D5.4 Document on test requirements

PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks
Mail info@promotion-offshore.net
Web www.promotion-offshore.net

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CONTACT

Cornelis Plet – DNV GL
cornelis.plet@dnvgl.com

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Document Name: Document on test requirements
Responsible partner: DNV GL
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Work Package leader: Cornelis Plet
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Task lead: Nadew Belda

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APPROVALS

	Name	Company
Reviewer:	Klaus Würflinger	Siemens
Reviewer:	Dragan Jovcic	University of Aberdeen
Task leader:	Nadew Belda	DNV GL
WP Leader:	Cornelis Plet	DNV GL

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LIST OF CONTRIBUTORS

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.

PARTNER	NAME
DNV GL	Nadew Belda, Cornelis Plet, Rick Scharrenberg
Mitsubishi	Claudia Spallarossa, Fredrick Page, Sho Tokoyoda, Inagaki Takashi, Kazuyori Tahata
ABB	
TU Delft	Marjan Popov

Content

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NOMENCLATURE

ABBREVIATION	EXPLANATION
AC	Alternating Current
CB	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
PIR	Pre-Insertion Resistor
DCB	Residual Current Breaker
TIV	Transient Interruption Voltage
VSC	Voltage Sourced Converter
WP	Work Package
IEC	International Electrotechnical Committee

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EXECUTIVE SUMMARY

To date, there is no international standard describing the requiremensts, applicable tests and test procedures oof HVDC circuit breaker. This document provides a general guideline for list of tests that shall be applied to HVDC circuit breakers for its operation and performance verification. Since there is no international standard for HVDC circuit breakers, the document is compiled using AC circuit breaker standards, CIGRE technical brochures, VSC converter valve standard and Chinese draft standard for HVDC circuit breakers as references.

Chapter 1 introduces the purposes of different test programmes in relation to HVDC circuit breaker. For the purpose of harmonizing the definitions and terminologies related to HVDC circuit breaker operation, the terms and definitions developed by CIGRE JWG A3/B4-34 are presented in Chapter 2. Wave trace related terminologies and timing definitions during operation of HVDC circuit breaker are presented in a generic manner. Timing definitions are further divided into protection system related, circuit breaker related and system related definitions. These definitions are used thoughout this deliverable and later in deliverables 5.5, 5.6 and 5.7.

In Chapter 3 service conditions for HVDC circuit breakers are described. This is adopted from AC circuit breaker standards. The ratings related to HVDC circuit breaker which shall be specified in the name plate of the equipment are described in this chapter. The latter is also adopted from AC circuit breaker standards; however, by carefully selecting and adapting what is applicable to HVDC circuit breakers. These ratings are described interms of the terms and definitions discussed in Chapter 2.

Design and construction of HVDC circuit breaker is briefly described in Chapter 4. The terms related with internal components of HVDC circuit breaker as well as the build-up of HVDC circuit breaker for higher voltage rating is discussed.

The tests intended to verify the functionality and performance of HVDC circuit breaker in a type test program are discussed in Chapter 5. These tests are sub-divided into dielectric, operational, making and breaking tests as well as endurance tests. However, it should be noted in PROMOTioN project the focus is on the demonstration of DC short-circuit current interruption performance of HVDC circuit breakers and this is carried out using the test circuits designed in tasks 5.6 and 5.7.

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1 INTRODUCTION

1.1 MOTIVATION

Similar to AC circuit breaker testing, the testing of HVDC circuit breaker shall involve different ranges of tests taking into account the operational environment of the equipment. Thus, before carrying out tests, it is important to define the service conditions as well as the equipment ratings for which it is designed.

The purpose of this document is to provide a generic list of technology independent key characteristics, functionality and associated ratings of DC circuit breakers that are to be verified in a type testing programme. These characteristics can be directly translated to verifiable ratings and corresponding test requirements.

1.2 PURPOSE OF TESTING AND RELATION TO PROMOTION

Power equipment is typically tested to understand it's behaviour, verify ratings, verify functionality, or to assess the equipment's quality, operational performance or condition. A distinction can be made between different types of test programmes which have different purposes and are typically carried out at different phases of a component's life cycle. In order to provide insight into the purpose of deliverables 5.4, 5.5 and 5.6 and their relation to the tests which will be carried out in work package 5 and work package 10, an explanation of these different test programmes is given.

- **Development tests** – are carried out by the manufacturer typically in in-house laboratoria during the component or material development phase to understand and verify functionality, behaviour of raw materials, sub-components and sub-systems all the way to the finished prototype of the finished component. The type of tests, the test requirements, the test procedures are all tailored to the development phase and the specific aspect which is being tested. Therefore, often these tests are not described in standards. These tests are typically aimed at gaining understanding and learning rather than verifying a defined level of performance.
- **Qualification tests** – are aimed verifying a defined level of performance, functionality or quality of a technology. Typically, these tests are carried out on fully developed production prototypes, often in an independent lab or in-house but witnessed by an independent expert. The purpose of these tests is to convince (potential) customers that the technology meets a certain (minimum) level of adequacy. As such, the tests often verify full functionality and the maximum lifetime stresses a component can handle or is subjected to. These tests are often pre-scribed in standards or recommended practises. A distinction can be made two different types of qualification tests.
    - **Technology qualification tests** – In technology qualification tests, the maximum design capability of a technology class is verified. This verifies both the design, the compatibility of subcomponents but also a manufacturer's ability to produce it. The ratings that are used to derive

the test stresses are determined by the design ratings of the technology and are provided by the manufacturer. This test is done without a specific application or project in mind. When the technology is applied, it may be implemented with different lower performance parameters than the ones used for the qualification tests. These tests are the most onerous tests that are applied to a technology. It is often also referred to as a pre-qualification test.

  - **Project qualification** – This test is also often referred to as a type test, and is aimed at verifying the design of a specific component in a technology class, for a specific project or application. This test is similar to a technology qualification test but often less onerous (reduced ratings, or reduced functionality) and the difference is that the applied test stresses are determined by the application or project and are typically provided by a customer such as a developer or a TSO. Type tests are typically pre-scribed in standards.
- **Factory tests** – are aimed at verifying quality of production and are carried out on the final component. A distinction can be made between non-destructive tests and destructive tests as explained below. Factory acceptance tests for power equipment are typically standardised.
  - **Routine tests** – are a set of non-destructive basic quality checks that are carried out on every manufactured component before it is packed and transported.
  - **Sample tests** – are an extensive set of destructive tests carried out on samples taken regularly from the manufactured components to check the quality and stability of the production process
- **Commissioning tests** – are non-destructive tests carried out after the component is transported and installed at site to verify basic functionality and quality of installation. It is also a check to verify no damage was incurred during transport. Often the commissioning tests are part of the installation steps necessary to get more complex systems up and running in a stepwise fashion. Commissioning tests for power equipment are typically standardised.
- **Maintenance tests** – are typically non-destructive tests carried out regularly on the commissioned component during it's operational lifetime to verify basic functionality, or to obtain information about the components condition. Maintenance tests for power equipment are typically pre-scribed by the user's own maintenance and condition assessment programs or developed on a case by case basis.

For large and complex systems, some of the above tests can be combined. This is because it is not economically viable to build a test circuit which can supply enough power to test the system to full ratings and functionality, or because it is too expensive to build a dedicated system or component for testing only. For example, HVDC converter stations are not tested in full until they are assembled and commissioned on-site. Hence the commissioning tests in some way constitute a type test for the full system. Subparts of the converter station are however qualified individually with separate type and factory acceptance tests. For large one-off power transformers, the factory acceptance and type tests are also often combined.

