

TECHNICAL SPECIFICATION



**High voltage direct current (HVDC) power transmission – System requirements
for DC-side equipment
Part 1: Using line-commutated converters**



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**High voltage direct current (HVDC) power transmission – System requirements
for DC-side equipment
Part 1: Using line-commutated converters**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

HIGH VOLTAGE DIRECT CURRENT (HVDC) POWER TRANSMISSION – SYSTEM REQUIREMENTS FOR DC-SIDE EQUIPMENT

Part 1: Using line-commutated converters

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IEC TS 63014, which is a Technical Specification, has been prepared by IEC technical committee 115: High Voltage Direct Current (HVDC) transmission for DC voltages above 100 kV.

The text of this Technical Specification is based on the following documents:

Enquiry draft	Report on voting
115/167/DTS	115/178/RVDTS

Full information on the voting for the approval of this technical specification can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific document. At this date, the document will be

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HIGH VOLTAGE DIRECT CURRENT (HVDC) POWER TRANSMISSION – SYSTEM REQUIREMENTS FOR DC-SIDE EQUIPMENT

Part 1: Using line-commutated converters

1 Scope

This Technical Specification is intended to provide an overall and consistent set of guidelines to facilitate the specification of equipment for the DC-side of a high-voltage direct current (HVDC) system using line-commutated converters. For point-to-point HVDC transmission systems, this document covers all DC-side equipment located between the converter valves and the DC overhead line or cable termination, excluding the converter valves themselves. For back-to-back HVDC systems, this document covers all DC-side equipment excluding the converter valves themselves. Throughout this publication, the terms 'direct voltage' and 'DC voltage' are used interchangeably, as are 'direct current' and 'DC current'.

Traditionally, the largest items of such equipment, such as the DC smoothing reactor and DC harmonic filters, have generally been located outdoors but increasingly the trend is to locate such equipment indoors (although not in the valve hall itself) to provide protection from pollution. Although product standards exist for some DC-side equipment types, many such items of equipment have only standards written for AC applications and, in such cases, the purpose of this document is to provide guidance as to how to specify the additional requirements (particularly with regard to testing) for such equipment to cover their use in DC conditions.

The converter itself is excluded from this scope, being covered by IEC 60700-1 [1]¹ and IEC 60700-2 [2].

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.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60060-1, *High-voltage test techniques – Part 1: General definitions and test requirements*

IEC 60071-1, *Insulation co-ordination – Part 1: Definitions, principles and rules*

IEC 60071-5, *Insulation co-ordination – Part 5: Procedures for high-voltage direct current (HVDC) converter stations*

¹ Numbers in square brackets refer to the Bibliography.

IEC 60076-6:2007, *Power transformers – Part 6: Reactors*

IEC 60099-9:2014, *Surge arresters – Part 9: Metal-oxide surge arresters without gaps for HVDC converter stations*

IEC 60168, *Tests on indoor and outdoor post insulators of ceramic material or glass for systems with nominal voltages greater than 1000 V*

IEC 60353, *Line traps for a.c. power systems*

IEC 60358-1, *Coupling capacitors and capacitor dividers – Part 1: General rules*

IEC 60383 (all parts), *Insulators for overhead lines with a nominal voltage above 1 000 V*

IEC 60437, *Radio interference test on high-voltage insulators*

IEC 60633, *Terminology for high-voltage direct current (HVDC) transmission*

IEC TS 60815-4, *Selection and dimensioning of high-voltage insulators intended for use in polluted conditions – Part 4: Insulators for d.c. systems*

IEC 60871-1:2014, *Shunt capacitors for a.c. power systems having a rated voltage above 1 000 V – Part 1: General*

IEC 60871-4:2014, *Shunt capacitors for AC power systems having a rated voltage above 1 000 V – Part 4: Internal fuses*

IEC TS 61245, *Artificial pollution tests on high-voltage ceramic and glass insulators to be used on d.c. systems*

IEC 61462, *Composite hollow insulators – Pressurized and unpressurized insulators for use in electrical equipment with rated voltage greater than 1 000 V – Definitions, test methods, acceptance criteria and design recommendations*

IEC 61466 (all parts), *Composite string insulator units for overhead lines with a nominal voltage greater than 1 000 V*

IEC 61850-9-2, *Communication networks and systems for power utility automation – Part 9-2: Specific communication service mapping (SCSM) – Sampled values over ISO/IEC 8802-3*

IEC 61869-9, *Instrument transformers – Part 9: Digital interface for instrument transformers*

IEC 61869-14, *Instrument transformers – Part 14: Specific requirements for DC current transformers²*

IEC 61869-15, *Instrument transformers – Part 15: Specific requirements for DC voltage transformers³*

IEC TS 61936-2, *Power installations exceeding 1 kV AC and 1,5 kV DC – Part 2: DC*

² Under preparation. Stage at the time of publication: IEC/FDIS 61869-14:2017.

³ Under preparation. Stage at the time of publication: IEC/FDIS 61869-15:2017.

IEC 62217, *Polymeric HV insulators for indoor and outdoor use – General definitions, test methods and acceptance criteria*

IEC 62231, *Composite station post insulators for substations with a.c. voltages greater than 1 000 V up to 245 kV – Definitions, test methods and acceptance criteria*

IEC 62271-1, *High-voltage switchgear and controlgear – Part 1: Common specifications for alternating current switchgear and controlgear*

IEC 62271-100:2008, *High-voltage switchgear and controlgear – Part 100: Alternating current circuit-breakers*

IEC 62271-102:2001, *High-voltage switchgear and controlgear – Part 102: Alternating current disconnectors and earthing switches*

IEC 62271-109:2008, *High-voltage switchgear and controlgear – Part 109: Alternating-current series capacitor by-pass switches*

IEC 62772, *Composite hollow core station post insulators for substations with a.c. voltage greater than 1 000 V and d.c. voltage greater than 1 500 V – Definitions, test methods and acceptance criteria*

IEC TS 62896, *Hybrid insulators for AC and DC for high-voltage applications – Definitions, test methods and acceptance criteria*

IEC Guide No. 111, *Electrical high-voltage equipment in high-voltage substations – Common recommendations for product standards*

IEC/IEEE 65700-19-03:2014, *Bushings for DC application*

3 Terms and Definitions

For the purposes of this document, the terms and definitions given in IEC 60633 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1 DC switching devices

3.1.1 Types of DC switching device

3.1.1.1

high-speed DC switch

type of switching device used on an HVDC scheme, required to open or close rapidly (<1 second), including in some cases the need to commutate load current into a parallel conducting path, but with no requirement to interrupt fault or load current

Note 1 to entry: DC switching devices are usually based on a single-phase unit of an AC circuit-breaker, appropriately modified for their DC applications. Their capabilities to perform faster opening and closing than disconnect switches are used but the function of breaking short-circuit currents is not required.

3.1.1.2

DC commutation switch

type of high-speed DC switch specifically designed to commutate load current into an alternative parallel current path

Note 1 to entry: The metallic return transfer switch (MRTS) and the earth return transfer switch (ERTS) defined in IEC 60633 are well-known examples of DC commutation switch.

3.1.1.3

mechanical switch

mechanical switching device forming part of a high-speed DC switch

3.1.2 Applications of DC switching devices

3.1.2.1

neutral bus switch

NBS

DC commutation switch connected in series with the neutral bus on a bipolar HVDC scheme, designed to commutate current out of the pole conductor or neutral bus and into the electrode line or dedicated metallic return conductor or earth in response to a fault in a converter or neutral bus

3.1.2.2

neutral bus earthing switch

NBES

neutral bus ground switch

NBGS

DC commutation switch connected from the neutral bus to the station earth mat on a bipolar HVDC scheme, designed to provide a temporary earth connection in the event of an open-circuit fault on the electrode line until the imbalance of current between the two poles can be reduced to a safe minimum level or the electrode line connection can be restored

3.1.2.3

bypass switch

BPS

high-speed DC switch connected across each converter valve group in HVDC schemes using more than one independent converter per pole, designed to close rapidly to bypass a converter group that is being taken out of service and commutate the current back into a valve group that is being taken back into service

3.1.2.4

line paralleling switch

LPS

DC commutation switch placed in series with one or more high-voltage pole conductors, allowing two or more lines to be connected in parallel or to revert to single-line operation while conducting load current

3.1.2.5

converter paralleling switch

CPS

high-speed DC switch connected in series with each converter at the high-voltage DC terminal in HVDC schemes where two or more converters are connected in parallel onto a common pole conductor, designed to allow additional converter(s) to be connected in parallel or disconnected without affecting the load current in the other converter

3.2 Filter components

3.2.1 Filter capacitors

3.2.1.1

main DC filter capacitor

high-voltage DC filter capacitor which is exposed to a substantial direct voltage

3.2.1.2

auxiliary capacitor

LV filter capacitor

capacitor in a DC filter not exposed to direct voltage across its terminals (such as C2 in Figure 5)

3.2.1.3

DC neutral bus capacitor

capacitor connected between the DC neutral bus and the substation earth

3.2.1.4

DC surge capacitor

capacitor connected between the DC line and the substation earth (directly or indirectly) to serve the primary function of reducing the amplitude and steepness of lightning surges applied to the substation equipment

3.2.2 Filter resistors

3.2.2.1

resistor

power resistor forming part of some types of harmonic filter bank and connected in parallel and/or series with the LV filter capacitors and/or filter reactors, usually at the neutral side of the filter

3.2.2.2

resistor element

single part of resistor, which is not possible to be divided into smaller parts (such as a grid, a mat, a spring coil, etc. depending on the technology)

3.2.2.3

bank of resistor elements

mechanical assembly of several single elements electrically connected together, plus a mechanical structure, insulating parts, terminals, etc.

3.2.2.4

resistor module

part of the resistor in one enclosure (if applicable)

3.2.3

filter reactors

power reactor forming part of a harmonic filter bank, responsible (sometimes together with the LV filter capacitors, where used) for defining the tuned frequency(ies) of the filter bank and usually connected at the neutral side of the filter

3.3 Surge arresters

3.3.1

continuous operating voltage

COV

maximum continuous voltage characterized by the voltages CCOV, PCOV, DCOV and ECOV where applicable and that may be applied continuously between the arrester terminals

Note 1 to entry: Operation voltages of several arrester types can vary significantly during different operation conditions of the HVDC converters (e.g. depending on firing angles, tap position) as well as in different configuration of the DC system (e.g. metallic return configuration). The specified requirements shall consider the applicable operating conditions accordingly.

3.3.2

crest value of continuous operating voltage

CCOV

highest continuously occurring crest value of the voltage across the arrester excluding commutation overshoots and commutation notches and calculated with a system model valid for up to approximately 5 kHz

3.3.3

peak value of continuous operating voltage

PCOV

highest continuously occurring crest value of the voltage at the equipment on the DC side of the converter station including commutation overshoots, commutation notches and ripple calculated with a model which takes into account stray capacitances/inductances of converter transformers, valves, buswork, etc. and valid for at least 50 kHz

3.3.4

DC component of continuous operating voltage

DCOV

highest mean or average of the continuous operating voltage across the arrester excluding harmonics and commutation overshoots

3.3.5

equivalent continuous operating voltage

ECOV

RMS value of the sinusoidal power-frequency voltage or direct voltage at a metal-oxide surge arrester stressed by operating voltage of any wave shape that generates the same power losses in the metal-oxide material as the actual operating voltage

3.3.6

switching impulse protective level

SIPL

residual voltage of a surge arrester subjected to a discharge current corresponding to the coordination switching impulse current

3.3.7

lightning-impulse protective level

LIPL

residual voltage of a surge arrester subjected to a discharge current corresponding to the coordination lightning-impulse current

3.3.8

steep-front impulse protective level

SFIPL

STIPL

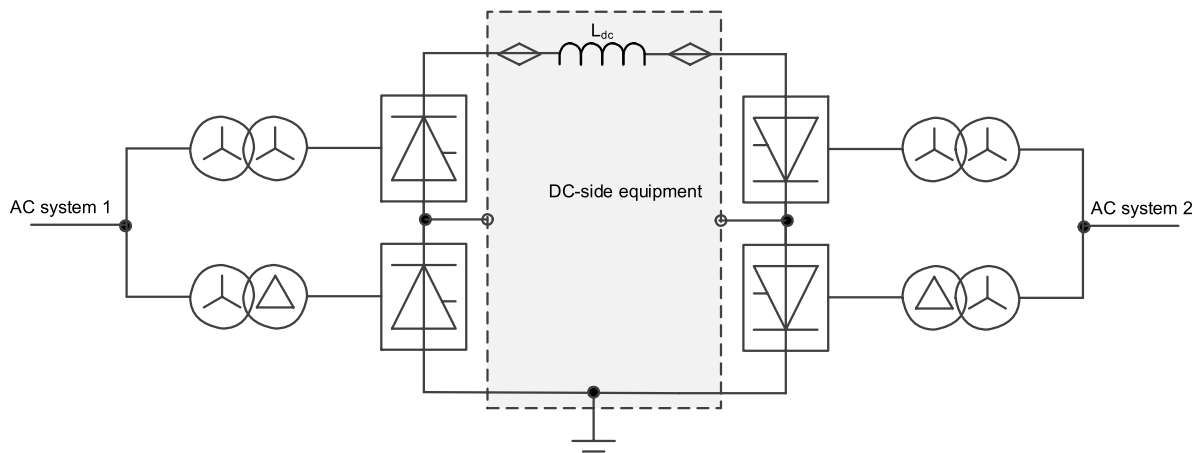
residual voltage of a surge arrester subjected to a discharge current corresponding to the coordination steep-front impulse current

4 General

4.1 Overview

"DC-side equipment" is the overall name given to a collection of high-voltage equipment located on the DC side of the HVDC converter in a converter station, excluding the converter itself.

