D5.5 Document on test procedures

PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks
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Work Package and deliverable involve a large number of partners and contributors. The names of the partners, who contributed to the present deliverable, are presented in the following table.

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NOMENCLATURE

ABBREVIATION	EXPLANATION
AC	Alternating Current
CB	Circuit Breaker
DCCB	Direct Current Circuit Breaker
DCL	DC Current Limiting Reactor
FB	Full Bridge
HB	Half Bridge
HVAC	High voltage AC
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
ITIV	Initial Transient Interruption Voltage
LCC	Line Commutated Converter
MMC	Modular Multi-Level Converter
MTDC	Multi-Terminal HVDC
NLC	Nearest Level Control
OHL	Overhead Line
PCC	Point of Common Coupling
TIV	Transient Interruption Voltage
VSC	Voltage Sourced Converter
WP	Work Package
D5.4, D5.6, D…	PROMOTioN deliverables 5.4, 5.6, etc.

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CONTENT

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EXECUTIVE SUMMARY

This document provides general information and guidelines for conducting tests of HVDC circuit breakers. In order to verify the test requirements defined in deliverable 5.4, the type of tests and sequence of execution, number of tests and pass/fail criteria are described.

Test procedures described in IEC standards for AC switchgear (IEC 62271-1, IEC 62271-100, IEC 60060-1) as well as the IEC standards of DC switchgear for railway applications (IEC 61992-1, IEC 61992-2) are used as guides in the development of this document. Also, the tests of HVDC circuit breakers conducted as part of TWENTIES project are studied and some of the tests are adopted from the test reports thereby.

This document does not describe an exhaustive list of tests, but rather the main categories of tests that can be applied to HVDC circuitb breakers. However, only a limited sub-set of the tests described in this document fall within the scope of PROMOTioN – i.e. interruption tests. The exact scope and test procedure will be decided upon discussion between DNV GL KEMA laboratories and the manufacturer on a bilateral basis.

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1 INTRODUCTION

1.1 MOTIVATION

For the test requirements described in D5.4 and their specified relevant conditions, this document provides test procedures that prescribe how the requirements should be verified. This includes any pre-conditioning, the sequence, magnitude (and duties) and duration of tests, any applied test factors, any technology specific additional tests and defined pass/fail criteria.

The test shall be carried out on a complete switchgear including its control and auxiliary circuits. It must be clear that the tests to be conducted as part of PROMOTioN project are mainly DC current interruption tests. However, in this document a general test procedure is presented. The main focus of the test procedure are the following points;

- **Type of test**: given a service condition, the range of tests which are part of type test programme have been defined in deliverable 5.4. These are dielectric, current withstand/let-through, or current making/breaking tests
- **The number of repetitions per test:** Depending on the type, a test shall be repeated number of times in order to have sufficient level of confidence on the performance of the device. For the tests carried out on a single equipment, whether maintenance between tests is allowed or not, etc.
- **Test duties:** Depending of the type of test, range of values can be defined between the lowest duty to the highest duty. For instance, considering current breaking capability, a circuit breaker needs to be tested for range of current from few amperes up to rated breaking current.
- **Duration between test duties:** if several test duties are defined for a given type of test, what is the minimum/maximum duration between tests. For HVDC circuit breaker, this typically should consider the thermal limits of the energy absorption components of the test breaker.
- **Test sequence:** if different types of tests are to be carried out, in what order shall it be conducted. Test sequence has impact on the performance. For example, overload current withstand test is followed by temperature rise test.
- **Duration between tests:** The maximum duration between different test sequences as well as between test duties, etc.
- **Pass/Fail criteria:** What is the success criteria for each test? A HVDC circuit breaker consists of different components for various purposes. Does a failure of a single components means the failure of the whole equipment? For example, are failure to interrupt and failure to absorb energy interpreted separately?
- **Measurements**: the measurements that need to be taken during test; the maximum value of interrupted current, peak TIV, breaker operation time, di/dt, temperature, etc.

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- **Tolerances/validity**: the permitted difference between a specified test values and the actually measured values. In other words, when is the test considered as invalid test?
- **Number of test specimen**: how many devices shall be tested in a type test program in order to have sufficient level of confidence on the design? For example, up to a maximum of 4 specimens is recommended in IEC standards for AC circuit breaker (clause 6 of IEC 62271-1) and all the tests are carried out on each specimen.