HVDC circuit breakers can also be considered to be large and complex systems, which are too large to economically test to full ratings and functionality. They consist of submodules and other components, arranged such as to achieve the required ratings and functionality. A similar approach to testing of HVDC converters, where different functionalities and ratings are tested separately on subparts, is applied to HVDC circuit breakers. It is customary to verify dielectric withstand capability, operational performance, mechanical performance and functional performance separately on the ‘smallest indivisible building block’ of the system, taking into account the additional stresses due to uneven distribution across the modular series combinations of such building blocks.

In PROMOTioN, there is no specific HVDC circuit breaker or application. Also, the HVDC circuit breakers in PROMOTioN are not in their final stage of development, and as such do not have the full envisaged ratings or functionality yet. As such, the HVDC circuit breaker tests foreseen in work package 10 are somewhere between development and technology qualification tests. This means that the exact test programme (test requirements, procedures and parameters) will be determined in close collaboration with the manufacturer. In work package 10, only the short-circuit current interruption functionality of HVDC circuit breaker prototypes will be tested.

Work package 5 focusses on determining the aspects of HVDC circuit breaker technology that should be tested i.e. the requirements, and proposes procedures and a test circuit for how these aspects can be tested. As the PROMOTioN project aims to increase the technology readiness level of HVDC circuit breaker technology, the goal of work package 5 in determining requirements is to be comprehensive and include all aspects: dielectric, operational, making and breaking and endurance. Hence, in deliverable 5.4 a comprehensive list of test requirements is provided with the aim of fully qualifying the HVDC circuit breaker for commercial use.

The main challenge in testing HVDC circuit breakers is to deal with the energy absorption requirement during short-circuit current interruption, as this is fundamentally different from conventional AC circuit breaker tests, especially for reclosing operations. Also operational tests such as current withstand tests are different from conventional tests. Dielectric tests and mechanical tests are very similar in terms of test set-up to tests pre-scribed in AC circuit breaker and IGBT valves standards. Therefore, the focus in deliverable 5.5 is to develop test procedures which can be used to apply these short-circuit energy, overcurrent and dielectric test stresses. In case the required test stresses cannot be replicated economically, suggestions are made for testing ratings and functionality separately.

Deliverable 5.6 investigates different options for the test circuit used to test short-circuit current interruption which will be used in work package 10. In particular, the ability of AC short-circuit generators to deliver the required test stresses is analysed. Furthermore, the deliverable provides a description of how synthetic (temporal separation of voltage and current stresses to reduce test power) and multi-part testing (separate testing of ratings and functionality to reduce test power) can be applied to verify the HVDC circuit breaker performance.

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1.3 DOCUMENT OVERVIEW

The remainder of this document is organized as follows. In Chapter 2 the terms and definitions related to the operation of HVDC circuit breakers, which are developed by CIGRE JWG A3/B4-34, are provided. Chapter 3 describes service conditions and ratings applicable to HVDC circuit breaker. The design and construction of HVDC circuit breaker is briefly presented in a generic manner (independent of a given technology of HVDC circuit breaker) in Chapter 4. In Chapter 5 test requirements are discussed in detail.

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2 TERMS AND DEFINITIONS

CIGRÉ JWG A3/B4.34 developed Figure 2-1 which shows terminologies related to voltage and current waveforms as well as timing definitions during a fault current interruption by a generic HVDC circuit breaker. Since fault current interruption involves the disciplines of circuit breaker design, protection system design, and power system studies, these definitions are grouped into three categories, namely breaker related, protection related and system related (see Figure 2-1). This section is entirely taken from CIGRE TB A3/B4.34 [1]

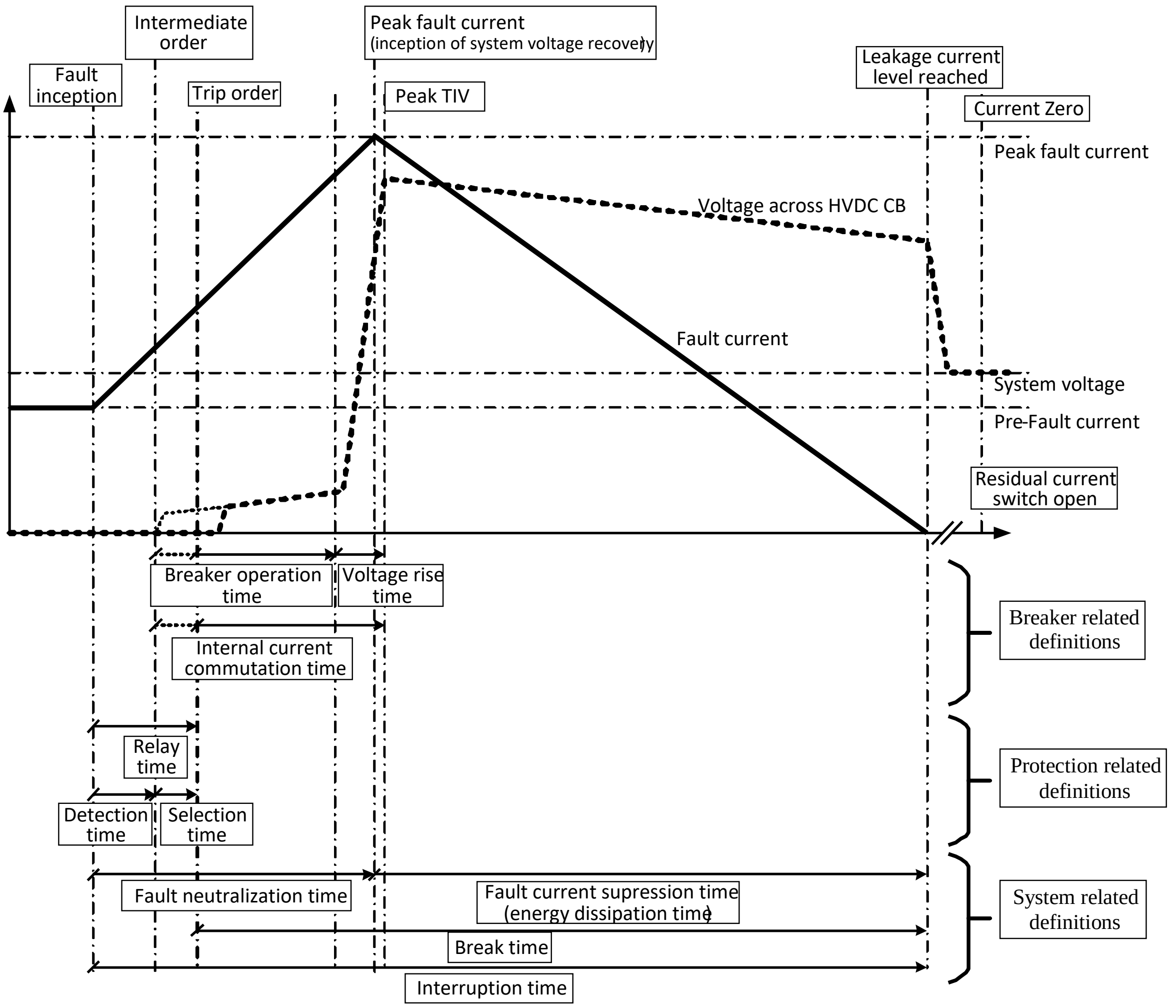

Figure 2-1: Timing defnitions and wave trace terminologies [1]

The terminologies and definitions shown in Figure 2-1 are described below.

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2.1 WAVE TRACE TERMINOLOGIES

Here the current and voltage waveforms that are seen by HVDC circuit breaker during normal operation and interruption process are defined.

2.1.1 LOAD /NOMINAL CURRENT

The rated current flowing through the breaker under normal operation condition.