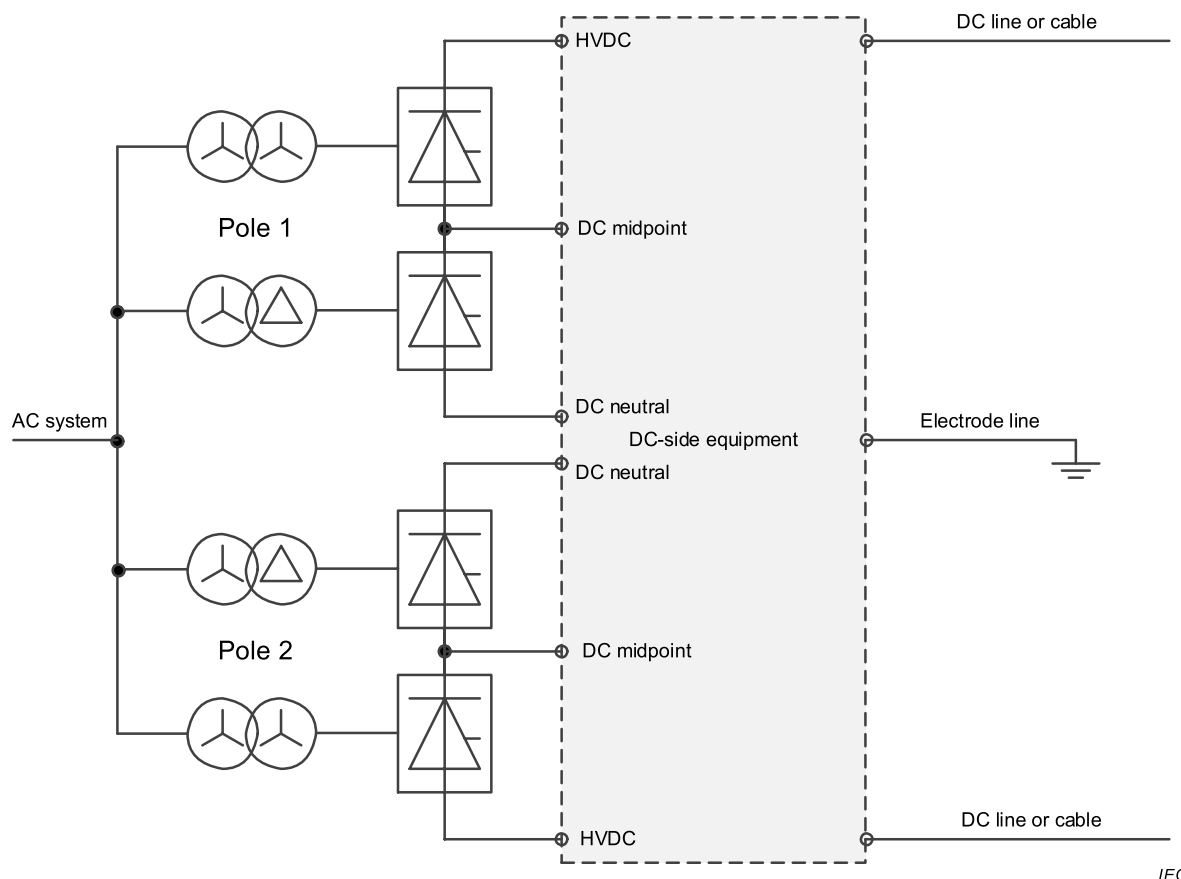
In a back-to-back HVDC converter station, the DC-side equipment (Figure 1) is relatively limited in extent, generally only comprising DC instrument transformers, valve and bridge surge arresters (inside), DC smoothing reactor (outside) and DC wall bushings interconnecting the DC smoothing reactor to the valve hall. Since there is no DC line that can be subject to frequent flashovers, the main function of the DC smoothing reactor in a back-to-back HVDC converter station is to prevent or limit the cross-modulation of harmonics from one AC system to the other. Some back-to-back HVDC converter stations have been built without DC smoothing reactors; in such cases, the only DC-side equipment are the DC instrument transformers and valve and bridge surge arresters.



IEC

Figure 1 – Scope of DC-side equipment for a back-to-back HVDC converter station with one 12-pulse bridge per end

In a converter station for a transmission HVDC scheme (Figure 2), the DC-side equipment is more extensive in scope. DC harmonic filters are usually required in order to prevent interference with nearby telephone systems, especially on DC overhead line schemes. Where fitted, DC harmonic filters generally occupy the largest amount of space of all DC-side equipment. DC smoothing reactors are always needed, their main function being to limit the amplitude and rate of change of current in the event of either a DC line fault or commutation failure. DC smoothing reactors for transmission schemes can be very large, with inductances of several hundred millihenries being common.



IEC

Figure 2 – Scope of DC-side equipment for a transmission HVDC converter station with one 12-pulse bridge per pole

The DC-side equipment for a transmission HVDC scheme usually also includes several types of DC switching devices, including DC disconnectors and several types of specialised "high-speed DC switch". The high-speed DC switches are normally derived from conventional AC circuit-breakers, but they are not circuit-breakers in the conventional sense of the word since they are not designed to break DC fault currents. Their function, instead, is typically to divert normal load current from one current path into another. There are many different applications of DC switching devices in a transmission HVDC scheme and these are described in greater detail in Annex B.

Finally, in transmission HVDC schemes that are equipped with earth electrodes to permit operation with an earth return current, the electrode line linking the converter station to the earth electrode may require additional DC filter equipment, surge capacitors, surge arresters and equipment to permit monitoring of the electrode line and detection of faults. Several common types of high-speed DC switch (for example the metallic return transfer switch) are associated with such applications.

Annex A provides more detailed descriptions of the purpose and typical characteristics of the various types of DC-side equipment.

Insulation coordination of the DC-side equipment is an important and complex topic. Basic principles are addressed in IEC 60071-5, but IEC TS 61936-2 also includes some common requirements related to safety and insulation coordination, for example clearance and creepage distances. In selecting insulation for DC systems, environmental conditions and pollution are very important aspects because of the tendency of DC equipment to attract airborne contamination. Pollution considerations for outdoor equipment are covered by IEC 60815-4. The creepage requirements for DC insulation vary greatly according to the level of atmospheric pollution. As a consequence, there can be major differences in creepage distance requirements depending on whether an insulator is located in a clean environment (the valve hall), a semi-clean environment (indoor DC yard, but separate from the valve hall) or a polluted outdoor environment.

4.2 Environmental conditions

Information about environmental conditions for the actual installation site of the converter station is relevant and can be vital to the design of the individual equipment. Equipment may be installed outdoors or indoors depending on the operation and project requirements. If both indoor and outdoor installations are applicable for the same project, the environmental conditions shall be clearly assigned to the individual application. IEC Guide No. 111 provides useful background information to aid in specifying environmental conditions.

The following data shall be specified as applicable:

- maximum dry bulb ambient temperature (°C);
- minimum dry bulb ambient temperature (°C);
- maximum wet bulb ambient temperature (°C);
- maximum 24-hour average dry bulb ambient temperature (°C);
- annual average ambient temperature (°C);
- minimum/maximum relative humidity;
- maximum wind speed (m/s);
- annual precipitation (mm);
- maximum precipitation in 24 hours (mm);
- maximum snow depth (cm);
- ice load (mm);
- solar radiation intensity (W/m²);
- soil resistivity(Ωm);
- pollution level / required creepage distances;
- type of pollutant (conducting/non-conducting; solid/liquid/gaseous);
- seismic requirements:
 - horizontal / vertical acceleration (m/s²);
 - seismic frequency spectra (if applicable);
 - relevant design standard and/or local building code.
- altitude above sea level
- keraunic level.

4.3 Choice of indoor versus outdoor DC yard

On most older HVDC schemes, up to about the year 2000, the DC-side equipment was located outside and the converter valves and their closely-associated valve and bridge surge arresters were located indoors, in the valve hall.

However, there has been a recent trend towards putting most or all of the DC-side equipment indoors, into an "indoor DC yard". In such cases, the DC-side equipment is usually not mounted in the valve hall itself (since this would be unnecessarily expensive) but in a separate annex to the converter building, usually specified with less-demanding requirements in terms of air quality and temperature/humidity control than the valve hall.

The main motivation for putting DC-side equipment indoors is to reduce the exposure of DC-side equipment to pollution and lightning strikes. This is much more important than with AC equipment because of the tendency of high-voltage DC equipment to attract pollution. By putting the DC-side equipment indoors (even in a room with relatively simple air-filtration systems compared with the valve hall), the level of pollution deposited on equipment can be dramatically reduced and since the insulation will not get wet, much shorter creepage

distances can sometimes be used. However, maintenance intervals should be considered since no washing by rain occurs indoors.

Indoor DC yards may therefore be preferable where there are:

- high levels of airborne pollution (coal dust is particularly troublesome, being highly conductive), or
- high levels of salt pollution, for example in coastal sites,
- high levels of sand pollution in desert sites,
- high risk of flashovers due to ingress of wildlife,
- high audible noise that may lead to complaints in public areas.

On the other hand, civil costs will be increased by specifying indoor DC yard equipment, so in sites with low levels of pollution but high civil costs, outdoor DC yard equipment will generally be more cost-effective. However, there is a possibility that the cost of an indoor installation is lower than that of an outdoor installation in the case of design conditions that require protection against both severe pollution and severe seismic conditions.

A secondary benefit of using indoor DC-side equipment is that audible noise emissions from the DC smoothing reactor and DC harmonic filters will be substantially reduced. However, if audible noise is the only consideration, providing a noise enclosure around the DC smoothing reactor will normally be a more cost-effective solution.

5 DC smoothing reactors

Requirements for DC smoothing reactors are defined in Clause 12 of IEC 60076-6:2007.

In addition, subject to agreement between the manufacturer and the purchaser, for dry-type air-cored reactors, the polarity reversal test can be a type test instead of a routine test and, as a consequence, the DC withstand routine test shall be performed twice, once with positive polarity and once with negative polarity.

6 DC switching devices

6.1 High-speed DC switches

6.1.1 General

HVDC transmission schemes typically include two types of fast-acting DC switches (with operating times generally of the order of 100 ms) on the DC side. These switches are commonly derived from conventional AC circuit-breakers but have additional requirements imposed by the DC current or voltage to which they are subjected. These DC switches are most commonly constructed from Air-Insulated Switchgear (AIS) but, for some applications, Gas-Insulated Switchgear (GIS) may be used. The first type of DC switch is not designed to break DC current but their fast switching action is required for protection, isolation and restoration of the interconnection. The other type of DC switch is capable of transferring DC load current into an alternative current path (for example, the metallic return transfer switch, MRTS, described in B.2.1).

Annex B describes the various different types of high-speed DC switch that may be used on an LCC HVDC scheme.

General requirements for AC circuit-breakers are defined in IEC 62271-100. However, no requirements related to DC applications are given in that standard.

The high-speed DC switches shall comply with the applicable technical standards for AC circuit-breakers and additional requirements specific to the DC application.

The basic switching requirements are:

- subsequent to the first arc extinction, no further arc shall occur across the main contacts of the high-speed switch;
- the opening of series main contacts on the complete switch assembly shall be synchronized sufficiently well to meet the requirements of the operating conditions;
- where the safe condition of the high-speed switch is in the closed position, the switch shall fail to the closed position. Under these conditions, the tripping of the switch shall be inhibited when subsequently there will be insufficient energy for a successful open-close operation.

The safe position of a switch is the position that should be reached in the event of a failure in order to prevent further consequential damage to the breaker or risk of injury to personnel. Taking the MRTS as an example, the safe position is the closed position since no arcing can take place and there is no risk of explosion. So in the event that an attempt to transfer the DC neutral current from the electrode line to the pole conductor does not succeed, the MRTS should be re-closed to avoid the risk of explosion.

NOTE In some applications, the auxiliary components associated with high-speed DC switches can include capacitors and reactors to create a resonant turn-off condition. The capacitor can, in addition, be pre-charged in order to speed up the switching process.

6.1.2 Comparison of operating duties

The main critical parameters for various types of DC switch application are summarised in Table 1. Explanations of the various types of DC switch, along with more detailed commentaries on the critical parameters for each, are given in Annex B.

Table 1 – Summary of main parameters affecting specification of high-speed DC switches

Parameter	MRTS ^a	ERTS	NBS	NBES	BPS	LPS	CPS
Current rating in closed position, permanent	●●○	●●○	●●○	●○○	●●○ ^b	●●○	●●○
Current rating in closed position, short duration	●●○	●●○	●●○	●●○	●●○	●●○	●●○
Current commutating ability	●●●	●●●	●●●	●○○	●●○	●●●	○○○
Voltage between terminals in open position	●●○	●○○ ^c	●○○	●○○	●●●	●●○	●●●
Voltage isolation to earth	●○○	●○○	●○○	●○○	●●●	●●●	●●●
Closing speed	●○○	●○○	●○○	●●●	●●●	●○○	●○○
Opening speed	●○○	●○○	●○○	●○○	●○○	●○○	●○○
Key:							
●●● = Critical							
●●○ = Important							
●○○ = Slight impact							
○○○ = Unimportant							
^a The MRTS and ERTS are also referred to as MRTB (metallic return transfer breaker) and ERTB (earth return transfer breaker) although these terms can be confusing since these switches have no ability to interrupt fault current.							
^b The steady-state current rating of the bypass switch can be alleviated by closing the parallel-connected disconnector, if installed.							
^c Where a dedicated metallic return is used in the system: ●●○ .							

6.1.3 Ratings

6.1.3.1 General

There are no applicable international standards for high-speed switches used in HVDC applications and therefore no complete set of standard rating definitions. However, such switches are usually based on AC circuit-breakers, for which IEC 62271-100 is applicable, and IEC 62271-100 can provide general guidance for some aspects of HVDC applications. There are, in addition, some ratings defined uniquely for DC switches. Table 2 summarises which ratings are covered by existing standards and which require specific definitions for HVDC.