1.2 DOCUMENT OVERVIEW

The remaining part of this document is organized in two chapters. Chapter 2 discusses test procedures of HVDC circuit breakers. The major tests categorized into operational tests, making/breaking tests and dielectric tests are described. In Chapter 3 unit testing, multi-part testing and multi-unit testing are discussed.

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2 TESTS AND PROCEDURES

The HVDC circuit breaker shall be capable of making, carrying and breaking dc currents under normal circuit condition as well as making, carrying (up to a specified limit for a specified duration) and breaking currents under abnormal conditions such as short circuit. In order to verify these capabilities at specified rating, range of tests are conducted in a type test programme.

The type tests which shall be performed on HVDC CBs are summarized in Table 2-1. The definitions and test procedures of these tests are briefly provided the following sections.

2.1 OPERATIONAL TESTS

2.1.1 MEASUREMENT OF RESISTANCE OF THE NORMAL CURRENT PATH

This can be performed by applying current up to rated nominal current for sufficiently long duration (until the temperature reaches thermal equilibrium; for instance, when temperature rise per hour is at the most 1 K) and measuring the voltage drop between the teminals. Low voltage dc source can be used for this purpose.

The measurement of resistance is also performed in combination with temperature rise test, before and after the temperature rise test in the normal current path, when the device is at ambient air temperature in both cases. The acceptable deviation between the two measurements shall be defined. For AC switchgear, a maximum of 20% difference is recommended as acceptable [1].

2.1.2 TEMPERATURE RISE TEST

Temperature rise test shall be carried out in a laboratory while reproducing as much as possible the final installation condition [2]. The current equal to or greater than the maximum value of rated service current shall be used for temperature rise test. The IEC 61992-1 standard for DC switchgear recommends the temperature rise test shall be carried out at a rated (nominal current) followed by stipulated overload currents [2].

The test shall be made over a period of time sufficient for the temperature rise to reach a stable value. For example, this condition is deemed to be reached when the increase of temperature does not exceed 1 K in 1 h [1]. Temperature measurements shall be conducted for hottest spots with thermal-elements located as near as possible and sufficient temperature measurements shall be made regularly, at not more than 30-minute interval.

The HVDC circuit breaker shall be able to conduct current without any sign of distress and must reach thermal equilibrium without exceeding the thermal limits of its internal components (which are specified in advance or by manufacturer).

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2.1.3 SHORT-TIME CURRENT WITHSTAND TESTS

As defined in deliverable 5.4, short duration current withstand tests shall be carried out on the test breaker. Proper test circuits supplying the required current for the desired duration are used for this purpose. The short-time withstand currents can be temporary overload currents or short-time over currents as a result of energization of uncharged cable or line. Depending on protection strategy of HVDC grid, there could be short-time withstand current during selective clearing.

2.1.3.1 TEMPORARY OVERLOAD WITHSTAND CURRENT

For a HVDC circuit breaker designed for a specified nominal current, the maximum overload current and its duration shall be specified. During overload withstand test, current can be increased in steps and the time duration shall be measured after the maximum overload current is reached [3]. This shall be followed by temperature rise test described above. The temperature rise test is in turn followed by another overload current withstand test, for example at 150% of rated nominal current for a specified duration. For instance, 20-minutes overload current at 150% of nominal current is conducted in [4]. The exact values at each sequence can be specified by manufacturer and sequence of tests shall prove this.

2.1.3.2 SHORT-TIME SHORT-CIRCUIT CURRENT WITHSTAND

In addition to the overload currents, the short-time withstand current pulses which the HVDC circuit breaker shall be capable of withstanding without damage to its components needs to be specified. Figure 2-1 shows demonstration of short-time withstand current including overload withstand currents for HVDC circuit breaker.

The value of withstand currents and the corresponding durations shall be specified by the manufacturer. The test shall be performed with all switching devices in the normal current path in a closed position and at ambient temperature, and no break operation shall be performed (the switching devices shall remain closed position during the test). Therefore, the test shall ensure supply of the desired current only for the specified duration.