2.1.2 FAULT CURRENT

The current flowing through the circuit breaker during short-circuit (abnormal) operation condition

2.1.3 PROSPECTIVE FAULT CURRENT

The shape of the fault current that results when no interruption attempt is made by any circuit breaker in the system.

2.1.4 TRANSIENT INTERRUPTION VOLTAGE (TIV)

The voltage across the HVDC CB terminals as a function of time during DC current interruption process. This is the counter voltage, higher than the system voltage, generated by a circuit breaker to suppress the fault current. This must not be confused with TRV in AC circuit breakers which is imposed on the circuit breaker by the surrounding system whereas the TIV in DC circuit breakers is self-imposed by the circuit breaker.

MAXIMUM VALUE OF TIV

The maximum value of the voltage across the two terminals of the HVDC CB (TIV) during the interruption process. This is shown as peak TIV in Figure 2-1.

2.1.5 RESIDUAL CURRENT

The current that is flowing through the surge arrester part of the breaker after current is interrupted. Since the surge arrester stacks are subjected to a system voltage after current interruption by the circuit breaker, there is a small leakage current through the arresters due to their non-linear resistance characteristics.

2.2 TIMING DEFINITIONS

The timing definitions are further grouped into protection related, circuit breaker related and system related terminologies.

2.2.1 PROTECTION RELATED TERMINOLOGIES

These are terms related to the protection system

2.2.1.1 DETECTION TIME

This is a time interval between fault inception and fault detection by a local protection relay.

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2.2.1.2 SELECTION TIME

Time interval needed to decide which breakers in the grid should interrupt. The selection time ends when the trip order has been received by the corresponding breaker. The protection system may send intermediate orders to breakers in the grid during the selection time.

Note: depending on the protection scheme, the instants of the ends of detection and selection time may coincide.

2.2.1.3 INTERMEDIATE ORDER (ONLY FOR HYBRID BREAKERS)

Any order given before the trip order to start the interruption process. For HVDC CBs with the possibility of pre-activation, intermediate orders can be sent and start internal current commutation processes into branches to prepare the final commutation into the energy absorber path. This final commutation into the energy absorber path would only happen when the trip order is received.

2.2.1.4 RELAY TIME

Smallest time interval comprising detection time and selection time. The relay time ends with the reception of the trip order at the HVDC CB, but other intermediate orders may have been sent by the protection system at an earlier stage during the relay time.

NOTE: Depending on the protection scheme, there might be no separation of detection and selection time.

2.2.2 BREAKER RELATED TERMINOLOGIES

Here the timing terminologies related to HVDC circuit breaker operation are provided. Circuit breakers may be distinguished based on relative values these timing.

2.2.2.1 BREAKER OPERATION TIME

Time interval between the reception of the trip order and the beginning of the rise of the TIV. If intermediate (preliminary) orders are sent in some topologies, e.g. some hybrid HVDC CBs, the time interval starts with the reception of the intermediate order. The breaker operation time is part of the internal current commutation time.

NOTE: This time interval may be most relevant when comparing different HVDC CB topologies and can vary significantly.

- In case of mechanical HVDC CBs, this time interval consists of the mechanical interrupter opening time and arcing time.
- In case of electronic HVDC CBs, this time interval consists of the power electronic switching off time.
- In the case of hybrid HVDC CBs, this time interval consists of the power electronic switching off time in the nominal current branch, the current commutation time from the nominal current branch and the opening time of the mechanical disconnector in the nominal current branch

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2.2.2.2 INTERNAL CURRENT COMMUTATION TIME

It starts with the reception of the trip order and ends when the peak transient interruption voltage (TIV) is reached. If the protection systems also give intermediate orders before the trip order, this time may also start earlier.

2.2.2.3 ARCING TIME [ONLY FOR MECHANICAL BREAKERS]

This is the time interval from contact separation of interrupter until current zero through interrupter. Although contacts are separated, an arc is generated between contacts and fault current continues to flow through an arc during this time interval. This term is defined for only mechanical breakers.

2.2.2.4 VOLTAGE RISE TIME

This is the time interval during which the breaker builds up most of the counter voltage necessary to decrease the fault current. For most of today's proposed HVDC CB topologies this is the time during which the current is commutated into the energy absorbers.

NOTE 1: This is the time necessary to charge the internal capacitors of the breaker and stray capacitances (e.g. test lab equipment).

NOTE 2: For some breaker topologies (e.g. pure semiconductor based) the breaker operation time is insignificantly small and the voltage rise time may coincide with the internal current commutation time

2.2.3 SYSTEM RELATED TERMINOLOGIES

Here the timing terminologies important for the system are defined.

2.2.3.1 FAULT NEUTRALIZATION TIME

The time interval between fault inception and the instant where the fault current starts to decrease (peak fault current). Due to the counter voltage created by the HVDC CB the fault is effectively neutralized and the system voltage for the healthy part of the system can start to recover.

NOTE 1: This time is exactly the period where the fault current through the breaker rises and could also be called "fault current rise time".

NOTE 2: In a network, it may be very hard to determine exactly when the fault current starts to decrease under transient (and oscillating) conditions. As the voltage rise time is typically very short compared to the fault current rise time, the time difference between the instants of peak fault current and the peak of the TIV is very small. The maximum TIV is easier to determine and may thus be used as the end of the "fault neutralization time", instead.

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2.2.3.2 FAULT CURRENT SUPPRESSION TIME

Time interval between the peak fault current and the instant when the current has been lowered to residual current level (or below); i.e. the end is the instant at which the current flowing through the HVDC CB falls to a value that a mechanical disconnecting switch (residual current switch) can interrupt. This time is typically the time during which the energy in the system is dissipated in the HVDC CB's energy absorbing elements.

2.2.3.3 BREAK TIME

Time interval from the instant the breaker receives the trip order and the instant when the current has been lowered to residual current level (or below).

NOTE: This definition is analogous to the AC breaker standard (IEC 62271-100, clause 3.7.135)

2.2.3.4 INTERRUPTION TIME

This is the time interval between fault inception and the instant when the current has been lowered to residual current level (or below).

NOTE: This definition refers to IEC 60050, def. 448-13-14.

For nominal current interruption, the wavetraces and the timing definitions are provided in Figure 2-2.