Table 2 – Table of standard ratings in accordance with IEC 62271-100 and their applicability to high-speed DC switches

Name	Clause in IEC 62271-100:2008	Applicability to high-speed DC switches		
		Applicable without modification	Applicable with modification	Not applicable
Rated voltage (U_r)	4.1		✓	
Rated insulation level	4.2		✓	
Rated frequency (f_r)	4.3			✓
Rated normal current (I_r) and temperature rise	4.4		✓	
Rated short-time withstand current (I_k)	4.5		✓	
Rated peak withstand current (I_p)	4.6		✓	
Rated duration of short circuit (t_k)	4.7		✓	
Rated supply voltage of closing and opening devices and of auxiliary and control circuits (U_a)	4.8	✓		
Rated supply frequency of closing and opening devices and auxiliary circuits	4.9	✓		
Rated pressures of compressed gas supply for insulation, operation and/or interruption	4.10	✓		
Rated short-circuit breaking current (I_{sc})	4.101			✓
Transient recovery voltage related to the rated short-circuit breaking current	4.102			✓
Rated short-circuit making current	4.103		✓	
Rated operating sequence	4.104		✓	
Characteristics for short-line faults	4.105			✓
Rated out-of-phase making and breaking current	4.106			✓
Rated capacitive switching currents	4.107		✓	
Inductive load switching	4.108			✓
Opening time	4.109		✓	
Closing time	4.109		✓	
Number of mechanical operations	4.110		✓	
Classification of circuit-breakers as a function of electrical endurance	4.111			✓

6.1.3.2 Modified ratings

6.1.3.2.1 General

The following ratings are modified for HVDC applications of high-speed DC switches and therefore differ from the equivalent standard ratings defined in IEC 62271-100.

6.1.3.2.2 Equivalent (AC) rated voltage (U_{requiv})

Although not recommended, where necessary in order to define other ratings of the DC switch, the equivalent AC rated voltage may be taken to be the next applicable standard AC rated voltage higher than the maximum operating direct voltage at the specific location of operation.

6.1.3.2.3 Rated insulation level

Insulation levels for HVDC equipment are generally not standard levels as for AC equipment but instead are defined by the insulation coordination study for the project.

Insulation levels shall be defined for both lightning and switching impulse wave shapes and may be defined separately for the following two cases:

- between open terminals;
- between terminals and earth. For testing purposes, it may be necessary to define insulation levels separately for the cases with open and closed contacts.

6.1.3.2.4 Rated normal current (I_r) and temperature rise

In the context of high-speed DC switches, rated normal current is defined as the maximum continuous DC current experienced by the equipment in the closed position.

6.1.3.2.5 Rated short-time withstand current

The rated short-time withstand current is the RMS value to which the switching device is subjected in its closed position under short-circuit conditions. It depends on system specific parameters and should be determined by system studies.

6.1.3.2.6 Rated peak withstand current

The rated peak withstand current is the initial current crest value to which the switching device is subjected in its closed position under short circuit conditions. It depends on system-specific parameters and should be determined by system studies.

6.1.3.2.7 Rated duration of short circuit

The rated duration of short circuit is the interval of time to which the switching device is subjected in its closed position. It depends on system-specific parameters and should be determined by system studies.

6.1.3.2.8 Rated overload current ($I_{r_overload}$)

The rated overload current is the maximum short-duration overload current to which the DC switch can be subjected in operation in the closed position. Between two applications of overload currents, a cooling time is needed for the DC switch to reach the standard load conditions. This cooling time shall be specified by the manufacturer

6.1.3.2.9 Rated short-circuit making current

In the context of high-speed DC switches, the standard values of short-circuit making current defined in IEC 62271-100 do not apply. The rated short-circuit making current for each type of DC switch shall be determined by studies for the HVDC project in question.

6.1.3.2.10 Rated operating sequence

As opposed to the AC circuit-breaker whose function is to break and interrupt fault current, the function of a DC switch is to isolate the system or commutate current. In this application, the ability of the DC switch to close or reclose is important for the protection of the device.

Switches that are required to carry or commutate DC current can have protection schemes that will initiate an auto-reclose if the DC current is not below a predetermined level. The reclosing cycle (dead time) shall be as short as possible to avoid the excessive arc energy that can appear when failing to commutate DC current.

However, DC switches generally do not require the multiple open-close-open cycles that are typical of conventional AC circuit-breakers. The rated operating sequence should therefore be determined on a case by case basis taking into account how the DC switch is to be used. The total number of operations under load conditions and the dead time between two opening operations should be given by the manufacturer of mechanical switch and surge arresters.

6.1.3.2.11 Rated capacitive switching current

The rated capacitive switching current for a DC switch is related to the capacitance that can be discharged as a result of switch operation, and should be determined by system studies.

6.1.3.2.12 Opening time

In the context of high-speed DC switches, the rated opening time is the interval of time between the instant of energising the opening release, the switch being in the closed position, and the instant when the contacts have separated.

NOTE This rating is equivalent to the opening time defined in 3.7.133 (a) of IEC 62271-100:2008 except that the DC switch is effectively a single-pole device and it is therefore not appropriate to define the time based on the opening of all poles.

6.1.3.2.13 Closing time

In the context of high-speed DC switches, the rated closing time is the interval of time between energising the closing circuit, the switch being in the open position, and the instant when the contacts touch.

NOTE This rating is equivalent to the closing time defined in 3.7.136 of IEC 62271-100:2008 except that the DC switch is effectively a single-pole device and it is therefore not appropriate to define the time based on the closing of all poles.

6.1.3.2.14 Number of mechanical operations

DC switches do not operate more frequently than AC circuit-breakers (no normal operation under load or no-load conditions). Therefore two classes of mechanical endurance are defined for mechanical switches:

- M0 with 1 000 operation sequences, for mechanical switches designed for duties requiring a normal number of operations;
- M1 with 2 000 operation sequences, for mechanical switches designed for special service duties requiring enhanced numbers of operations.

The number of operations to be expected also depends on the switch function (i.e. whether it is an MRTS, BPS or other application) and should therefore be specified by the purchaser separately for each switch type.

6.1.3.3 Additional ratings specific to HVDC

6.1.3.3.1 General

The following ratings are specific to HVDC applications of high-speed DC switches and therefore have no equivalent in IEC 62271-100.

6.1.3.3.2 Rated direct voltage (U_{rdc})

The rated direct voltage is defined as the maximum continuous direct operating voltage. For DC switching devices, a rated voltage to earth as well as a rated voltage between terminals need to be specified. Rated direct voltages for HVDC equipment are generally not standard levels as for AC equipment, but instead are defined by the design studies for the project. Rated direct voltages are typically a few percent higher than the nominal direct voltage in order to allow for measurement errors and control imbalances.

6.1.3.3.3 Rated direct voltage between open terminals (U_{rdcp})

Maximum direct voltage appearing between the terminals of an open DC switch in operation.

6.1.3.3.4 Rated direct voltage from terminals to earth (U_{rdce})

Maximum direct voltage appearing between one or both terminals of a DC switch and earth in operation. In some applications (for example bypass switches), this rating can differ between the cases where the contacts are open or closed.

6.1.3.3.5 Maximum commutating current

The maximum direct current that the complete DC switch is required to commute safely to a parallel conducting path.

NOTE The commutating current rating applies to the complete DC switch assembly including the parallel resonant LC circuits and surge arresters as appropriate.

6.1.4 Tests

6.1.4.1 General

Presently, there are no international testing standards specifically developed for high-speed DC switches. Where they are composed of AC circuit-breakers, the following testing requirements are applicable.

The testing requirements and common specification for AC circuit-breakers are included in parts 1, 100, 102 and 109 of the IEC 62271 series.

In general, all clauses of the above-referenced standards are applicable to DC switches except where stated in the 6.1.4.2 to 6.1.5.5.

6.1.4.2 Type test

6.1.4.2.1 General

All of the applicable testing requirements outlined in IEC 62271-100 shall be followed. In addition to performing the test at power frequency, the test shall also be performed by applying the appropriate direct voltage as described below.

Tables 3 to 6 summarise the dielectric type tests to be performed on four types of high-speed DC switch: commutation switches (such as MRTS), bypass switch, converter paralleling switch and line paralleling switch.

The dielectric type tests shall be performed on a completely assembled switch mounted on a supporting structure, including grading elements if the switch is normally equipped with these. Where terminals are specified to be floating, the potential of the floating terminal shall be adjusted according to the theoretical voltage distribution across the open switch by suitable measures.

6.1.4.2.2 Calculation of test voltages

For tests that are performed with direct voltages, test voltages shall be calculated by multiplying the applicable rated direct voltage (U_{rdcp} or U_{rdce}) given in 6.1.3.3 by the test safety factors stated in Tables 3 to 6.

NOTE Unlike AC systems, the term "rated voltage" in an HVDC system is project-specific and is related to the maximum direct operating voltage to earth of the HVDC system.

For power-frequency voltage tests, the provisions in the existing IEC standards shall be followed. For impulse tests, the test levels are defined from insulation coordination studies.

Figure 3 explains the notation used in the tables in respect of where the test voltages are applied.

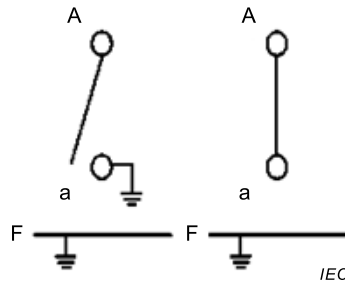


Figure 3 – Key for application of test voltages

6.1.4.2.3 Conditions of switching device during dielectric tests

Dielectric tests shall be made on the mechanical switch completely assembled, as in service; the outside surfaces of insulating parts shall be in a clean condition. The mechanical switch shall be mounted for test with minimum clearances and height as specified by the manufacturer.

Tests are valid if the height above ground during the tests is less than or equal to the height used in service.

When the manufacturer states that supplementary insulation such as tape or barriers is required to be used in service, such supplementary insulation shall also be used during the tests.

If arcing horns or rings are required for the purpose of system protection, they may be removed or their spacing increased for the purpose of the test. If they are required for voltage grading, they shall remain in position for the test.

For mechanical switches using compressed gas for insulation, dielectric tests shall be performed at minimum functional pressure (density) for insulation as specified by the manufacturer. The temperature and pressure of the gas during the tests shall be noted and recorded in the test report.

WARNING – In the dielectric testing of mechanical switches incorporating vacuum switching devices, precautions should be taken to ensure that the level of possible emitted X-radiation during high-voltage testing is within safe limits. National safety codes can influence the safety measures established.

6.1.4.2.4 Direct voltage withstand test (dry and wet)

a) Test procedure:

1 hour, each polarity. Wet tests are applicable only for outdoor designs.

b) Pass criteria:

No disruptive discharge.

c) Test conditions:

As defined in Table 3.

Table 3 – Test conditions for direct voltage test

Switch condition	Voltage applied to	Earthed terminals	Floating terminal	Test voltage	Applicability to various switch types ●=Mandatory; ○=Applicable if specified; ○=Not applicable			
					Commutation switch	By-pass switch	Converter paralleling switch (CPS)	Line paralleling switch (LPS)
Closed	Aa	F		$1,5 \times U_{rdce}$	●	○	●	●
Open	A	aF		$1,5 \times U_{rdcp}$	●	●	●	●
	A	F	a	$1,5 \times U_{rdce}$	○	○	○	○
	a	AF		$1,5 \times U_{rdcp}$	●	●	●	●
	a	F	A	$1,5 \times U_{rdce}$	○	○	○	○

6.1.4.2.5 Partial discharge test

a) Test procedure:

1 hour, each polarity. No separate partial discharge test is necessary if PD measurement is performed during DC withstand voltage test under dry condition.

b) Pass criteria:

No more than 10 pulses of partial discharge with magnitude equal to or greater than 2 000 pC are recorded during the last 10 min of the test. Pulses that are proven to be external to the test object shall be disregarded.

c) Test conditions:

As defined in Table 4.

If switches are part of a DC GIS, the requirements should be agreed between the manufacturer and the purchaser.

Table 4 – Test conditions for partial discharge test

Switch condition	Voltage applied to	Earthed terminals	Floating terminal	Test voltage	Applicability to various switch types ●=Mandatory; ○=Applicable if specified; ○=Not applicable			
					Commutation switch	By-pass switch	Converter paralleling switch (CPS)	Line paralleling switch (LPS)
Closed	Aa	F		$1,3 \times U_{rdce}$	●	○	●	●
Open	A	aF		$1,3 \times U_{rdcp}$	●	●	●	●
	A	F	a	$1,3 \times U_{rdce}$	○	○	○	○
	a	AF		$1,3 \times U_{rdcp}$	●	●	●	●
	a	F	A	$1,3 \times U_{rdce}$	○	○	○	○

6.1.4.2.6 Polarity reversal test

a) General

In some designs of switch, the polarity reversal test is not critical, for example live-tank designs in which there is no highly stressed solid dielectric material in the insulating gap of the switch. In such cases, the polarity reversal test may be omitted with the agreement of the purchaser and the manufacturer.

b) Test procedure:

90 min; change polarity; 90 min; change polarity; 45 min. Time for polarity reversal shall be agreed between the manufacturer and the purchaser.

c) Pass criteria:

No more than 10 pulses of partial discharge with magnitude equal to or greater than 2 000 pC are recorded during any 10-min period of the test. Pulses that are proven to be external to the test object shall be disregarded. The time during which polarity is being reversed is not considered to be part of the test and data collected during this period is not considered to be relevant.

d) Test conditions:

As defined in Table 5.

If switches are part of a DC GIS, the requirements should be agreed between the manufacturer and the purchaser.