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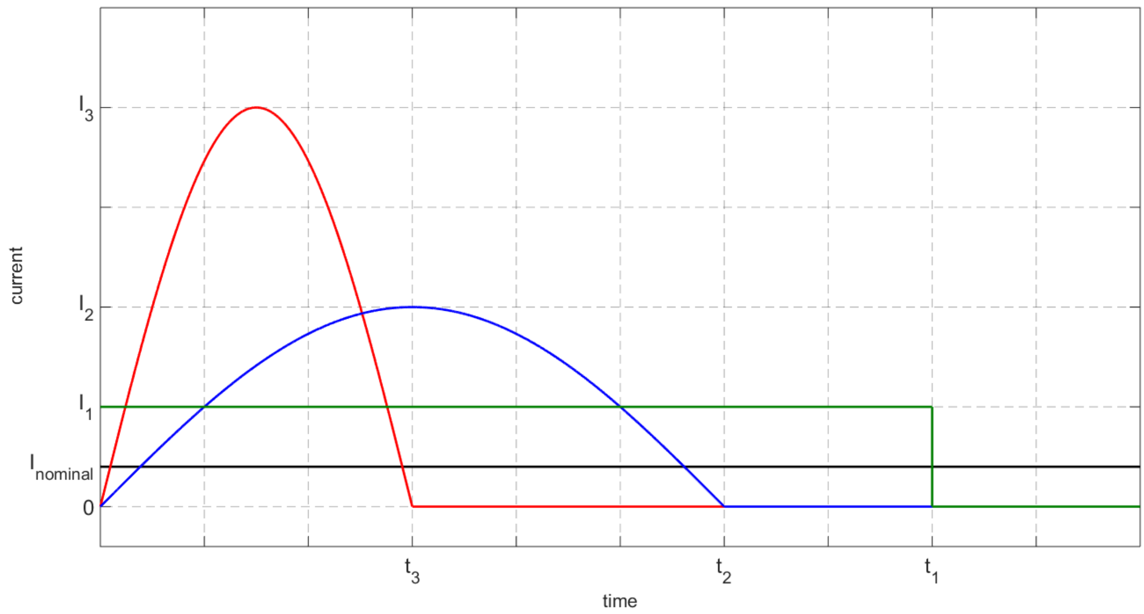

Figure 2-1: Example demonstrating short-time current withstand tests. Different current withstand levels applied for different durations.

After the test, no part of the device shall show significant deterioration and the device shall be capable of operating normally, carrying its rated normal current without exceeding temperature-rise limits and withstanding the voltage specified under dielectric tests. Also, no-load operations can be performed to verify the test object is not damaged.

2.2 BREAKING AND MAKING TESTS

2.2.1 DC SHORT-CIRCUIT CURRENT INTERRUPTION TESTS

For breaking test, the test circuit shall produce interruption current up to rated breaking current of the circuit breaker within the breaker operation time. Depending on the initial current at the moment the breaker receives the trip order, the average di/dt of the test current within the breaker operation time can be defined. This explained in D5.4.

The number of interruption tests at a rated breaking current shall be defined and the minimum number of successful breaking operations out of the complete test shall be defined as a success criteria. In addition to rated current breaking tests, lower duties at lower currents shall be defined. In other words, the test duties in the range from nominal current to rated breaking capability shall be defined. Similar test duties as for AC circuit breaker can be defined; for example, the test duties could be nominal/service current (I_{nom}), T10, T30, T60 and T100 which are the test duties at 10%, 30%, 60% and 100%, respectively, of the rated breaking current of the

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HVDC circuit breaker. Upon agreement with the manufacturer of the HVDC CB, the time duration between each test duty shall be defined. If possible the number of tests of each duty shall be specified as well.

Note that the test duties T10, T30, T60 and T100 are adopted from AC circuit breaker test duties. Nevertheless, different and/or additonal test duties shall be defined because some HVDC circuit breaker perform better for high duty than low duty. Moreover, the HVDC circuit breakers should be able to break range of values of current up to the rated breaking current. For all the cases the breaker operation time shall be kept the same.

A distinctive characteristic of HVDC circuit breaker compared to AC circuit breaker is that it has to absorb mega joules (MJs) energy during current interruption. The rated energy absorption of the circuit breaker shall be specified. Therefore, while defining the test duties, energy duties shall also be defined.

2.3 DIELCTRIC TESTS

Dielectric stresses are applied across open terminals of the circuit breaker as well as across terminal-to-earth. Depending on the application environment of the test circuit breaker, wet (outdoor application) and/or dry (indoor application) test conditions shall be specified. Dielectric tests across open circuit breaker shall be carried out on the HVDC circuit breakers along with a series residual current breaker. This is due to the fact that the metal oxide surge arresters (MOSA for energy absorption) are connected in parallel with the normal current path of the breaker; and applying dielectric voltage higher than the rated voltage of the circuit breaker in the absence of residual current breaker turns the surge arresters into conducting mode.