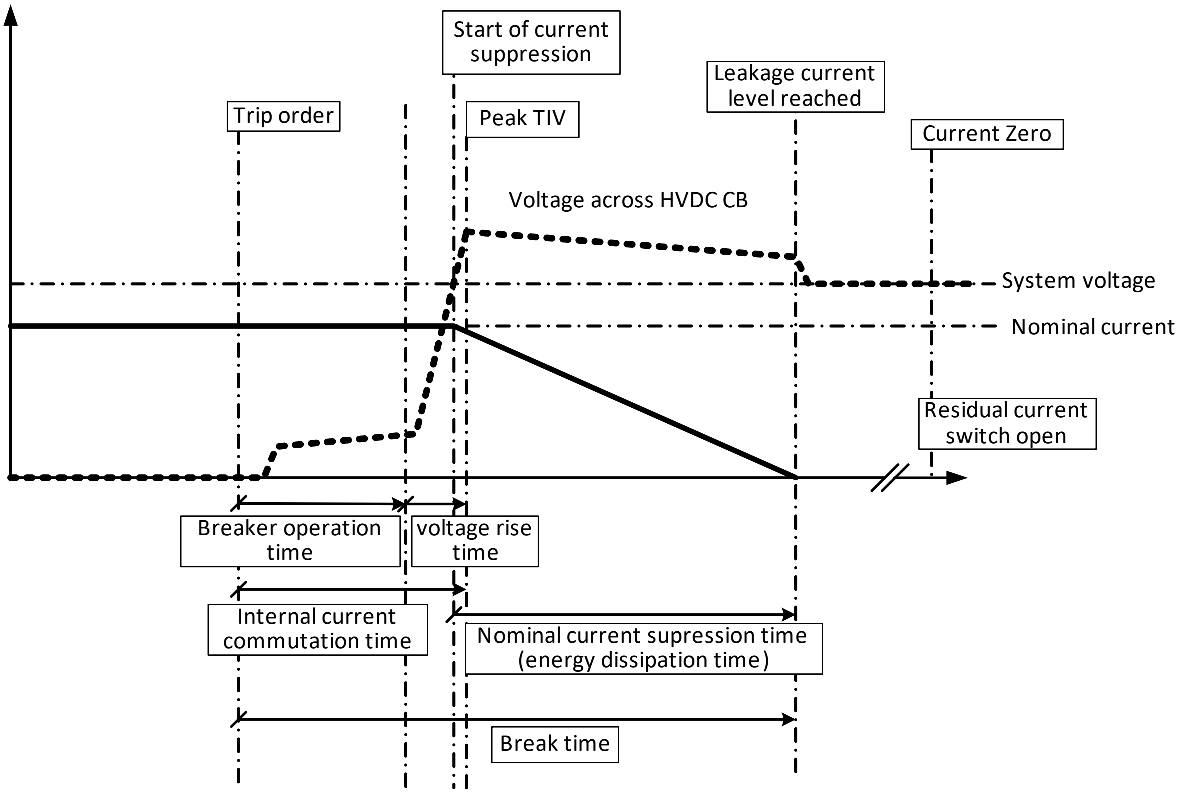

Figure 2-2: Nominal current interruption [1]

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3 RATINGS

This section lists specifications for DC circuit breakers adapted from similar specifications of AC circuit breakers defined in IEC standards [2], [3], [4]. It is organized in two sections. First, the requirements imposed on a DC circuit breaker by the environment in which it is installed is presented. Then, the specifications that are related to the system in which the DC circuit breaker technology is used and is installed.

3.1 NORMAL SERVICE CONDITIONS

The normal service conditions describe the environmental conditions for which the DC circuit breaker is designed. For AC circuit breakers, the normal service conditions for indoor and outdoor installations are described in IEC 62271-1

3.1.1 TEMPERATURE RANGE

The temperature range describes for which ambient temperatures the DC circuit breaker is designed. For AC circuit breakers, the preferred values are indicated in IEC 62271-1.

3.1.2 POLLUTION LEVELS

The pollution level indicates for what environments the DC circuit breaker is designed (indoor, lightly polluted areas outdoor, highly polluted areas outdoor etc.). For AC circuit breakers, the applicable pollution levels are described in IEC 62271-1.

3.1.3 ALTITUDE

The altitude condition describes the maximum altitude for which the DC circuit breaker is designed. For AC circuit breakers, the insulation withstand level of external insulation is increased for higher altitudes, as described in IEC 62271-1.

3.1.4 HUMIDITY

The humidity condition describes the maximum humidity for which the DC circuit breaker is designed. Preferred values for AC circuit breakers are described in IEC 62271-1.

3.1.5 SEISMIC

The seismic condition describes for what environments the DC circuit breaker is designed. For AC circuit breakers, the different vibration classes are described in IEC 60255-21-1.

3.1.6 WIND SPEED

The wind speed condition describes the maximum wind speed for which the DC circuit breaker is designed. Preferred values for AC circuit breakers are described in IEC 62271-1.

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3.1.7 ICE COATING

The ice coating condition describes the thickness of the ice coating for which the DC circuit breaker is designed. Preferred values for AC circuit breakers are described in IEC 62271-1.

3.2 HVDC CB RATINGS

The rated values resulting from the system in which the circuit breaker is installed combined with the capabilities of the DC circuit breaker.

3.2.1 RATED VOLTAGE

The rated voltage is equal to the maximum system voltage for which the DC circuit breaker is designed. It indicates the maximum value of the "highest system voltage" of networks for which the DC circuit breaker may be used [2].

3.2.2 RATED INSULATION LEVEL

The rated insulation level indicates the maximum voltage that the DC circuit breaker can withstand. This is further classified into rated short duration DC withstand voltage and rated lightning impulse withstand voltage.

For AC circuit breakers, different voltage levels are used for short-duration withstand voltages and lightning impulse withstand voltages based on the voltage classes in which the AC circuit breaker is used.

3.2.3 RATED NORMAL CURRENT AND TEMPERATURE RISE

3.2.3.1 RATED NORMAL/NOMINAL CURRENT

The rated normal/nominal current of DC circuit breakers is the DC the current which DC circuit breakers shall be able to carry continuously under specified conditions of use and behaviour [2].

3.2.3.2 TEMPERATURE RISE

The temperature rise condition indicates the maximum temperature of various parts of the DC circuit breaker at a specified maximum ambient temperature. For AC circuit breakers, these maximum values are described in IEC 62271-1.

3.2.4 RATED SHORT-TIME WITHSTAND CURRENT

The current which the DC circuit breaker can carry in the closed position during a specified short time under prescribed conditions of use and behaviour. Several current-time combinations can be specified.

3.2.5 RATED OPERATION TIMES

The rated operation times can be specified in three different values.

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1 Breaker operation time
2 Internal current commutation time
3 Break time

These are defined in Section 2.2. The breaker operation time and the internal current commutation time are determined by the speed of operation the circuit breaker technology whereas the break time is dependent on both the circuit breaker and the system.

3.2.6 RATED SHORT-CIRCUIT BREAKING CURRENT

For HVDC CB the rated short-circuit breaking current is the maximum short-circuit current which the circuit breaker shall be capable of breaking under the conditions of use. This is within a fault current neutralization time described in Section 2.2.3.1. The circuit breaker shall be capable of breaking any short-circuit current up to its rated short-circuit breaking current.

3.2.7 RATED MAXIMUM TRANSIENT INTERRUPTION VOLTAGE (TIV)

For HVDC CB the maximum TIV is the maximum transient voltage across the terminals of the circuit breaker which is normally higher than the rated system voltage to suppress the current to zero. The TIV appears across the HVDC CB while the short-circuit current is still flowing leading to energy absorption requirement of the circuit breaker.

3.2.8 RATED ENERGY ABSORPTION

This is additional duty of HVDC CB as compared to AC circuit breakers that results due to absence of natural current zero in DC system. This constitutes the magnetic energy stored in the inductance of the system as well as the electrical energy supplied by the system during current suppression phase of the interruption process.

The rated energy absorption of a HVDC CB shall be defined in relation to the magnitude of the series dc current limiting reactor, the rated short-circuit breaking current and the rated voltage of the system.

3.2.9 NUMBER OF RECLOSING OPERATIONS

The number of reclosing operations shall be defined based on the circuit breaker technology and taking the thermal limit of the energy absorption components of the HVDC CB into account.

3.2.10 TIME BETWEEN RECLOSING OPERATIONS

Depending on the protection philosophy of the system as well as on the de-ionization time of transmission lines, the time between reclosing operations shall be defined.

3.2.11 RATED POWER LOSSES

The power dissipated by full-pole HVDC CB under normal operation.

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3.2.12 NUMBER OF OPERATIONS BEFORE MAINTENANCE

This is the number of mechanical operations before maintenance is performed and is specified by the manufacturer.