Table 5 – Test conditions for polarity reversal test

Switch condition	Voltage applied to	Earthed terminals	Floating terminal	Test voltage	Applicability to various switch types			
					Commutation switch	By-pass switch	Converter paralleling switch (CPS)	Line paralleling switch (LPS)
Closed	Aa	F		$1,25 \times U_{rdce}$	●	○	●	●
Open	A	aF		$1,25 \times U_{rdcp}$	●	●	●	●
	A	F	a	$1,25 \times U_{rdce}$	○	○	○	○
	a	AF		$1,25 \times U_{rdcp}$	●	●	●	●
	a	F	A	$1,25 \times U_{rdce}$	○	○	○	○

6.1.4.2.7 Radio Interference Voltage (RIV) test

a) Test procedure:

The test is performed generally as described in IEC 62271-1. A voltage of $1,1 \times$ the applicable rated direct voltage (U_{rdce} or U_{rdcp} as appropriate) shall be applied to the switch and maintained for at least 5 min. The voltage shall then be decreased by steps down to $0,3 \times$ the applicable rated direct voltage, raised again by steps to the initial value and finally decreased by steps to $0,3 \times$ the applicable rated direct voltage. At each step, a radio interference measurement shall be taken and the radio interference level, as recorded during the last series of voltage reductions, shall be plotted versus the applied voltage; the curve so obtained is the radio interference characteristic of the switch. The amplitude of voltage steps shall be approximately $0,1 \times$ the applicable rated direct voltage.

b) Pass criteria:

The switch shall be considered to have passed the test if the radio interference level at $1,1 \times$ the applicable rated direct voltage does not exceed 2 500 μ V.

c) Test conditions:

As defined in Table 6.

Table 6 – Test conditions for RIV test

Switch condition	Voltage applied to	Earthed terminals	Floating terminal	Test voltage	Applicability to various switch types			
					Commutation sSwitch	By-pass switch	Converter paralleling switch (CPS)	Line paralleling switch (LPS)
Closed	Aa	F		$1,1 \times U_{rdce}$	●	○	●	●
Open	A	aF		$1,1 \times U_{rdcp}$	●	●	●	●
	A	F	a	$1,1 \times U_{rdce}$	○	○	○	○
	a	AF		$1,1 \times U_{rdcp}$	●	●	●	●
	a	F	A	$1,1 \times U_{rdce}$	○	○	○	○

RIV tests are not applicable to switches where both terminals operate at <100 kV with respect to the earth.

Subject to agreement between the purchaser and the manufacturer, RIV tests may be performed using an alternating voltage source as described in IEC 62271-1, instead of direct voltage. In this case, the RMS value of the alternating test voltage shall be the direct test voltage divided by $\sqrt{2}$.

6.1.4.2.8 Lightning-impulse withstand test

a) Test level:

The rated lightning-impulse withstand voltage to earth (U_{pe}) or across the open switch (U_{pp}), as appropriate.

b) Test procedure:

The test is performed generally as described in IEC 62271-1. 15 impulses, each polarity.

c) Pass criteria:

No internal disruptive discharges; number of external disruptive discharges ≤ 2 . The following test procedure B of IEC 60060-1, adapted for switching devices that have self-restoring and non-self-restoring insulation, is the preferred test procedure. The switching device has passed the impulse tests if the following conditions are fulfilled:

- each series has at least 15 impulses;
- the number of disruptive discharges shall not exceed two for each complete series;
- no disruptive discharge on non-self-restoring insulation shall occur. This is confirmed by 5 consecutive impulse withstands following the last disruptive discharge.

This procedure leads to a maximum possible number of 25 impulses per series.

In some DC switch applications when the switch is in the open position, one terminal can experience a direct voltage with respect to earth while the other terminal can experience a lightning strike. This can occur, for example, on an MRTS in the open position where one terminal will experience a direct voltage (the resistive voltage drop of the pole conductor) and the other terminal could be subjected to lightning strikes taking place on the electrode line. In such cases, consideration should be given to performing the impulse tests with a direct voltage, equal to the maximum experienced in service, applied to the floating terminal.

Some insulating materials retain a charge after an impulse test, and, for these cases, care should be taken when reversing the polarity. To allow the discharge of insulating materials, the use of appropriate methods, such as the application of three impulses at about 80 % of the test voltage in the reverse polarity before the test, is recommended.

d) Test conditions:

As defined in Table 7.

Table 7 – Test conditions for lightning-impulse withstand test

Switch condition	Voltage applied to	Earthed terminals	Floating terminal	Test voltage	Applicability to various switch types ●=Mandatory; ◐=Applicable if specified; ○=Not applicable			
					Commutation switch	By-Pass switch	Converter paralleling switch (CPS)	Line paralleling switch (LPS)
Closed	Aa	F		U_{pe}	●	●	●	●
Open	A	aF		U_{pp}	●	●	●	●
	A	F	a	U_{pe}	○	○	○	○
	a	AF		U_{pp}	●	●	●	●
	a	F	A	U_{pe}	○	○	○	○

6.1.4.2.9 Switching impulse withstand test

a) Test level:

The rated switching impulse withstand voltage to earth (U_{se}) or across the open switch (U_{sp}), as appropriate.

b) Test procedure:

The test is performed generally as described in IEC 62271-1. 15 impulses, each polarity.

c) Pass criteria:

No internal disruptive discharges; number of external disruptive discharges ≤ 2 . The following test procedure B of IEC 60060-1, adapted for switching devices that have self-restoring and non-self-restoring insulation, is the preferred test procedure. The switching device has passed the impulse tests if the following conditions are fulfilled:

- each series has at least 15 impulses;
- the number of disruptive discharges shall not exceed two for each complete series;
- no disruptive discharge on non-self-restoring insulation shall occur. This is confirmed by 5 consecutive impulse withstands following the last disruptive discharge.

This procedure leads to a maximum possible number of 25 impulses per series.

Similarly to the lightning-impulse withstand test described in 6.1.4.2.8, some DC switch applications may experience a direct voltage with respect to earth on one terminal while the other terminal may experience a lightning strike. In such cases, consideration should be given to performing the impulse tests with a direct voltage, equal to the maximum experienced in service, applied to the floating terminal.

Some insulating materials retain a charge after an impulse test, and for these cases care should be taken when reversing the polarity. To allow the discharge of insulating materials, the use of appropriate methods, such as the application of three impulses at about 80 % of the test voltage in the reverse polarity before the test, is recommended.

d) Test conditions:

As defined in Table 8.

Table 8 – Test conditions for switching impulse withstand test

Switch condition	Voltage applied to	Earthed terminals	Floating terminal	Test voltage	Applicability to various switch types ●=Mandatory; ◐=Applicable if specified; ○=Not applicable			
					Commutation switch	By-pass switch	Converter paralleling switch (CPS)	Line paralleling switch (LPS)
Closed	Aa	F		U_{se}	●	●	●	●
Open	A	aF		U_{sp}	●	●	●	●
	A	F	a	U_{se}	○	○	○	○
	a	AF		U_{sp}	●	●	●	●
	a	F	A	U_{se}	○	○	○	○

6.1.4.2.10 Power frequency withstand test

a) Test level:

The test level U_{tacp} (between terminals of the switch) or U_{tace} (from terminals to earth) is derived from the lightning-impulse withstand level U_{pp} or U_{pe} , respectively. The power frequency test voltage should be chosen from Table 1 or Table 2 of IEC 62271-1:2017 using the line with the same or next lower lightning-impulse withstand voltage and the column with comparable test conditions. The same test levels U_{tacp} and U_{tace} are also used for the routine tests defined in 6.1.4.3.1.

b) Test procedure:

1 min. The mechanical switch shall be subjected to short-duration power-frequency voltage withstand tests in accordance with IEC 60060-1. For each test condition, the test voltage shall be raised to the test value and maintained for 1 min. The tests shall be performed in dry conditions and also in wet conditions for outdoor mechanical switches.

c) Pass criteria:

No disruptive discharges

d) Test conditions:

As defined in Table 9.

Table 9 – Test conditions for power frequency withstand test

Switch condition	Voltage applied to	Earthed terminals	Floating terminal	Test voltage	Applicability to various switch types ●=Mandatory; ◐=Applicable if specified; ○=Not applicable			
					Commutation switch	By-pass switch	Converter paralleling switch (CPS)	Line paralleling switch (LPS)
Closed (for metal-enclosed switch gear only)	Aa	F		U_{tace}	◐	◐	◐	◐
Open	A	aF		U_{tacp}	●	●	●	●
	A	F	a	U_{tace}	○	○	○	○
	a	AF		U_{tacp}	●	●	●	●
	a	F	A	U_{tace}	○	○	○	○

6.1.4.3 Routine test

6.1.4.3.1 Dielectric test on the main circuit

The routine dielectric test shall be performed using the test voltage defined in 6.1.4.2.10, generally in accordance with IEC 62271-100 or 7.101 of IEC 62271-109:2008, depending on whether the safe position of the switch is open or closed. Tests shall be performed both on a switch in the open position with one terminal earthed, and on a switch in the closed position. However, the test on a switch in the closed position may be omitted subject to agreement between the purchaser and the manufacturer if it can be shown that such a test has no value.

When using an alternating voltage source during the routine test, instead of a direct voltage, the RMS value of the alternating test voltage shall be the specified direct test voltage divided by $\sqrt{2}$.

6.1.4.3.2 Mechanical operating test

The mechanical operating test shall be performed in accordance with 7.101 of IEC 62271-100:2008.

Auto-reclosing is, in general, not relevant for high-speed DC switches but for those switches where fast closing is required (for example, the bypass switch), the following additional test shall be performed:

- five open-close operating cycles O – t – C where $t = 0,1$ s.

6.1.5 Special test on current commutation capability

6.1.5.1 General

This special test is applicable to all DC switches with commutation duties, i.e. MRTS, ERTS and NBS and shall be conducted upon agreement between the purchaser and the manufacturer. If the arc voltage characteristics of the commutation switch are known and previously verified by physical tests on a real switch of equal or greater rating, it is sufficient to perform calculations in relation to the oscillation characteristics of the interrupter and resonant circuit.

A DC commutation switch typically consists of the following arrangement:

- gas-filled circuit-breaker;
- parallel L/C- oscillation circuit, optionally with active charging circuit;
- parallel surge arrester arrangement.

6.1.5.2 Test objective

For DC commutation switches, a rated commutating current has to be specified. This current is the maximum direct current the DC switch is able to commutate. The commutation type test shall be performed to prove the commutation capability of the DC switch at the specified rated commutating current.

6.1.5.3 Test conditions

An example of one type of test circuit is shown in Figure 4. Other test circuits and procedures can be used as long as they stress the test object in the same way.

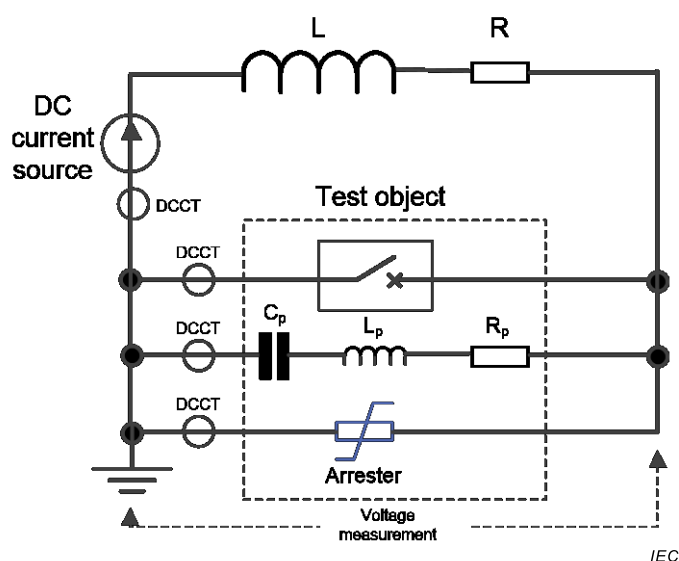


Figure 4 – Test circuit for commutation test

For convenience of testing, the test may be performed at reduced direct voltage, however, care should be taken that the decay of the DC test current caused by the arc voltage during the arcing interval of the DC switch does not significantly change the equivalency of the test. The inductance and the time constant of the test circuit should be chosen adequately.

The commutating current is defined as the instantaneous value of the DC current through the DC switch assembly at the instant of arc extinction within the switching units of the mechanical switch.

The commutation type test shall be performed at following conditions:

- lock out pressure of the switching unit's gas filling for minimum ambient temperature, corresponding to the rated filling level for operation as defined in IEC 62271-1;
- rated supply voltage of operating device;
- nominal hydraulic pressure, if applicable.

6.1.5.4 Test duties

The following test duties and numbers of commutating operations shall be performed during commutation type test:

- commutating current during test: ≥ 100 % of required commutation current in service;
- number of commutating operations: 15.

6.1.5.5 Acceptance criteria

The DC switch has passed the type test if:

- the DC test current has successfully been commutated from the DC switch to the parallel surge arrester without any restriking across the main contacts in a sequence of at least 15 operations performed. One unsuccessful commutating operation is permitted if the test sequence is extended by another successful operation;
- visual inspection of the active parts of the interrupter units after the test do not show any damage, undue wear or impairment of the functionality of the DC switch.

6.2 DC disconnectors and earthing switches

6.2.1 General

Disconnectors and earthing switches used on the DC side of HVDC converter stations serve a similar purpose to those used in AC substations. Their primary purpose is to connect and disconnect DC filters, to isolate sections of the DC-side equipment or to provide connections to earth. The required isolation could be for normal operating conditions or for maintenance purposes. In fulfilling their maintenance-related roles, it is important in some applications that, in order to provide safe conditions, the switch be able to withstand higher than normal system voltages across the open switch.

6.2.2 Ratings

6.2.2.1 General

There are no applicable international standards for disconnectors and earthing switches used in HVDC applications and therefore no complete set of standard rating definitions. However, such disconnectors and earthing switches are usually based on standard AC equipment, for which IEC 62271-102 is applicable. IEC 62271-102 can therefore provide general guidance for some aspects of HVDC applications. There are, in addition, some ratings defined uniquely for DC applications in 6.2.2.2 to 6.2.2.3.6. Table 10 summarises which ratings are covered by existing standards and which require specific definitions for HVDC.