Dielectric stress tests are classified into DC voltage withstand, lightning impulse and switching impulse tests. For DC voltage withstand tests, the test duration shall be defined (at least 60 s is recommended for AC circuit breakers in case the duration is not specified by relevant standards). In case a polarity reversal is required, the sequence and duration shall be specified. For high voltage AC circuit breakers, dielectric stress voltage is applied starting at sufficiently low voltage to prevent any effect of overvoltage due to switching transients [5]. Unless otherwise there is unforeseen condition for HVDC CBs, the same procedure can be applied. The rated voltage of the circuit breaker is applied across the open terminals and the maximum transient interruption voltage (TIV) is applied between terminals of circuit breaker and earth.

For lightning impulse withstand test, the standard voltage surges with rise time of 1.2 µs and decay time of 50 µs (time to half value) is applied for a specified number of times. Fifteen number of impulses of a specific polarity at specified withstand level are recommended for AC switchgear in IEC 60060-1 [5]. The lightning impulse test is deemed as success for the test object if not more than two disruptive discharges occur during the complete test series and no sign of failure shall be observed across terminal-to-earth. For instance, 15 number of tests were performed for HVDC circuit breaker in Twenties project based on the same criteria as for AC circuit breaker [4].

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In IEC standard 62271-1 different dielectric withstand levels of AC circuit breakers of different voltage classes have been specified. The dielectric withstand levels for a HVDC CBs can be adapted from the closest values specified in IEC 62271-1.

2.4 SUMMARY OF TEST PROCEDURE

The test procedures discussed in this deliverable are summarized in Table 2-1. The test parameters, test duration, number of tests and pass/fail criteria are described briefly.

Table 2-1: Summary of HVDC circuit breaker tests

Tests and Procedures	Test parameter	Duration	Number of tests	Pass/fail criteria	Remark	Relevant Standards/documents
Temperature rise test	Rated nominal current conduction	Sufficiently long enough until change in temperature is 1 K per hour	This test is repeated in combination with other tests	- Temperature of a component or at a given spot does not exceed the maximum allowed limit - No thermal run away	Resistance of the normal current path is measured before and after temperature rise test	[2] [3] [6]
Short-time current withstand	- 200% of rated nominal current - 150% of rated nominal current	- few minutes (shall be defined) - Few minutes (shall be defined)	- Following temperature rise test - Following temperature rise test	- No sign of distress or degradation - No thermal run away - Shall operate normally after test		[3]
Current let-through	- Half sine waves at different peak and frequency	- Magnitude in proportion with frequency	- To be defined	- No sign of failure - Shall operate normally after the test		[3]
Making/breaking	- Lower than rated nominal current - Rated nominal current - Rated breaking current - Duties based on rated breaking current T10, T30, T60, T100	- Within breaker operation time - Sufficient di/dt to produce the rated breaking current/duties within breaker operation time	- Number of tests shall be defined later	- Successfully interrupt without failure - No thermal limit exceeded - Normal operation after test	- A test shall supply rated energy to the test breaker	[4]
Rated insulation level	- DC voltage withstand across open terminals - Peak TIV withstand	- Sufficient duration (shall be defined later) - Sufficient	- To be defined - To be defined	- No discharge - No discharge - Not more than	- Depending the application, the shall be performed under wet	[3] [4]

	terminal to earth - Lightning impulse (between terminals and terminal to earth	duration (shall be defined later) - Standard lightning impulse tests from	- 15 times per polarity	two discharge - No sign of failure or degradation	and/or dry condition	

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3 UNIT TESTING, MULTI-PART TESTING AND MULTI-UNIT TESTING

3.1 COMPONENT TESTING

In the design stage of HVDC CB, component by component test can be performed on individual elements of the circuit breakers. However, the HVDC circuit breaker is itself a system where the sequence, timing and interaction of the functional units is crucial for its overall performance. Thus, separate test of the internal components of the breaker cannot lead to the conclusion that it is equivalent to the testing of the overall performance of the breaker. As much as possible, the test shall be carried out on complete breaker unit having control and auxiliary circuits.

Nevertheless, before the overall performance of the HVDC circuit breaker the following components can be tested individually,

1. Series inductor
2. Residual current breaker
3. Interrupter/Fast mechanical disconnectors
4. Surge arrestor
5. Power electronic valves
6. Control & protection system

3.2 UNIT TESTING

In case a test cannot be carried out on a full-pole breaker, it may be carried out on a single module (breaker unit) or test duties can be split, for example, interruption duties and energy absorption duties. The former is called unit testing and the latter is called multi-part testing.