3.2.13 SELF-PROTECTION OVER-CURRENT THRESHOLD

On the occasions the protection system fail to send a trip signal to the proper circuit breaker within the expected relay time, the short-circuit current may rise to a value beyond the capability of the circuit breaker. Thus, in order to avoid this situation circuit breakers might be equipped with self-protection based on local measurements. Under this condition, the resulting current may rise to a value larger than the rated short-circuit breaking current.

If such a functionality is defined for a circuit breaker, the self-protection over-current threshold shall be specified by the manufacturer.

3.2.14 RATED SUPPLY VOLTAGE OF CLOSING AND OPENING DEVICES AND OF AUXILIARY AND CONTROL

Whether the opening and closing devices (both power electronic and mechanical) are supplied independently or from the system this needs to be specified. The rated values of the supply voltage shall be specified. If the power is supplied from the system, then the minimum system voltage should be specified. For AC circuit breakers, these values are tabulated in IEC standards [2].

3.2.15 RATED SUPPLY FREQUENCY OF CLOSING AND OPENING DEVICES AND OF AUXILIARY CIRCUITS

The standard values of rated supply frequency are DC., 50 Hz and 60 Hz [2]

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4 DESIGN AND CONSTRUCTION

This chapter aims to provide a basic overview of the design and construction choices in how the required functionality and ratings can be achieved. Terminology to describe various parts and subsystems is introduced to be able to clearly describe the test object.

HVDC CBs are systems consisting of several components and subcomponents that each have a distinct function. Several components may be combined in series and/or parallel connection to achieve higher ratings or add functionality. The resulting combination is referred to as a functional unit. The smallest/lowest rated part of the HVDC CB which contains all required functionality is referred to as a breaker unit.
Component

- Functional unit
- Control & Protection
- Module
- Breaker unit
- Fully rated breaker (full-pole)

Some components such as the series inductor, or the residual current breaker, may be tested and considered separately.

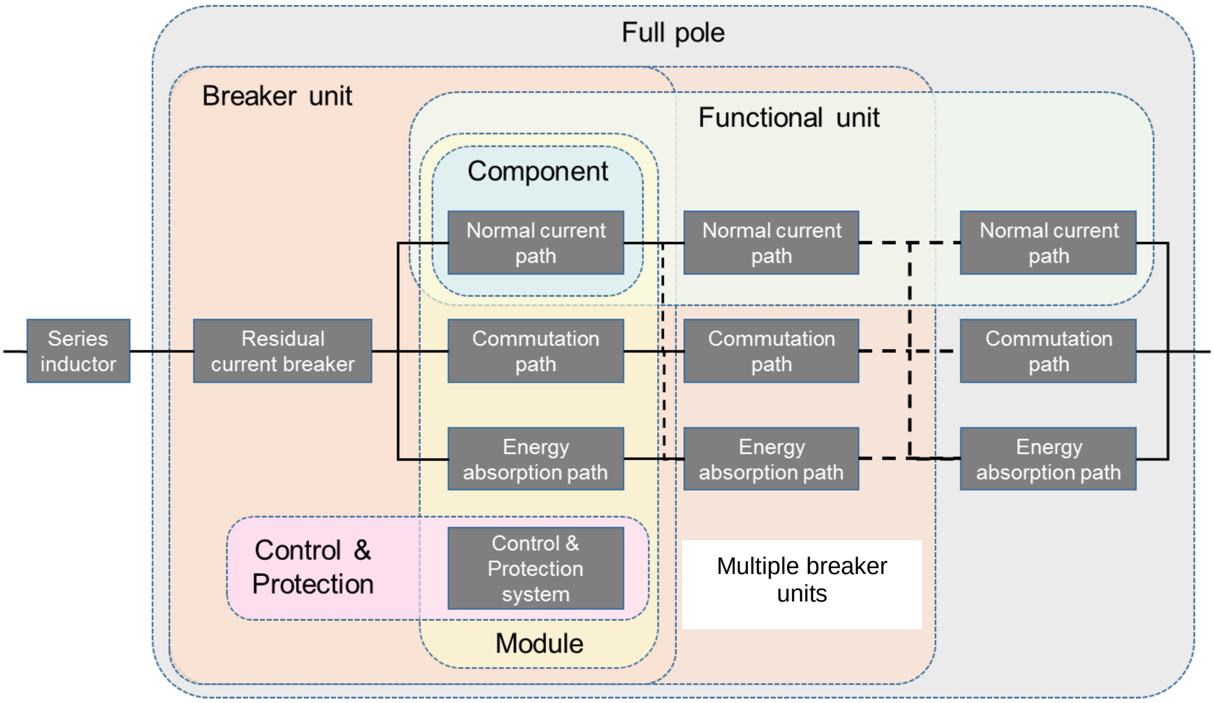

Figure 4-1 – Generic HVDC circuit breaker schematic diagram

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A component may be further subdivided into sections (assemblies of subcomponents) or levels, depending on the HVDC CB technology and physical implementation.

Each component (except for the control and protection system) requires dielectric insulation from earth. The component is either insulated by air, or placed within an earthed enclosure filled with an insulating medium. It is mechanically supported by mounting it on a support structure (tower) or suspend it hanging in air. Some components, each module, a functional unit, or multiple modules may share the same support structure. Alternatively, different components of the same HVDC CB may be placed in different support structures.

Most HVDC CB concepts only require components which are installed in series with the line. Only optical connections (for communication or low power loads) and perhaps cooling connections are required between ground and high voltage components. The exact order in which the series inductor (DCL), residual current breaker (RCB), and modules are installed with respect to the line and bus side of the HVDC CB (illustrated in Figure 4-2), determines the dielectric strength requirements of these components.

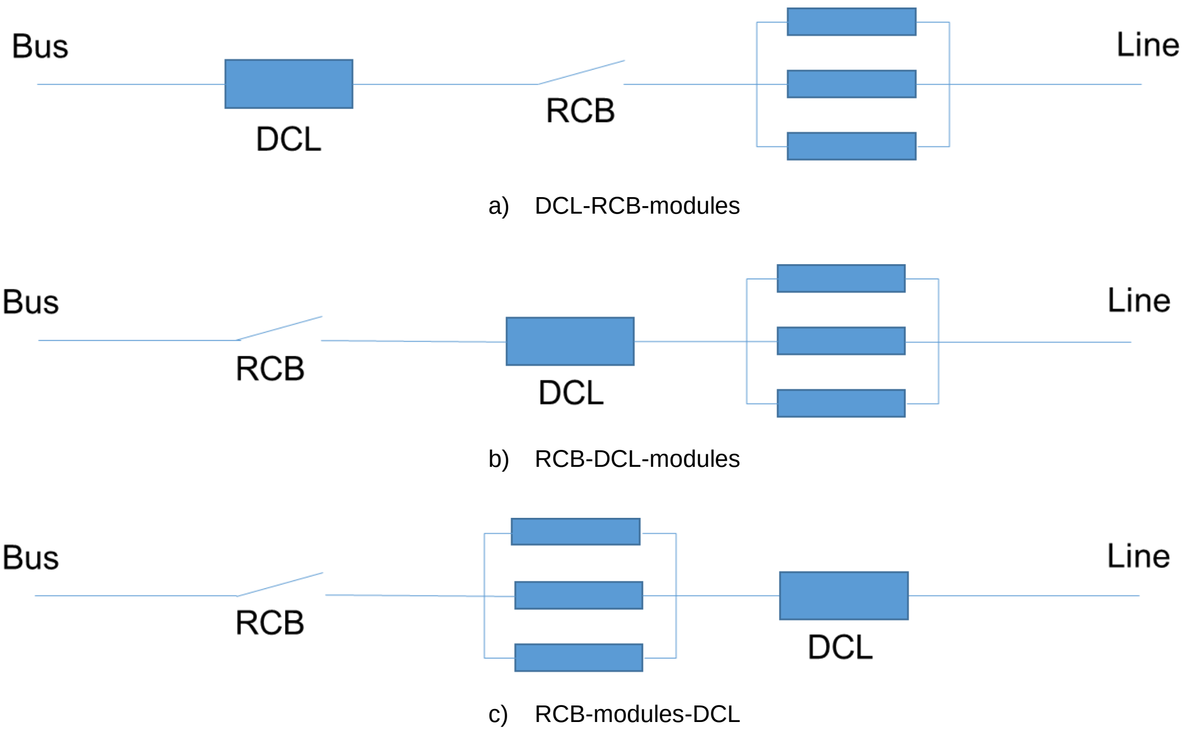

Figure 4-2 – Order of series connection of components

The connection shown in Figure 4-2 a) is often used to illustrate HVDC CB concepts. However, in this option, the modules are exposed to any travelling waves coming from the line side and the series inductor cannot be separated from the system. In option b), the series inductor and the residual current breaker have been swapped around, allowing for separation of the series inductor from the bus. However, the modules are still