Table 10 – Table of standard ratings in accordance with IEC 62271-102 and their applicability to HVDC disconnectors and earthing switches

Name	Clause in IEC 62271-102:2001	Applicability to HVDC disconnectors and earthing switches		
		Applicable without modification	Applicable with modification	Not applicable
Rated voltage (U_r)	4.1		✓	
Rated insulation level	4.2		✓	
Rated frequency (f_r)	4.3			✓
Rated normal current (I_r) and temperature rise	4.4		✓	
Rated short-time withstand current (I_k)	4.5		✓	
Rated peak withstand current (I_p)	4.6		✓	
Rated duration of short circuit (t_k)	4.7		✓	
Rated supply voltage of closing and opening devices and of auxiliary and control circuits (U_a)	4.8	✓		
Rated supply frequency of closing and opening devices and auxiliary circuits	4.9	✓		
Rated pressures of compressed gas supply for insulation, operation and/or interruption	4.10	✓		
Rated short-circuit making current	4.101	✓		
Rated contact zone	4.102	✓		
Rated mechanical terminal load	4.103	✓		
Rated values of the bus-transfer current switching capability of disconnectors	4.104		✓	
Rated values of the induced current switching capability of earthing switches	4.105			✓
Rated values of mechanical endurance for disconnectors	4.106		✓	
Rated values of electrical endurance for earthing switches	4.107		✓	

6.2.2.2 Modified ratings

6.2.2.2.1 General

The following ratings are modified for HVDC applications and therefore differ from the equivalent standard ratings defined in IEC 62271-102.

6.2.2.2.2 Equivalent (AC) rated voltage (U_{requiv})

Where necessary in order to define other ratings of the equipment, the equivalent AC rated voltage shall be taken to be the next standard AC rated voltage higher than the maximum operating direct voltage of the HVDC system.

EXAMPLE For an HVDC scheme with a nominal direct voltage of 500 kV, the equivalent AC rated voltage (where necessary for the purpose of defining other ratings) would be 550 kV.

6.2.2.2.3 Rated insulation level

Insulation levels for HVDC equipment are generally not standard levels as for AC equipment but instead are defined by the insulation coordination study for the project.

Insulation levels shall be defined for both lightning and switching impulse wave shapes and may be defined separately for the following two cases:

- between open terminals;
- between terminals and earth. For testing purposes it may be necessary to define insulation levels separately for the cases with open and closed contacts.

6.2.2.2.4 Rated normal current (I_r) and temperature rise

In the context of HVDC disconnectors, rated normal current is defined as the maximum continuous DC current experienced by the equipment in the closed position.

6.2.2.2.5 Rated overload current ($I_{r_overload}$)

The rated overload current is the maximum short-duration overload current to which the DC disconnector can be subjected in operation.

6.2.2.2.6 Rated overload duration (t_{overload})

The rated overload duration is the maximum duration of the rated overload current.

6.2.2.2.7 Rated short-time withstand current

The rated short-time withstand current is the RMS value to which the switching device is subjected in its closed position under short-circuit conditions. It depends on system-specific parameters and should be determined by system studies.

6.2.2.2.8 Rated peak withstand current

The rated peak withstand current is the initial current crest value to which the switching device is subjected in its closed position under short-circuit conditions. It depends on system-specific parameters and should be determined by system studies.

6.2.2.2.9 Rated duration of short circuit

The rated duration of short circuit is the interval of time to which the switching device is subjected in its closed position. It depends on system-specific parameters and should be determined by system studies.

6.2.2.2.10 Rated values of the bus-transfer current switching capability of disconnectors

The rated bus-transfer current requirement depends on system-specific parameters and should be determined by system studies, if and when applicable.

6.2.2.2.11 Rated values of mechanical endurance for disconnectors

The endurance requirements should be based on the criteria placed on the device by the system-operating parameters and maintenance programme (see IEC 62271-102:2001, 4.106).

6.2.2.2.12 Rated values of electrical endurance for disconnectors and earthing switches

It is unlikely that an earthing switch will be required to make during a short circuit, however inadvertently closing into an energized line may occur. For this reason the DC earthing switch should be specified class E1 at a minimum (see IEC 62271-102:2001, 4.107).

6.2.2.3 Additional ratings specific to HVDC

6.2.2.3.1 Time duration of overload current

The maximum time duration of the overload current defined in 6.2.2.2.5.

6.2.2.3.2 Fault current

The maximum short-duration (<1 s duration) current flowing through the equipment in the closed position. The waveshape shall also be defined.

6.2.2.3.3 Making current

The maximum current, either continuous or fault current, that the equipment is required to be able to make safely.

6.2.2.3.4 Rated direct voltage (U_{rdc})

The rated direct voltage is defined as the maximum continuous direct operating voltage. For DC switching devices, a rated voltage to earth as well as a rated voltage across terminals need to be specified. Rated direct voltages for HVDC equipment are generally not standard levels as for AC equipment, but instead are defined by the design studies for the project. Rated direct voltages are typically a few percent higher than the nominal direct voltage in order to allow for measurement errors and control imbalances.

6.2.2.3.5 Rated direct voltage between open terminals (U_{rdcp})

Maximum continuous direct voltage appearing between the terminals of an open DC disconnector or earthing switch in operation.

6.2.2.3.6 Rated direct voltage from terminals to earth (U_{rdce})

Maximum continuous direct voltage appearing between one or both terminals of a DC disconnector or earthing switch and earth in operation.

7 DC GIS

7.1 General

Where the HVDC converter station is located in an area of high pollution, for example close to the sea, the DC-side equipment is sometimes located inside a building – as discussed already in 4.3. However, the resulting building is large. An alternative can be to house as much as possible of the DC equipment inside a gas-insulated metallic enclosure (DC GIS). While the DC smoothing reactor and DC filters cannot practicably be housed inside GIS, most of the remaining components can (as described in 7.2). The use of DC GIS offers the potential for considerable reduction of space.

At the time of writing, there is limited industry experience of the use of GIS on the DC side of HVDC converter stations, but one such installation has been in service since 2000 [3].

Test requirements for DC GIS are currently under development in CIGRÉ and it is not possible to define requirements in this document.

7.2 DC GIS configuration (components of DC GIS)

DC GIS may consist of DC switches, DC disconnectors, external or internal fitting DC current transformers, DC voltage transformers, earthing switches, surge arresters, DC buses, DC bushings and insulation cable terminations. DC GIS may be divided into several gas sections in order to manage gas quality and maintenance procedures.

For the complete assembled GIS, the following ratings/requirements shall be specified for each switching device:

- rated voltage/insulation level;
- rated normal current;
- permitted temperature rise;
- required short-time withstand current and duration;
- polarity reversal operation (during blocking state/deblocking state);
- type of insulation gas and rated pressure;
- type of driving mechanism and rated control voltage;
- rated pressure for operation;
- location (indoor/outdoor).

8 DC filter components

8.1 General

The main purpose of DC filters is to limit harmonic currents on the DC line, thus mitigating telephone interference on nearby open-wire telephone lines. The converter can be seen as a voltage source for the harmonics generated on the DC side and the filtering system consists of the smoothing reactor, providing a series impedance, and the DC filter providing a low shunt impedance for the harmonics generated by the converter.

DC filters for HVDC systems normally comprise a high-voltage main DC filter capacitor bank together with tuning reactor(s) and, in some cases, damping resistors and auxiliary capacitors. DC filters are commonly arranged as double tuned or triple tuned banks according to the specific harmonic limits of different HVDC Projects.

Figure 5 shows a double-tuned DC filter where C1 is the main DC filter capacitor bank. The total direct voltage, pole to neutral, is taken up by the main DC filter capacitor bank, C1. The other filter components, L1, L2, R1, R2 and C2 will only be subjected to alternating currents and voltages, mainly the characteristic converter harmonics 12th, 24th, 36th etc. There may also be a substantial 2nd and 6th harmonic caused by harmonics and asymmetry in the AC system voltage. The main DC filter capacitor bank, C1, has to be designed and tested for the combined voltage stress from the pole to neutral direct voltage and the voltage caused by the harmonic currents in the filter. The other filter components only have to be designed and tested for AC current and voltages and the requirements on those are very similar to corresponding AC filter components except their terminal to earth insulation, which may be exposed to direct voltage as a result of the direct voltage on the neutral bus.

Also, for other commonly-used DC filter configurations, for example single-, double- and triple-tuned filters, the complete direct voltage stress is on the main DC filter capacitor bank and the other filter components only see AC current and voltage across their terminals, except their terminal to earth insulation, which can be exposed to direct voltage.

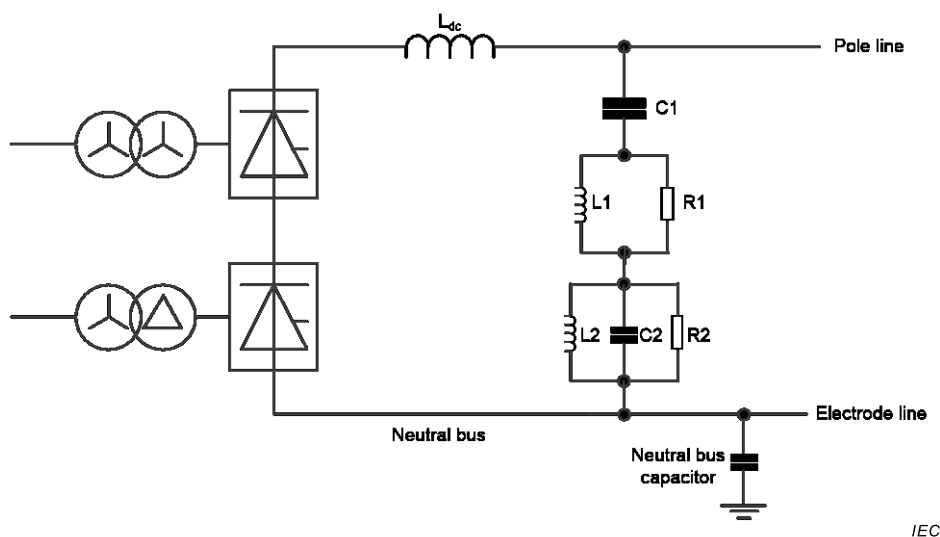


Figure 5 – Typical arrangement of shunt DC filter

8.2 Main DC filter capacitor

8.2.1 General

General requirements for power capacitors are defined in IEC 60871-1. However, no requirements related to DC applications are given in that standard.

The purpose of this document is to give complementary requirements and guidelines to IEC 60871-1 in order to specify capacitors for high-voltage DC applications. The DC capacitors are assumed to be of the same general type as in IEC 60871-1, i.e. capacitor units that are mounted in capacitor banks to meet the required voltage rating and capacitance. This document does not apply, for example, to capacitors of the self-healing metallized dielectric type, or coupling capacitors.

8.2.2 Design requirements for DC capacitors

The capacitors should be equipped with grading resistors to obtain a proper direct-voltage distribution. For internally fused and fuseless DC capacitors, these grading resistors (internally) are mounted across each series group of elements inside the capacitor unit.

Grading resistors are designed to ensure the limits of the considered uneven voltage distribution factor (k -factor) in combination with the estimated grading current.

The capacitor units should be equipped with either internal fuses or without fuses. External fuses are not suitable for DC capacitor applications because, unlike AC filter capacitors, there are not usually a large number of parallel units and because the load current is low.

8.2.3 Rated voltage

The rated voltage for a DC capacitor bank with combined direct and alternating voltage stress shall be defined as:

$$U_{Nb} = k \times U_{rdc} + \sqrt{2} \times U_m + \sqrt{2} \times \sqrt{\sum_{n \neq m} U_{n-max}^2} \quad (1)$$

where

U_{Nb} is the rated voltage of the capacitor bank;

U_{rdc} is the rated direct voltage across the capacitor bank;

U_{n-max} is the RMS AC voltage of harmonic order n across the capacitor bank;

m is the harmonic order for the maximum AC voltage component across the capacitor bank;

k is the DC uneven voltage distribution factor. Typically $1,0 < k < 1,3$ and is to be defined by the manufacturer.

The rated voltage of the capacitor unit is defined as:

$$U_N = \frac{U_{Nb}}{S} \quad (2)$$

where

S is the number of series connected capacitor units in the capacitor bank.

8.2.4 Base voltage for creepage calculation

Creepage distance requirements for the main DC capacitor shall consider different insulation distances between different terminals: HV terminal to earth, HV terminal to LV terminal and LV terminal to earth. The respective base voltages shall be determined according to the operation characteristics, i.e. direct voltage, alternating voltage or combinations of both. The uneven voltage distribution factor k shall be considered as described above for the HV terminal to LV terminal creepage requirement. The creepage distance in each case shall be calculated based on the maximum steady-state RMS voltage across the relevant part of the DC filter capacitor:

$$U_{rms} = \sqrt{(k \times U_{rdc})^2 + \sum_n U_{n-max}^2} \quad (3)$$

where

U_{rms} is the rms voltage to be used as base for creepage calculation;

U_{rdc} is the rated direct voltage across the capacitor bank;

U_{n-max} is the RMS AC voltage of harmonic order n across the capacitor bank.

The creepage requirement for the HV terminal to earth is defined without the k -factor and without AC harmonic components, i.e.:

$$U_{rms} = U_{dc} \text{ (for HV to earth)} \quad (4)$$

For hanging designs, the suspended string insulator is designed based on the creepage requirement of the HV terminal or LV terminal to earth as applicable.

The required creepage distance is determined from U_{rms} multiplied by the unified specific creepage distance (USCD) as defined in IEC 60071-5.

Other requirements for insulators are given in Clause 12.

NOTE Capacitor specification in this document specifies a rated voltage for the bank (U_{Nb}) and a base voltage for creepage calculation. The rated voltage for the bank (U_{Nb}) is used for the dielectric design of the capacitor unit; the base voltage for creepage calculation is used for the insulation and creepage distances of the insulators and bushings.

