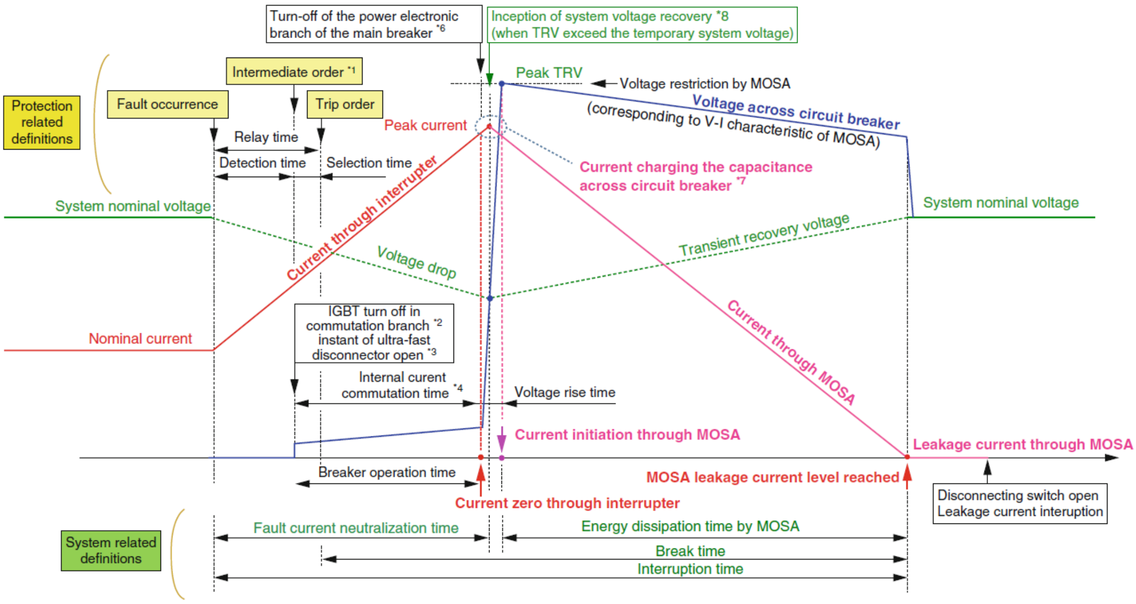

Figure 15: Voltage and current behaviour during DC current interruption with a hybrid mechanical and power electronic DC circuit breaker.
Note *1: Any order before the trip order to start the interruption process such as operations shown in notes 2 and 3.
Note *2: The instant to turn off the load commutation IGBT devices immediately after a fault detection.
Note *3: The instant to open the ultra-fast disconnector in commutation branch (main circuit).
Note *4: Time required to commutate the fault current from the commutation branch with the load commutating IGBT devices to power electronic branch of the main breaker.
Note *5: The instant to turn off the power electronic branch in the main breakers, which immediately block and interrupt the current after a time delay to ensure the voltage withstand of the ultra-fast disconnector.
Note*6: The recovery voltage is initiated when the voltage across the breaker (TRV) exceeds the temporary system voltage. The current through MOSA is initiated when the TRV is clipped bi the restriction voltage by MOSA.
Note *7: During the voltage rise time, the stray capacitance across the DC circuit breaker is charged.

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