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exposed to travelling waves. In option c), the series inductor reflects travelling waves coming from the line side, and the residual current breaker can be used to disconnect both the modules and the reactor from the system.

Some HVDC CB concepts require components which are installed as a shunt between the line and earth. For example, in some cases power needs to be supplied to components in the commutation path, or a resistor is used to charge capacitors from the line voltage.

Some HVDC CB concepts can be equipped with additional components which will enable controlled line energisation (making) functionality. This could for example be a pre-insertion resistor. In this document, this is not considered to be part of the DC circuit breaker functionality.

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5 TEST REQUIREMENTS

In this chapter test requirements are provided, applicable to full-pole HVDC CB as well as to its sub-parts such as a unit of a HVDC CB. The test requirements are divided into three parts, namely dielectric, operational and making and breaking tests are described.

5.1 DIELECTRIC TESTS

Dielectric tests are carried out to verify the high voltage withstand capability of the HVDC CB. The HVDC CB and its sub-parts should have sufficient insulation strength, clearance distances, and creepage distances to meet the system insulation coordination requirements and withstand the voltages generated during fault current interruption. Two separate dielectric strengths should be considered. Firstly, the dielectric strength between terminal of the test object and earth which concerns the support structure, and secondly the dielectric strength between terminals of the test object.

Components such as the series inductor and the residual current breaker are likely to have their own individual support structures and may be tested separately.

The insulation strength during steady-state as well as during transient conditions should be tested in hot (maximum operating temperature) and cold state.

5.1.1 TEST OBJECT

If different types of support structures are used within the HVDC CB, then each type should be tested. These may be tested all at once or separately.

If a single support structure supports more than one module, more than one functional unit, or more than one component, then all intended components should be installed during the test.

If a single module consists of more than one structure such that there is more than one support structure per module, then the tests should cover the worst stresses experienced by any of the module support structures [4]. The support structure to be used for the tests may be a representative separate object including representation of the adjacent parts of the module, or may form part of the assembly used for single module or multiple module tests. It should be assembled with all ancillary components in place and should have the adjacent earth potential surfaces properly represented. Any coolant should be in a condition representative of the most onerous service condition for the purpose of the test [4].

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5.1.2 SUPPORT STRUCTURE

The principal objectives of these tests are [4]:

a) to verify the voltage withstand capability of the insulation of the support structures, cooling ducts, light guides and other insulating components associated with the support structure. If there is insulation to earth other than the support structure, then additional tests may be necessary;
b) to verify that the partial discharge inception and extinction voltages are above the maximum operating voltage appearing on the support structure.

As the main difference compared to AC CBs, the impact of travelling waves during current interruption should be taken into account here. If a circuit breaker builds a counter voltage while the travelling waves still persist, the superposition of the two appear across the terminal to earth. This shown via simulation results in deliverable 5.3. (Please refer to Figure 3.11 of D5.3).

5.1.2.1 DC VOLTAGE WITHSTAND, LIGHTNING IMPULSE WITHSTAND AND SWITCHING IMPULSE WITHSTAND TESTS

IEC standard 62271-1 tabulates different short-duration voltage withstand levels and lighting impulse levels for different AC voltage classes. Similar table can be adopted for HVDC CBs based on DC voltage classes. Although no standard listing DC voltages exist yet, based on existing and current trends in HVDC power transmission, CIGRE TB 684 proposed the following recommended DC voltages for DC grid application [5].
±100 kV, ±150 kV, ±200 kV, ±250 kV, ±320 kV, ±400 kV, 500 kV, ±600 kV, ±800 kV, ±1100 kV.

Similar recommendation but slightly different voltage levels are defined in Chinese standard [6].

Based on system voltage for which a HVDC circuit breaker is designed, the withstand levels can be extrapolated from the closest values defined in IEC standard [2].

The fact that HVDC CBs have surge arresters connected across its terminals (for absorbing system inductive energy during interruption) may impose different test conditions as compared to AC CBs. When the HVDC CB is in open position, the residual current breaker in series with HVDC CB is open to avoid current leaking through the surge arresters across the HVDC CB terminals. Thus, the long-term DC withstand tests may be carried out in combination with the residual current breaker. Only short term DC withstand tests may be carried out on the module(s).

5.1.3 BETWEEN TERMINALS

The dielectric strength of a HVDC CB and its functional units between the module's terminals should be able to withstand the self-imposed TIV and any reverse voltage spikes due to remnant capacitor charge or reverse recovery related effects.

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These tests are intended to verify the design of the module regarding its voltage-related characteristics for various types of overvoltage (d.c., a.c., switching impulse and lightning impulse overvoltage). The tests should demonstrate that [4]:

a) the module will withstand the specified overvoltage;
b) partial discharges will be within specified limits under specified test conditions;
c) the internal voltage grading circuits have sufficient power rating;
d) the module electronic circuits behave as expected.

The static and transient voltage distribution over series connected modules, or components in a functional unit, should be within the dielectric strength between terminals of the module or component.

If any redundant components, sub components or levels exist in the test object, these should be short-circuited or bypassed during the tests.

5.1.3.1 DC VOLTAGE WITHSTAND TESTS

During normal operation, the components in a HVDC CB experience negligible voltage stress (only dictated by voltage drop in normal current path) between terminals.

During current commutation, some HVDC CB technologies apply a reverse voltage spike with a maximum value equal to the pre-charged capacitor voltage. In some cases, this is maximally equal to the system voltage. The dv/dt of this spike is determined by the interruption current, the capacitors and inductors (including stray) within the breaker. During current suppression, HVDC CB modules apply TIV between the module terminals for a limited duration up to several milliseconds. After current suppression, the residual current breaker will open and provide insulation to the system voltage.

These voltage stresses are replicated by the HVDC CB itself during the current interruption tests if one or more modules are tested. If this is not the case, and individual components are tested, then the dielectric stress caused by other components should be represented.

The long-term DC voltage across the circuit breaker when it is in open position appears across the residual current breaker, which may be tested individually.

The magnitude of the TIV voltage across the breaker during current interruption process depends on the protective voltage level of the surge arrestors which will be used in the installed HVDC CB. The duration will depend on the size of fault current limiting reactor used, and the difference between the system voltage and the TIV magnitude.

5.1.3.2 IMPULSE WITHSTAND TESTS

Lightning impulse voltage from ac circuit breaker standards of similar rating can be applied.

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Lightning impulse superimposed on nominal dc voltage across open switch could also be applied. Otherwise, test values determined by a system insulation coordination study may be applied.