8.2.5 Tests for DC capacitors

8.2.5.1 General

Tests are performed on the capacitor units. The tests in IEC 60871-1 are in general also followed for DC capacitors where applicable. The test levels are however adapted to the rated voltage of the DC capacitors. In general, the principle is that the ratio between test voltage and rated voltage for the AC capacitor should be the same as the ratio between the peak value of the test voltage and rated voltage for the DC capacitor. This means that, in general, the test factor (relation between test voltage and rated voltage) is divided by $\sqrt{2}$ for DC capacitors.

8.2.5.2 Routine tests

8.2.5.2.1 Capacitance measurement

Capacitance measurement shall be performed as per IEC 60871-1:2014, Clause 7, but the capacitance should be measured at a voltage of:

$$\frac{U_{\text{N}}}{\sqrt{2}} \pm 10\% \quad (5)$$

Capacitance tolerance for capacitor units shall be in accordance with IEC 60871-1:2014, Annex B. Capacitance tolerance for banks should be agreed upon between the purchaser and the manufacturer.

8.2.5.2.2 Measurement of the tangent of the loss angle ($\tan \delta$) of the capacitor

Measurement of $\tan \delta$ shall be performed in accordance with IEC 60871-1:2014, Clause 8. The tangent of loss angle should be measured at a voltage of:

$$\frac{U_{\text{N}}}{\sqrt{2}} \pm 10\% \quad (6)$$

It should be noted that the losses in the grading resistors will normally dominate over the dielectric losses. This test will therefore serve as a quality check of the capacitor and not primarily as a measurement of dielectric losses.

8.2.5.2.3 Voltage test between terminals

The test should be performed generally as per IEC 60871-1:2014, Clause 9; however, the test should be performed as a DC test with a test voltage of $2,6 \times U_{\text{N}}$.

8.2.5.2.4 AC voltage test between terminals and container

The test should be performed as per IEC 60871-1:2014, Clause 10. The test voltage should be in accordance with the following equation:

$$U_t = 2,5 \times \frac{U_N}{\sqrt{2}} \times n \quad (7)$$

Where

U_t is the power-frequency test voltage (RMS);

U_N is the rated voltage of the capacitor unit;

n is the number of units in series relative to the electrical potential to which the containers are connected.

8.2.5.2.5 Measurement of resistance of grading resistor

The choice of the method is left to the manufacturer. The test shall be made after the voltage test between terminals.

The manufacturer shall define the acceptance criteria that ensure a proper direct voltage distribution both internally in the capacitor unit and between capacitor units in the capacitor bank.

The grading resistors shall also serve the purpose of internal discharge device as per IEC 60871-1:2014, Clause 11.

8.2.5.2.6 Sealing test

The test shall be performed as per IEC 60871-1:2014, Clause 12.

8.2.5.2.7 Discharge test (internally fused capacitors only)

The test should be performed generally as per IEC 60871-4:2014, 5.1.2; however, the discharge shall be made from a direct voltage of:

$$1,5 \times U_N \quad (8)$$

8.2.5.3 Type tests

8.2.5.3.1 Thermal stability test

The test should be performed generally in accordance with Clause 13 of IEC 60871-1:2014; however, the applied voltage can be either AC or DC.

a) AC test:

An AC voltage (50 or 60 Hz) adjusted to generate losses equivalent to 1,44 times the highest steady-state continuous losses experienced at operating conditions with combined AC and DC voltage.

b) DC test:

A direct voltage not less than $1,2 \times U_N$. The generated losses shall be equivalent to 1,44 times the maximum steady-state continuous losses experienced during operating conditions with combined AC and DC voltage.

NOTE When performing the tests using a direct voltage, dielectric losses will not be reproduced. Therefore, the direct test voltage will need to be higher than the RMS test voltage would be in the case of AC testing, in order to compensate for the lack of dielectric losses.

8.2.5.3.2 AC voltage test between terminals and container.

The test shall be performed as per IEC 60871-1:2014, 15.1.

The 60-s power-frequency test voltage shall be at least:

$$U_t = 2,5 \times \frac{U_N}{\sqrt{2}} \times n \quad (9)$$

where

U_t is the power-frequency test voltage;

U_N is the rated voltage of the capacitor;

n is the number of units in series relative to the electrical potential to which the containers are connected.

U_t should be rounded to the nearest higher standard short-duration power-frequency test voltage from Table 3 of IEC 60871-1:2014.

8.2.5.3.3 Lightning-impulse voltage test between terminals and container

The test shall be performed in accordance with IEC 60871-1:2014, 15.2.

The test voltage shall be selected from the standard rated lightning-impulse withstand voltages in Table 3 of IEC 60871-1:2014. The lightning-impulse voltage corresponding to the power frequency test voltage chosen for 8.2.5.3.2 shall be used.

8.2.5.3.4 Overvoltage test

The overvoltage test is not applicable for DC capacitors. The main purpose of this test is to verify the capability of the capacitor to withstand the overvoltages that occur at switching the capacitor by an AC circuit-breaker. Such overvoltages occur only infrequently on a DC capacitor and are not sufficient to have an effect on the ageing of the capacitor, which is the purpose of the overvoltage test.

8.2.5.3.5 Long-duration DC test (special test)

a) Test procedure:

The long-duration DC withstand test shall be performed with the capacitor container temperature equal or higher to the maximum container temperature as defined in 8.2.5.3.1. The test shall have a duration of not less than 1 000 h and shall be performed with a direct voltage not less than 1,4 times the rated direct voltage (U_{dc}). In order to reduce DC current requirements for this test, the test may be performed on similar dielectric systems and on elements (groups of elements) without series connection and with no grading resistors in parallel.

b) Acceptance criteria:

To verify no breakdown, the capacitance measurements performed before and after the voltage test shall differ by less than an amount corresponding to the breakdown of an element.

c) Validity of test

The long-duration test is a test on the elements (their dielectric design and composition), and on their processing (element winding, drying and impregnation) when assembled in a capacitor unit. Each ageing test will also cover other capacitor designs, which are allowed to differ from the tested design within the applicable limits stated in Annex A of IEC 60871-2:2014.

8.2.5.3.6 Short-circuit discharge test

The test shall be performed in accordance with IEC 60871-1:2014, Clause 17.

The test voltage shall be:

$$\frac{U_N}{\sqrt{2}} \times 2,5 \quad (10)$$

8.2.5.3.7 Disconnecting test on internal fuses

This test is applicable for capacitors equipped with internal fuses. The test shall be performed in accordance with 5.3 and Annex A of IEC 60871-4:2014. A direct test voltage shall be used. The disconnection test shall be performed at the lower voltage limit of $0,7 \times U_N$ and at the upper voltage limit of $2,2 \times U_N$.

The voltage test after opening the container shall be at a DC voltage of $2,3 \times U_N$.

8.2.5.3.8 Voltage polarity reversal test

A direct voltage of $1,25 \times U_N$ shall be applied for 90 min. The voltage shall then be reversed within 20 ms to the same value of opposite polarity; after 90 min a new reversal, within 20 ms, shall be performed and the voltage is kept for 45 min. The capacitance should be measured before and after the test; the capacitance change should be less than what corresponds to one failed internal element.

NOTE The short time, 20 ms, for polarity reversal is required to simulate polarity reversal under service conditions.

8.3 Filter resistors

8.3.1 General

To date, there is no standard available that is specifically applicable for the resistors of HVDC filter circuits. IEC TR 62001-4 [4] describes the construction of resistors used in AC harmonic filters. As the construction of a DC harmonic filter bank is, in many respects, quite similar to that of an AC harmonic filter bank, the resistors will be similar as well. However, during some configurations, such as metallic return operation, the filter resistors can be additionally subjected to direct voltage stresses to earth. This needs to be considered for the rating of the support insulators.

Since resistors applied in DC filters are usually of dry-type construction, the following information refers to dry type resistors with air cooling by natural convection. If the resistors are not air-insulated but use water, oil or any other insulation type, the insulation rules shall be adapted accordingly.

Environmental conditions specified in 4.2 shall be taken into account in the design of the resistors (mechanical and electrical).

8.3.2 Technical data

Table 11 is a checklist of data that could be used by the contractor for purchasing the equipment or to inform the purchaser of the design parameters.

Table 11 – Ratings for resistors

Resistor design parameters	Units
Rated harmonic frequency (frequency where the highest current value is expected)	Hz
Nominal resistance at nominal current and frequency (at 20 °C ambient temperature)	Ohm
Rated resistance at maximum continuous current and rated frequency (at maximum ambient temperature)	Ohm
No-load resistance (at 20 °C ambient temperature)	Ohm
Tolerance on nominal resistance	%
Tolerance on rated resistance ^a	%
Tolerance on no-load resistance	%
Maximum tolerance on resistance ^b	%
Maximum inductance at rated harmonic frequency	mH
Current ratings	
Nominal continuous current, including harmonics	A RMS ^c
Maximum continuous current, including harmonics	A RMS ^c
Harmonic current spectrum ^d , steady state	n / A RMS
Maximum temporary current(s), including harmonics	A RMS ^c
Temporary harmonic current(s) spectrum	n / A RMS
Duration of temporary current(s)	sec
Transient current^e	
Amplitude, peak value	kA
Time to crest	ms
Energy for maximum transient single-shot event	kJ
Lightning-impulse withstand voltage (LIWV)	
High-voltage terminal to earth	kV
Low-voltage terminal to earth	kV
High-voltage terminal to low voltage terminal	kV
Switching-impulse withstand voltage (SIWV)	
High-voltage terminal to earth	kV
Low-voltage terminal to earth	kV
High-voltage terminal to low voltage terminal	kV
Applied AC test voltage to earth (50 Hz or 60 Hz, 1 min)	kV RMS
Creepage distances	
HV Terminal to LV terminal	mm
HV Terminal to earth	mm
LV terminal to earth – external to housing	mm
LV terminal to earth – internal to housing	mm
^a The specified tolerance should include manufacturing tolerance and resistance variation with ambient and working temperature at rated current. ^b The specified tolerance should include the above one plus the variation due to working temperature at maximum continuous current. ^c RMS in this case refers to the root-sum-of-squares of the individual harmonics. ^d The harmonic current spectrum is specified in terms of the order number and the RMS value of the individual harmonic currents. ^e The resistor should endure the transient current after being permanently loaded with maximum continuous current.	

8.3.3 Design aspects

8.3.3.1 General

A resistor can be divided into modules when its power is too high (several hundreds of kW) or when the voltage across the resistor is too high. Figure 6 shows a typical arrangement of a resistor composed of one module.

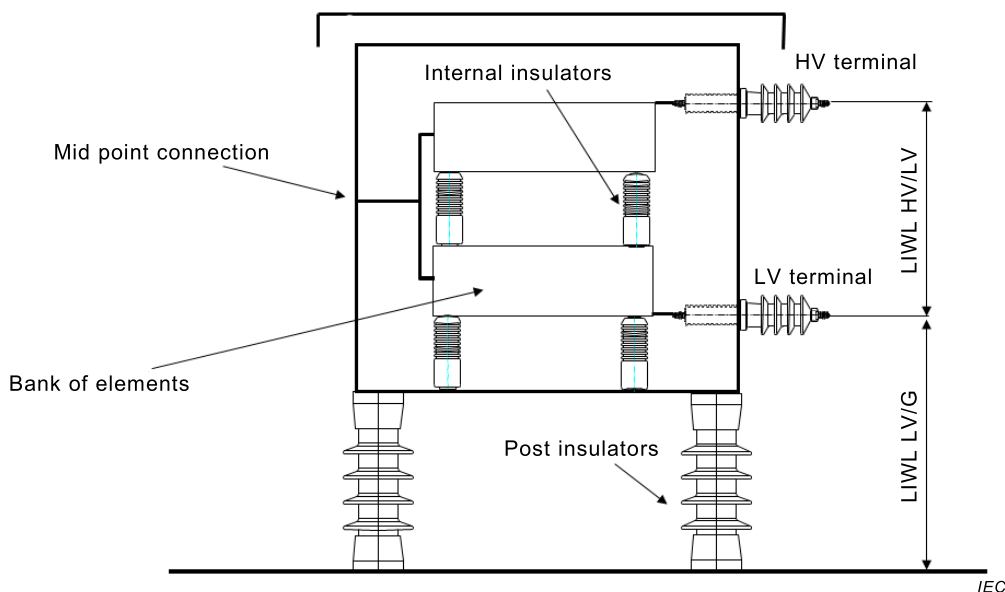


Figure 6 – Typical scheme of a resistor composed of one module

8.3.3.2 Resistance and inductance values

The nominal resistance is defined at nominal current and ambient temperature of 20 °C. The manufacturer shall define the nominal resistance at no load depending on the temperature rise and alloy of the resistor. The rated resistance is defined at rated current and maximum ambient temperature.

The resistors should be designed with low inductance and with low frequency-dependency of resistance. Maximum inductance at a defined frequency (most commonly rated harmonic frequency) or $R/L\omega$ ratio should be specified in the resistor's specification. The maximum variation of resistance versus frequency should be specified in the resistor's specification, if applicable.

Since the variation of the ohmic value with temperature (ambient and working temperatures) has an impact on the filter's performance, tolerance on ohmic value has to be defined and specified. The variation of ohmic value over the working temperature range is to be specified.

Since the power dissipated by each resistor element depends on the voltage across this element and the voltage in turn depends on the ohmic value of every element, it is important to limit resistance difference between resistor elements, banks and modules. A common value of 2 % is recommended. This value shall be taken into account in the insulation design of the resistor since the voltage distribution across the resistor is linked to the ohmic value of each resistor part.

The resistor modules shall be equipped with nameplates that include the main technical characteristics, description, manufacturer and year of manufacturing, type and serial numbers. Nameplates should be mounted, if possible, such that a person at ground level can conveniently read them.

8.3.3.3 Active parts

Depending on the resistance stability required over the working temperature range, the alloy for the manufacturing of elements should be chosen for the stability of its electrical characteristics as a function of temperature.

The resistor elements should be built and assembled in a way that provides a good heat exchange between the alloy and the cooling environment (usually air, but it can be oil or water).