When dimensioning the test parameters for a single breaker unit, the assumption regarding the stress distribution shall be specified (i.e. whether the stresses are equally or unequally distributed among series connected breaker units). If unequal stress distribution is considered (which could be related with the design realization), then the percentage distribution of the total stress on each breaker unit shall be specified[1]. Tests shall be carried out on a breaker unit with the test parameters corresponding to the maximum stress distribution. Moreover, the components which are common to a single breaker unit as well as the full-pole breaker need to be tested properly. In case there are components common to both a single module and full-pole breaker, these shall be carried out in multi-part testing, first as part of single breaker unit and then after with stresses on full-pole breaker applied to only this component.

[1] The stress distribution is specified by manufacturer

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3.2.1 UNIT TESTING WITH REDUCED FREQUENCY AC SHORT-CIRCUIT GENERATOR METHOD

In deliverable 5.6, it is shown that AC short-circuit generators can be used for dc short-circuit current interruption tests of HVDC circuit breakers. Especially, short-circuit generators running at reduced power frequency can provide necessary stresses to a variety of HVDC circuit breakers having different rated breaking currents as well as different breaker operation times.

Upon using AC short-circuit generators for HVDC circuit breaker testing the following parameters needs to be defined. The frequency, voltage magnitude, the total circuit inductance and the short circuit making angles need to be adjusted to fulfil test requirements. These parameters are set based on the desired di/dt (which combines the test duty and the breaker operation time) and the rated energy absorption capability of the breaker.

After successful current interruption (just after energy dissipation phase), a dielectric stress shall be applied since under normal operation the circuit breaker will be subject to system voltage. A way to supply a dielectric stress after current interruption shall be specified.

3.2.2 UNIT TESTING WITH SYNTHETIC TEST CIRCUIT

If a single source cannot provide all the necessary stresses, multiple sources can be used to supply the desired stresses. In AC circuit breaker tests, synthetic test circuits are common due to the fact that current through and voltage across the circuit breaker appear at different time intervals. However, this is not the case for HVDC circuit breakers as the current through and voltage across the breaker appear simultaneously, demanding the circuit breaker energy absorption capability. The design of the test circuit for synthetic testing shall ensure this. For instance, a test may be able to produce the rated breaking current while it may not supply rated energy. Thus, synthetic test circuits can be designed so as to achieve both requirements. In deliverable 5.6 synthetic circuits for additional energy supply has been discussed.

3.3 MULTI-PART TEST

In the case, it is not possible to supply all the necessary stresses at the same time, tests can be carried out in several steps each time adjusting a given parameter (current, voltage and/or energy). In other words, if different functionalities of the circuit breaker cannot be verified in a single step, it can be performed in multiple stages. Each stage shall ensure the sufficient desired stress to be verified. For example, the following tests can be carried out on the HVDC circuit breaker part by part.

- Current interruption
- Current commutation
- Energy dissipation & thermal behaviour

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3.4 MULTI-UNIT TEST

The construction of full-pole HVDC circuit breaker may involve several breaker units rated for lower voltage and energy than a full-pole breaker. Provided that the test circuit can provide the necessary stresses, two or more units can be combined and tested together in case it is not possible to test a full-pole at a time. This might help in determining stress distribution among series connected breaker units.

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4 CONCLUSIONS

Together with D5.4, this document serves as a guiding reference for testing HVDC circuit breakers. Since there is no known HVDC circuit breaker product in service, the complete list of tests together with detailed test procedure and specified test parameters is difficult to provide at this stage. Only a general description of the fundamental tests and procedures have been presented.

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6 APPENDIX

PROMOTioN project aims to increase technology readiness level of HVDC circuit breaker technology and Table 6-1 shows tentative test requirements of different technologies of HVDC circuit breakers expected to be demonstrated within the project. Test circuits are designed for the parameters described in Table 6-1. Depending on the performance results during the practical tests some of these test parameters can be modified and this will be reported in the future documents.

Table 6-1: Test requirements associated with rated short-circuit breaking currents of different technologies of DCCBs (as provided by manufacturers)

Circuit breaker type	Breaker operation time (ms)	Rated system voltage (kV)[2]	Peak TIV (kV)	Maximum energy absorption (MJ)	Rated short-circuit breaking current (kA)
Active current injection	8	80	125	to be defined later	16
Hybrid type I	2	80	120	to be defined later	16
Sci-break	5	40	-	to be defined later	10

[2] This is the rated voltage of a single breaker unit. It is important for defining the peak TIV as well as for test-circuit design.

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