5.2 OPERATIONAL TESTS

Operational tests verify the HVDC CB's ability to withstand any of the stresses resulting from normal operation, complementing the dielectric tests with current stress i.e. thermal stresses.

5.2.1 MEASUREMENT OF RESISTANCE OF NORMAL CURRENT PATH

Different HVDC CB technologies are, amongst others, distinguished by the losses in the normal current path. In case the technology consists of power electronics in the normal current path (as is for example the case in the hybrid breakers), the total resistance of the normal current path includes the equivalent resistance of the series/parallel connected power electronic components as well as the resistance of the fast disconnectors.
The measurement can be done using a low voltage micro-Ohm meter.

The measurement can be done separately on a single normal current path component, the series inductor, and the residual current breaker. The total full pole resistance can then be found by adding the multiplying the resistance of a single normal current path component with the number of modules in a full pole, and adding this to the resistance of the series inductor and the residual current breaker.

5.2.2 MEASUREMENT OF ON-STATE POWER LOSSES

Different HVDC CB technologies are, amongst others, distinguished by the normal current path losses. In case the technology has any power electronics in the normal current path (as is for example the case in the hybrid breakers and power electronic breakers), the on-state power losses should be measured.

As the power losses are in part determined by the forward voltage drop of any power electronic components, the measurement should be done by measuring the voltage drop for a range of DC load current values, assuming no modulation of the power electronics occurs during normal operation.

5.2.3 TEMPERATURE RISE TEST

The HVDC CB should be able to withstand the rated load current for a long duration without experiencing a temperature rise which will lead to pre-mature or excessive thermal ageing. This is verified by applying the rated normal current for a sufficiently long time after thermal equilibrium is achieved and the HVDC CB's operating temperature has stabilised for a certain amount of time. The temperature of the critical parts of the HVDC CB is measured and compared to maximum operating temperatures.

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The measurement can be done at low voltage but at full load current. If no power electronics exist in the normal current path, the AC current with RMS value equal to the DC rated current may be used (in such case series inductor may need to be removed).

The measurement should be done on at least each complete smallest part of a HVDC CB which is thermally coupled. This practically means on every different type of structure in which components or subcomponents are installed on the same heatsink or are coolant flow series connected heatsinks. If components are demonstrably not thermally coupled, the tests may be carried out on each component separately.

In case the test object contains any redundant components in the normal current path, the test current should pass through the main normal current path of the component and not be bypassed.

The temperature rise test and the measurement of on-state power losses can be combined.

5.2.4 SHORT-TIME CURRENT WITHSTAND TEST

If the HVDC CB is specified to withstand temporary overcurrent, a short-time current withstand test should be performed to verify that the HVDC CB and its subparts do not exceed maximum operating temperatures and can continue normal operation afterwards.

The components in the normal current path should be pre-conditioned by bringing them to a thermal equilibrium and then applying the rated overcurrent for the rated duration. Any coolant should be in a condition representative of the most onerous service condition for the purpose of the test [4]. Test factors may be applied. Different current withstand levels may be defined as shown in Figure 5-1. The duration of each current withstand level should be defined whilst respecting the peak pulsed current ratings of any power electronics in the normal current path. For AC circuit breakers, the duration and the value of current are determined from $I_t^2 X t_t$, where I_t is the r.m.s value of the current and t_t is its duration [2]. After application of the overcurrent, normal load current should be applied for a pre-determined time.

The measurement should be done on at least each complete smallest part of a HVDC CB which is thermally coupled. This practically means on every different type of structure in which components or subcomponents are installed on the same heatsink or are coolant flow series connected heatsinks, with all components installed.

The current magnitude and durations to be applied can be derived from load flow studies determining the increased load currents which can flow in emergency operation or from fault analysis to determine the fault current for a downstream but out of jurisdiction fault.

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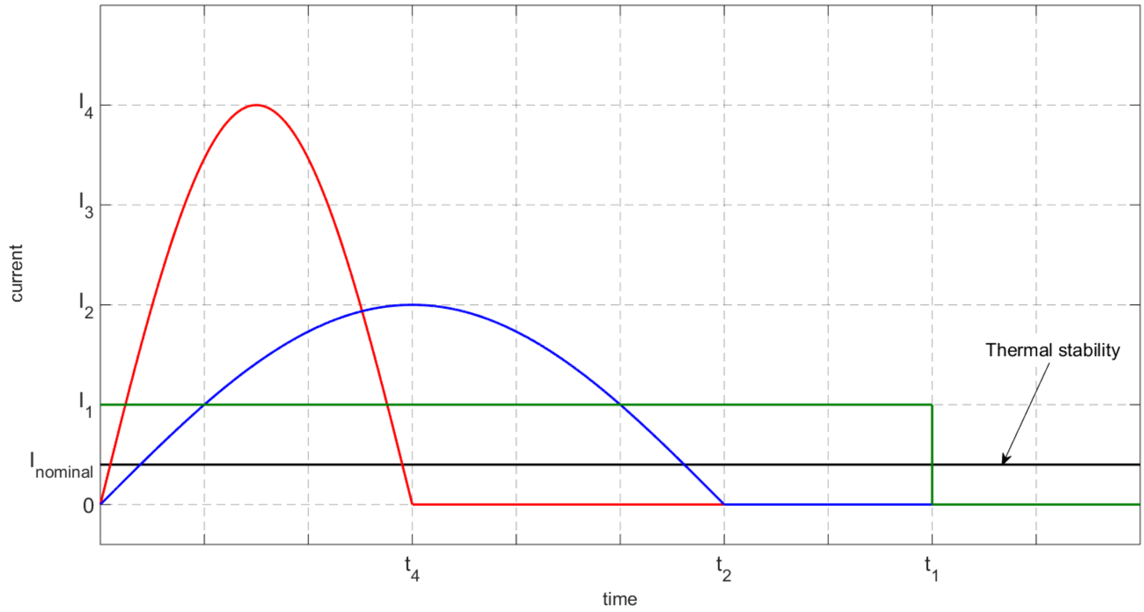

Figure 5-1: Short-time current withstand tests, different current withstand levels applied for different durations.

5.3 MAKING AND BREAKING TESTS

5.3.1.1 CLOSING ONTO ENERGISED LINE

Closing onto an energised line may be done by the HVDC CB instead of by specialised making components such as line-insertion resistors (for example in hybrid HVDC circuit breakers current limiting mode can be used). If this functionality is considered to be part of the HVDC CB, it may be tested by applying steady state voltages to each side of the breaker with a difference equal to the difference between maximum and minimum operating voltage of the HVDC system, and then applying a close command.

5.3.1.2 CLOSING ONTO DE-ENERGISED LINE

Some HVDC CBs may be able to energise a line without using pre-insertion resistors or other separate line charging equipment. This functionality may be tested by using the HVDC CB to charge a capacitance equal to that of the line to which it will be connected.

5.3.1.3 DC SHORT-CIRCUIT CURRENT INTERRUPTION TEST

Here the rated breaking current shall be specified along with breaker operation time. As DC short-circuit current interruption involves generation of the TIV by the circuit breaker as well as the energy absorption simultaneously, the rated values of the latter also need to be specified. Figure 5-2 depicts the waveforms (current, voltage and energy) during current interruption by HVDC circuit breaker. The breaker receives a trip

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order at time t_2. From t_2 until t_3 represents the breaker operation time. The breaker operation time is important parameter here and it should be specified.

The test shall supply the rated breaking current at the end of breaker operation time (at t_3 in Figure 5-2). However, depending on circuit breaker technology, there might be upper limit on the magnitude of initial current at the moment of reception of trip signal (at t_2 in Figure 5-2). For instance, for hybrid HVDC circuit breakers, the current shall not exceed the rated withstand and breaking current of power electronic components in the normal current path. Also, some pre-conditioning may be applied to bring the normal current branch of the breaker to thermal equilibrium before interruption tests are carried out.