In order to obtain a good lifetime of the resistor, active material should be corrosion resistant taking into account environmental constraints, successive heating-cooling cycles and working temperature. The working temperature should be limited to the level acceptable by its active part material with regards to creep strength at elevated temperatures. Corrosion resistance is quantified by the pitting resistance equivalent (PRE); refer to ASTM G48 [5] for the definition. A PRE of 20 minimum usually gives good results; a minimum of 32 is recommended for corrosion resistance to seawater. PRE should be defined according to the environmental conditions applicable to the project and agreed between the purchaser and the manufacturer.

The system studies for the project shall provide transient current and transient energy information to the resistor manufacturer. This data shall be used by the manufacturer to check that:

- the temperature rise due to transient energy (adiabatic mode), on top of heating due to maximum continuous current and respective overload current, is acceptable;
- the elements and connections will withstand the peak current without any deformation or vibration that could lead to flashovers;
- the insulation of the resistor is sufficient to withstand the peak voltage.

8.3.3.4 Mechanical design

8.3.3.4.1 Degree of protection

Depending on environmental and installation conditions, resistors can be without enclosure (indoor environment) or mounted in an enclosure for protection against rain and solid objects, including birds and other animals (outdoor environment). Enclosures should be designed in accordance with IEC 60529 [6]. Enclosures should permit sufficient air flow to provide the required cooling to the resistor.

If the resistor is composed of several modules, the modules shall be interchangeable as far as possible. Further, provision shall be made to facilitate fast and easy inspection and maintenance.

8.3.3.4.2 Material

Depending on the environmental site conditions and the working temperature, it may be advisable to make the enclosures of stainless steel, or hot dip galvanized structural steel (if this finish is compatible with the working temperature), or corrosion-resistant structural aluminium. The grade of material chosen for the manufacturing of the resistor shall depend on the expected lifetime and environmental conditions.

Enclosures can also be made of composite material if permitted by working temperatures. Composite material can reduce the size of the enclosure, especially when the voltage levels are high.

Insulating cylindrical housing tubes can also be used.

8.3.3.4.3 Seismic, wind and other environmental forces

Suitability of mechanical parts (insulators, enclosure, framework, etc) shall be verified for withstanding applicable mechanical forces provided by:

- dead weight of the resistor;
- snow and/or ice loads;
- wind load;
- seismic acceleration;
- forces on terminals;
- short circuit current forces.

8.3.3.5 Insulation

Typically, the resistor insulation design shall be based on 3 parameters:

- insulation across the resistor, between the high-voltage terminal and the low-voltage terminal;
- insulation between the high-voltage terminal and earth;
- insulation between the low-voltage terminal and earth.

Several voltage levels shall be taken into account for each parameter. The most stringent level shall be retained:

- maximum continuous voltage across the resistor, calculated from the resistor ohmic value and the maximum continuous current (Ohm's law), rms value. Power frequency voltage, RMS value;
- switching-impulse voltage, peak value;
- lightning-impulse voltage, peak value;

The voltage rating of the filter resistor shall be coordinated with the rated power and rated current of the resistor. Rated power is based on the RSS value (root sum square value) of individual harmonic currents.

Calculation of the voltage level on every component of the resistor (element, bank of elements, internal and external insulators, etc.) shall be made in order to determine the proper insulators and air gaps for each component and between components. Consideration shall be given to the effects of non-linear transient voltage distribution.

No conductive part of the resistor and its surrounding should be left at an undefined potential (floating). In this regard, electrical connections should be made between active parts and supporting conductive parts. Some of these connections may need to be dismantled for testing purposes. If, once modules are erected at site, it is impossible to remove the connections, insulation tests should be made before the connections are installed.

If the enclosure is made of conductive material, it should be either connected to one point of the resistor active part (for instance mid-point) or earthed. The choice of insulators (internal and external) and calculation of clearance distances for air insulation are dependent on the electrical potential of the enclosure. If the enclosure is not earthed, it shall be mounted on support insulators to provide the necessary electrical insulation to earth. The insulators may be mounted on a support structure for providing safety clearance for substation personnel to the equipment on HV potential. Alternatively, a fence may be provided around the resistor, for electrical safety of personnel.

Bearing in mind that the temperature rise of the resistor elements can be considerable, the choice of the insulation within a resistor module requires great care, since the high temperature of air will impact the insulation performance. The breakdown voltage of air at

these high temperature levels reduces significantly compared to the value at ambient temperature. 'Chimney effects' of vertically stacked resistors also need to be accounted for. Insulating material shall be able to withstand the high temperature and thermal shocks.

Should the altitude be above 1 000 m, a correction factor as per IEC 60071-5 and IEC 60060-1 shall be applied on the insulation.

8.3.3.6 Creepage distances

Creepage distance for every component should be calculated according to the environmental parameters on site. The base voltage for creepage calculation shall be the maximum continuous RMS voltage on the said components.

The required creepage distance is determined from the maximum continuous RMS voltage multiplied by the unified specific creepage distance (USCD) as defined in IEC 60071-5.

NOTE Under some circumstances, internal creepage distances may need to be larger than external creepage distances because pollution is still present but the insulation does not benefit from the washing action of rain.

Insulators shall be chosen according to the requirements given in Clause 12.

8.3.3.7 Terminals

Care should be taken for the design and the material selection of the electrical terminals to achieve adequate performance at high temperature. Further, the high temperature rise of the resistors requires the internal and external electrical connections of the resistors to be made with sufficient sag so as to avoid undue mechanical stress by thermal expansion. If not welded, connection shall be made with bolts and screws with provision to avoid loose connections due to frequent temperature cycles. Recommended limits for temperature and temperature rise of bolted and welded connections are given in Table 12. The temperature rise limits shall be calculated depending on the ambient air temperature.

Table 12 – Recommended temperature and temperature rise limits for bolted and welded connections

Contact material	Maximum temperature bolted connection (°C)	Maximum temperature welded connection (°C)
Bare copper	90	80
Silver, nickel or tin-coated copper	105	150
Stainless steel	150	500
Other materials	Material properties should be considered, notably in order to determine the maximum temperature rises.	

The resistor terminals can be located inside or outside the enclosure. If located inside, provision shall be made on the enclosure for cable entry, preferably from below to avoid insulated cable being exposed to a hot environment. If located outside, bushing can be covered with a cable box for cable connection protection.

In every case, dimensions and material of all connections shall be specified in order to avoid bad connections with the cable or busbar to which the resistor will be connected on site. Cantilever strength on the terminals shall also be specified.

8.3.3.8 Corona design

Depending on the operating voltage of the resistor, provision shall be made at the resistor enclosure to make it free of external corona. Test method is described in IEC 62271-1:2017, 6.9.

NOTE In case of high temperatures decreasing the corona onset voltage, it might be advantageous to specify a test at operating temperature.

8.3.3.9 Monitoring

Although such devices are not in service at the time of preparation of this document, it is expected in the future that the resistors can be equipped with sensors in order to monitor the aging of their components (active elements and insulation parts mainly), predict failures and start maintenance operations accordingly. For easier integration in the substation communication network, those sensors can be connected in accordance with the IEC 61850 series. Requirements should be agreed between the purchaser and the manufacturer.

8.3.3.10 Accessories

In certain applications where space is at a premium, resistor enclosures can include other components such as current transformers (CTs) and surge arresters. If such an arrangement is specified, the manufacturer will have to design the system (resistor + accessories) with respect to electrical, thermal and mechanical design rules.

8.3.4 Maintenance

The recommended intervals between internal inspections during maintenance should be stated by the manufacturer.

8.3.5 Tests

8.3.5.1 Routine tests

8.3.5.1.1 General

The following tests are recommended to be performed on every resistor manufactured.

8.3.5.1.2 Measurement of resistance

a) Test Procedure:

The resistance (i.e. the real part of the impedance of the resistor) is measured under no-load conditions and then the value is corrected to the operating temperature corresponding to nominal current and temperature. Resistance should be measured at rated harmonic frequency. The measurement shall be made at negligible current in order to avoid heating of the resistor during measurement. The measurement should be done in an ambient temperature range between 10 °C and 30 °C. Ambient temperature during measurement shall be recorded, and used to correct the measured resistance value to the design temperature in accordance with the following formula:

$$R_d = R_m(1 + \alpha(T_d - T_m)) \quad (11)$$

where

R_d is the resistance at design temperature;

R_m is the resistance at measured temperature;

α is the alloy temperature coefficient at design temperature;

T_d is the design temperature;

T_m is the ambient temperature during measurement.

b) Acceptance criterion:

R_d shall be within the specified tolerance on resistance value.

8.3.5.1.3 Power frequency voltage withstand test

a) Purpose of test:

This test is performed to prove the suitability for the expected operating duties of the insulation of the resistor elements to the enclosure (if any). For the purpose of this test, the electrical connections between enclosure and resistor elements (if existing) are removed and the test voltage is applied for 1 min between the resistor elements and the enclosure. Since the high operating temperature inside the enclosure will impact the insulation performance, the test voltage should be chosen to consider the effect of temperature, in accordance with the design calculation in 8.3.3.5.

In the case of resistors consisting of several series-connected resistor modules, the test voltage per module U_{tacm} is reduced according to the number of series-connected modules, taking into account manufacturing tolerances.

b) Calculation of test voltage:

For resistors with midpoint connected enclosure:

$$U_{tacm} = \frac{U_{tac}}{2 \cdot n} \times k_1 \quad (12)$$

For resistors without midpoint connected enclosure:

$$U_{tacm} = \frac{U_{tac}}{n} \times k_1 \quad (13)$$

where

U_{tac} is the power frequency withstand voltage for the complete resistor;

n is the number of modules in series;

k_1 is the test safety factor for consideration of possible non-linear voltage distribution between modules, defined as the ratio of maximum module voltage to average module voltage.

c) Acceptance criterion:

The insulation shall not suffer flashover during the test.

8.3.5.2 Type tests

8.3.5.2.1 General

Unless the manufacturer is able to prove, either by a test on a similar resistor or by calculation, that the resistor is correctly designed to achieve the performance required by the customer, the following tests are recommended to be performed on one item of each type of resistor.

The type tests shall be done on the complete resistor where feasible; otherwise they shall be made on each type of modules.

8.3.5.2.2 Measurement of inductance

a) Test procedure:

The inductance should be measured at rated harmonic frequency on one module.

Calculation can be done to determine the total inductance of the modules.

b) Acceptance criterion:

The inductance of the resistor shall be within the specified limits

8.3.5.2.3 Temperature rise test

8.3.5.2.3.1 Test settings

The test shall be done at all specified continuous loading conditions.

In general, the resistance is independent of frequency (the elements are thin and long, with almost no skin effect). In that case, the test currents are nominal continuous currents and maximum continuous currents specified in 8.3.2.

If the resistance is dependent on frequency (more than 1 % of resistance variation between fundamental and rated harmonic frequency), the test should be made with thermally equivalent 50 Hz or 60 Hz currents. The test currents are the square root of the sum of the squares of the current at fundamental and harmonic frequencies:

$$I_t = \sqrt{\frac{1}{R_t} \times \left[I_F^2 \times R_F + \sum_{n=2}^{n=N} I_{Hn}^2 \times R_{Hn} \right]} \quad (14)$$

where

I_t is the equivalent test current (50 Hz or 60 Hz);

I_F is the maximum continuous fundamental current;

I_{Hn} is the maximum continuous n th harmonic current;

R_t is the AC resistance at test current frequency, corrected to maximum working temperature;

R_F is the AC resistance at fundamental frequency, corrected to maximum working temperature;

R_{Hn} is the AC resistance at n th harmonic frequency, corrected to maximum working temperature;

N is the highest specified harmonic order.

If it is not practically possible to perform the test on a complete resistor, for example owing to limitations of test facilities and equipment, the test may be performed on one single resistor module with equivalent test current.

The test may be performed at any convenient ambient temperature. Loading of the resistor with the test current should be maintained for at least 30 min after steady-state conditions are achieved (steady state to be defined between purchaser and manufacturer in advance of the test). Depending on the resistivity variation of the alloy versus the temperature, it will be necessary to adjust the voltage across the resistor to maintain the test current at the specified value. The temperature measured at the end of the test should be corrected to maximum ambient temperature and should not exceed the expected design temperature. The temperature of all resistor insulation (internal and, where relevant, external) should also be measured to assess its voltage withstand capability and suitability for the long-term lifetime of the resistor.

8.3.5.2.3.2 Measurements

Voltage and current shall be recorded during the tests. It is preferable to have a real-time reading of these values during the test in order to detect thermal stability easily.

Temperature measurements shall be made on major resistor components, such as active parts, insulators, bushings, etc. Temperature can either be recorded versus time, or a thermal strip can be used to record the maximum temperature achieved. The manufacturer shall define the maximum permitted temperature on the different components in advance of the test.

The resistance values under various load conditions (when thermal stability has been reached) shall be calculated from voltage and current measurements. Hot ohmic values shall be within the specified tolerances. Variation between ohmic values at cold and hot conditions shall be lower than the specified maximum tolerance. Measurement of resistance according to 8.3.5.1.2 shall be done before and after temperature rise test. The change of cold ohmic value of the resistor before/after test should remain negligible (a few percent) to reflect the stability of the resistor material.

Acceptance criteria:

- hot ohmic values shall be within the specified tolerances;
- variation between ohmic values at cold and hot conditions shall be lower than the specified maximum tolerance;
- the change of cold ohmic value of the resistor is negligible;
- temperatures on major components shall be less than their respective permitted values.

8.3.5.2.4 Lightning-impulse test

a) Test procedure:

The test shall be performed in accordance with IEC 60060-1.

This test is done preferably on a resistor that has been subjected to a temperature rise test in order to verify that the insulation has not been damaged by temperature.

The test should be made with both negative and positive polarity applied to the high-voltage terminal with the low-voltage terminal earthed. The waveform should be standard lightning-impulse wave 1,2/50 μ s. However, if it is not possible to obtain the waveform due to low resistance, the best waveform possible with the test equipment will be acceptable. In this case, preference shall be given to retaining the front time. The time to half-value should not be less than 5 μ s.