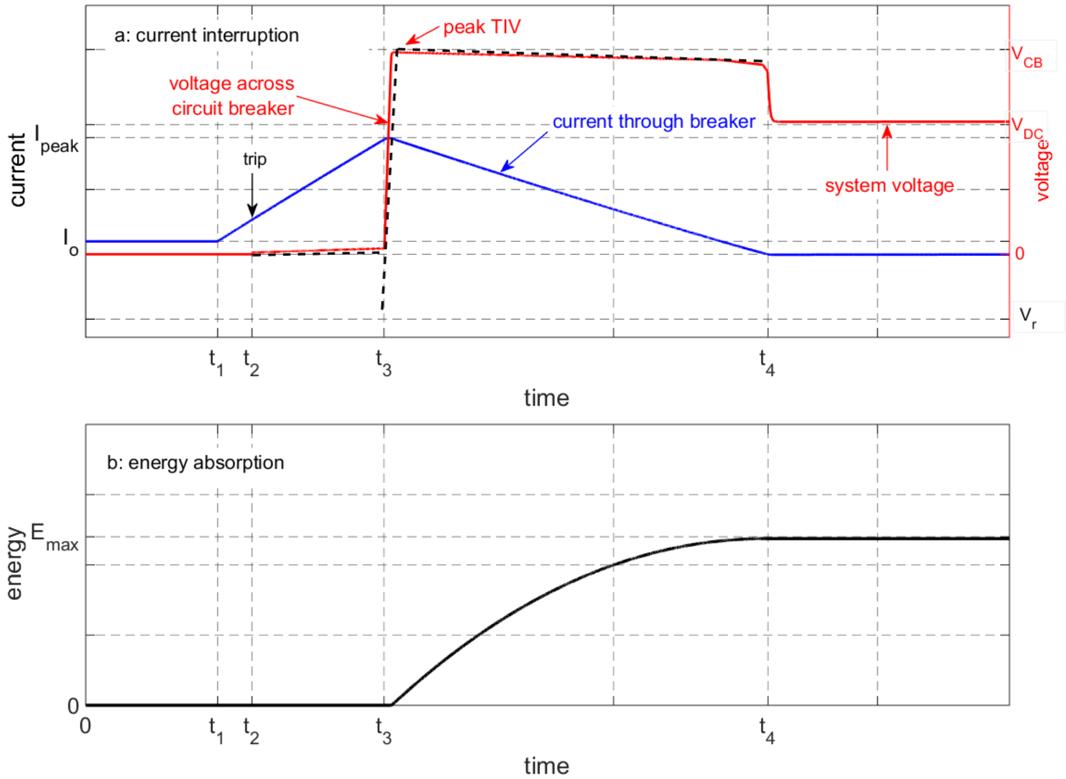

Figure 5-2: Short-circuit current interruption by HVDC circuit breakers

As described in Section 3.2.6, the circuit breaker shall be capable of breaking any current up to its rated breaking current. In some breaker technologies interrupting low current might be challenging compared to interrupting rated breaking current.

For AC circuit breakers, different test duties are specified as percentages of rated breaking current, e.g. T10 is test duty at 10% of the rated breaking current [3]. Similar approach can be applied to HVDC circuit breakers with specified rated breaking current. However, the main difference for HVDC circuit breaker, compared to test duties of AC circuit breakers, is that particular attention should be paid to the energy absorbed during each of

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the test duties. Under no circumstances the energy absorption during each of the test duties shall exceed the rated energy absorption capability of the breaker.

Although it is determined by the circuit breaker itself, the rated TIV of the HVDC circuit breaker shall also be specified. Clearly the TIV needs to be higher than the rated voltage of the system for which the breaker is intended (see Figure 5-2). In some cases, the TIV starts at negative initial value and rise to positive peak (see the dashed curve in Figure 5-2. However, the generation of the proper TIV by the circuit breaker needs to be verified by the test. It may also be necessary to test the generation of the TIV repeatedly as the material property of energy absorption branches could change.

During current breaking the circuit breaker absorbs the system energy as shown in Figure 5-2. The rated energy absorption of the circuit breaker has to be specified and while producing rated breaking current, tests shall fulfil the energy absorption requirement as well.

An important part of the HVDC circuit breaker performance is to commutate the current from one branch into another succesfully. The stray inductances between paths are one of the factors determining the speed of commutation. Current commutation may be verified by carrying out short-circuit current interruption tests with reduced energy absorption ratings i.e. smaller surge arrestors.

5.3.1.4 RECLOSING ONTO SHORT-CIRCUIT

Depending on transmission line type on which it is installed, a HVDC circuit breaker may need to reclose after a defined re-closure time. It may reclose while the fault still persists in the system. If the breaker is equipped with such functionality, it needs to be verified through testing for a defined number and timing of operations. In case the re-closing functionality is not part of the DC circuit breaker but of a separate device such as a pre-insertion resistance, then this will be tested separately.

Reclosing functionality mainly affects the energy absorption rating of the HVDC circuit breaker and its control & protection system (timing, and need for control of additional circuitry). These aspects may be tested separately.

5.3.2 SELF-PROTECTION

Some components of HVDC circuit breakers may be damaged if the current flowing through the branch containing these elements exceeds certain threshold for certain duration. If for some reason the protection system fails to send a trip order and/or if the trip order is delayed, the breaker itself should be able to interrupt current to avoid damage to its components. This puts stringent requirement of HVDC circuit breaker as the current under these circumstances could grow to a much higher value than the rated interrupted current. Thus, there should be sufficient margin between rated interruption current and self-protection so as to ensure

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unnecessary trips and avoid damage as well. The breaker can be tested for self-protection if such margin is clearly defined by the manufacturer of the equipment.

5.4 ENDURANCE TESTS

5.4.1 MECHANICAL ENDURANCE

The number of mechanical operations that a circuit breaker is able to carry out before programmed maintenance specified by the manufacturer. For AC circuit breakers, this is defined based of circuit breaker class (M1, M2), etc. [3]. Mechanical endurance tests are carried out without current in the main circuit. The number of mechanical operations shall be specified by the manufacturer the breaker.

5.4.2 ELECTRICAL ENDURANCE

The number of operations (close -open) that a circuit breaker can perform before maintenance is necessary. This is performed under rated service current condition. The number of operations that a circuit breaker can perform before maintenance shall be defined by the manufacturer.

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6 CONCLUSIONS

There are limited pre-standardization activities related with HVDC circuit breakers. CIGRE joint working group A3/B4.34 recently published a technical brochure on requirements and technical specification of state-of the art HVDC switchgear. The terms and definitions provided in this document as well as other deliverables of WP5 are are taken from this technical brochure (CIGRE JWG A3/B4.34 TB no. 683).

As for any power equipment, the ratings, normal service conditions design and construction shall be specified for HVDC circuit breakers. The range of tests applicable to HVDC circuit breakers to verify its performance and operation are provided along with their definitions. The type of tests applicable to different technologies HVDC circuit breaker categorized into dielectric, operational, making and breaking and endurance tests are described. This may not be exhaustive list of HVDC circuit breaker requirements and there might be unforeseen requirements in the future; however, it can serve as starting point towards standardization of the requirements of HVDC circuit breakers.

In PROMOTioN project, the main focus is demonstration of DC current interruption performance of HVDC circuit breakers. In deliverable 5.5 test procedures for the tests discussed in this document are discussed and in deliverable 5.6, test circuits potentially applicable for dc current breaking capabilities of HVDC circuit breakers are discussed.

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