A special resistor may be manufactured with a higher resistance value than the specified one to enable the correct lightning-impulse wave shape in accordance with IEC 60060 to be applied. However, this approach has limitations. For example, to increase the resistance implies either:

- reducing the conductor section, which reduces the exchange surface and therefore the capacity of the resistor to dissipate heat;
- increasing conductor length, which improves the capacity of the resistor to dissipate heat, or increasing the number of modules, which improves peak-voltage withstand;
- modifying the alloy, which modifies resistance variation with temperature.

Where this approach is used, the implication on the other aspects of the design shall be agreed to by all parties.

Since the high temperature of air inside the enclosure will impact the insulation's performance, the impulse voltage performance at high temperature should be verified by suitable methods (either by test or by calculation), in accordance with the design calculation as per 8.3.3.5.

In the case of resistors consisting of several series-connected resistor modules, the impulse voltage test should preferably be performed on the complete resistor with all modules connected in series. If this is not practicable due to laboratory limitations, the impulse voltage test may be performed on a per-module base. In that case, the test voltage U_{tlm} is calculated as follows:

$$U_{tlm} = \frac{U_{tl}}{n} \times k_2 \quad (15)$$

where

U_{tl} is the lightning-impulse voltage HV-LV for the complete resistor;

n is the number of modules in series;

k_2 is the test safety factor for consideration of possible non-linear voltage distribution between modules, defined as the ratio of maximum module voltage to average module voltage. k_2 will, in general, not be the same as k_1 because of stray capacitance effects.

b) Acceptance criterion:

The insulation shall not suffer flashover during the test.

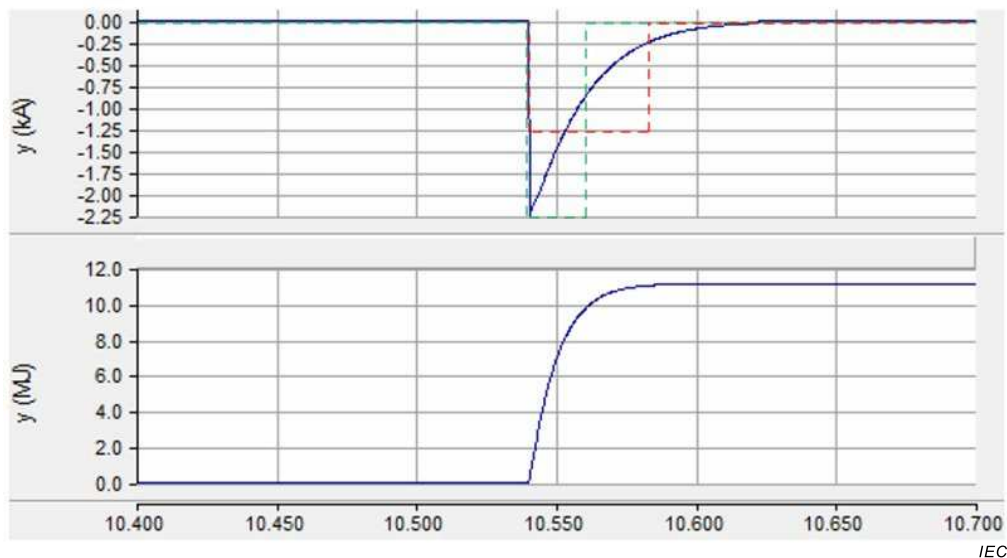
8.3.5.2.5 Verification of transient current performance

The verification shall be done by test unless a reference test on the same type of resistor exists so that verification by calculation can be done. It should be verified by calculation and/or by test that the resistor can withstand the mechanical and thermal stresses imposed by the specified transient current.

The peak value and the duration of transient current determine the maximum mechanical stress on the resistor.

The energy of transient current ($I^2 \times t$) determines the thermal stress on the resistor.

If the specified transient current is not constant, it will be difficult to reproduce it during a test. Then, its maximum value shall be used as the basis for testing (Figure 7). Testing duration can be adjusted so that transient energy is reached with the test current. A test at nominal transient energy but reduced current should not be admitted since the mechanical stress due to high current will not be applied to the resistor.



- Specified transient current
- - - Test current giving the same mechanical (even higher since duration at max level is longer) and thermal stresses than the specified transient current (same peak, same energy)
- - - Test current giving the same thermal stress than the specified transient current only (same energy but lower peak)

Figure 7 – Transient current performance of resistor

8.4 Filter reactors

Requirements for filter reactors for DC filters are defined in Clause 9 of IEC 60076-6:2007.

8.5 Auxiliary capacitors

8.5.1 General

General requirements for auxiliary capacitors for DC filters are defined in IEC 60871-1.

8.5.2 Rated voltage of the auxiliary capacitor banks

The minimum rating for the auxiliary capacitor bank shall be based on methods a) and b) below, whichever gives the highest value for U_{rated} .

a) the arithmetic sum of the RMS voltages:

$$U_{\text{rated}} = \sum_{n=1}^{n=50} U_{\text{hn}} \quad (16)$$

where

U_{hn} is the n^{th} harmonic voltage.

b) calculation in line with IEC 60871-1:2014, 19.2:

$$U_{\text{rated}} = \frac{U_{\text{trans-max}}}{\sqrt{2} \times 2,0} \quad (17)$$

where

$U_{\text{trans-max}}$ is the maximum transient voltage.

The capacitors shall withstand the transient and short-time stresses.

8.5.3 Base voltage for creepage calculation for auxiliary DC filter capacitors

Design in accordance with 8.2.4 of this document. U_{rms} is derived without any k -factor.

The required creepage distance is determined from U_{rms} multiplied by the unified specific creepage distance (USCD) as defined in IEC 60071-5.

8.6 Series blocking filters

Some transmission HVDC schemes include a series blocking filter in addition to the more conventional shunt DC filters. This requirement typically occurs where the DC transmission line runs in close proximity to AC lines and there is a risk of induced fundamental-frequency voltage in the HVDC connection. The fundamental-frequency current reaching the converter due to the induced voltage needs to be limited to an acceptable level, otherwise it would lead to DC and second harmonic components of current appearing on the AC side of the converter.

The blocking filter consists of a reactor in series with the DC circuit (which could either be part of the DC smoothing reactor or a separate reactor) and a tuning capacitor connected in parallel with it. A damping resistor may also be included in some designs. Test requirements are generally as defined above for DC smoothing reactors and filter capacitors.

DC series blocking filters operate primarily under AC harmonics. Hence, in principle, a DC series blocking filter capacitor bank by design is similar to an auxiliary DC filter capacitor bank (C2 in Figure 5) and therefore, designed and tested in accordance with the guidelines of IEC 60871-1.

For calculating the base voltage for creepage calculation for DC series blocking filter capacitors, the design is similar to auxiliary DC filter capacitors (C2 in Figure 5) and in accordance with 8.2.4 of this document. U_{rms} is derived without any k -factor.

The required creepage distance is determined from U_{rms} multiplied by the unified specific creepage distance (USCD) as defined in IEC 60071-5.

8.7 DC neutral bus capacitor

Large neutral bus capacitors are normally installed to provide an in-station path for triplen harmonics flowing to ground through the stray capacitances of the converter transformer.

In addition, in HVDC schemes using metallic return and systems with earth electrode and electrode lines, DC neutral bus capacitors are often used in combination with surge arresters to protect equipment connected to the neutral circuit from overvoltage.

Such capacitors are relatively large in capacitance (microfarads). General requirements for power capacitors are defined in IEC 60871-1. However, no requirements related to DC applications are given in that standard. Requirements for ratings and tests are generally as defined in 8.2 for the main DC filter capacitor.

9 Coupling capacitors and line traps for power line carrier (PLC)

Telecommunication systems in power grids generally use optical communications for the primary communication system, but may use power line carrier (PLC) systems as a backup. The main item of primary equipment associated with PLC systems are the high-voltage coupling capacitors used for injecting the PLC signal into the line and the line trap (series blocking filter), which prevents propagation of the PLC signal into undesired zones of the grid.

High-voltage DC coupling capacitors may also be fitted to the neutral bus and used for the injection of carrier signals for electrode line supervision (see Clause 13).

Coupling capacitors are small in terms of capacitance (nanofarads) in comparison with other filter capacitors. Coupling capacitors are generally column type. Requirements for ratings and testing of coupling capacitors, for both AC and DC applications, are defined in IEC 60358-1.

IEC 60353 covers the requirements for line traps for AC power systems. In most cases, requirements for line traps on the DC side of HVDC converter stations are also covered by IEC 60353. Additionally, some HVDC projects can include high frequency filters (e.g. RI filters) on the AC or DC side of the converter station. Such filters are similar in concept to PLC line traps but may cover different frequency ranges.

10 DC surge arresters

10.1 General

Requirements for gapless metal-oxide surge arresters for HVDC applications are described in detail in IEC 60099-9. Additional information on the procedure of insulation coordination for HVDC converter stations, which is relevant for the arrester design, is described in IEC 60071-5.

10.2 Surge arrester specification

10.2.1 General

Besides the environmental conditions described in 4.2, the following information is relevant to describe surge arresters correctly and shall be specified – if applicable – to the arrester manufacturer.

10.2.2 Continuous operating voltage (COV)

Depending on the specific location of the installation of the individual surge arresters within a converter station each type is exposed to operating voltages, which can consist of:

- AC power frequency voltage,
- AC harmonic frequency voltages,
- direct voltage,
- commutation overshoots, or

combinations of the above. Figure 8 illustrates the typical voltage across the DC converter bus arrester (CB) in rectifier mode.

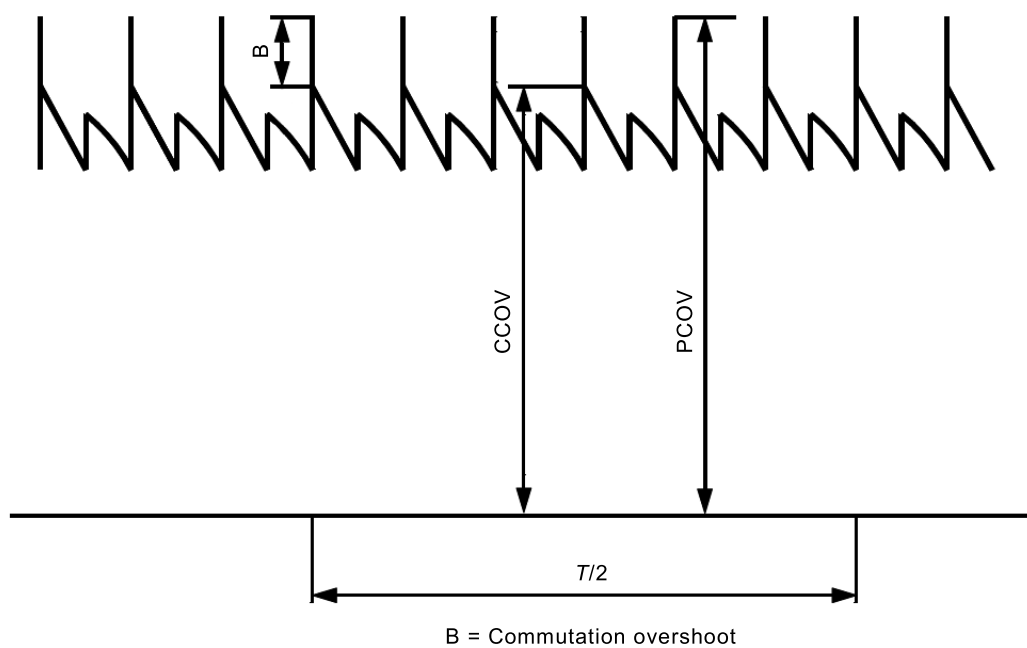


Figure 8 – Operating voltage of a converter bus arrester (CB), rectifier operation

Different definitions for operating voltages exist (see 3.3) and shall be used as applicable to describe the individually appropriate operating voltage:

- crest value of continuous operating voltage (CCOV),
- peak value of continuous operating voltage (PCOV),
- direct component of continuous operating voltage (DCOV),
- equivalent continuous operating voltage (ECOV).

NOTE In some applications, temporary operating voltages exceeding the continuous operating voltages may also be applicable. In such cases, possible impacts on the design need to be discussed between the HVDC system integrator and arrester manufacturer.

10.2.3 Protective characteristics

The protective characteristics of surge arresters are characterised by the residual voltage (peak voltage that appears between the terminals of an arrester) during the passage of a discharge current and by the energy absorbed by the surge arrester during transients. The arrester currents for which the residual voltages are specified are called the coordination currents. The maximum residual voltages correspond to the protective levels of an arrester for each voltage shape.

The following protective characteristics of the surge arresters shall be specified as applicable for the specific arrester type (see 3.3):

- switching-impulse protective level (SIPL),
- lightning-impulse protective level (LIPL),
- steep-front impulse protective level (SFIPL, STIPL).

10.2.4 Insulation withstand levels of arrester housing

An appropriate insulation withstand level shall be specified to avoid flashovers across the arrester housing. If the arrester is not connected to earth potential at one terminal, the insulation withstand levels of both terminals to earth shall be specified.

NOTE Some arrester housings can consist of several parts providing mechanical strength and protection against the environment.

10.2.5 Energy dissipation capability

The maximum energy dissipated in the arrester during system faults or operation shall be given as design criteria to the arrester manufacturer. A frequency of discharges may be specified to the manufacturer.

NOTE The energy dissipation requirement is not necessarily decisive for the arrester design as there may be other factors leading to inherently higher energy capabilities of the arresters.

10.3 Test requirements

For a detailed description of test requirements, refer to IEC 60099-9. Besides type tests (Clause 9) and routine tests (10.1), IEC 60099-9:2014 defines also "acceptance tests" with a definition that differs from the definition given in IEC 60050-151:2001, 151-16-23 [7]. "Acceptance tests" in IEC 60099-9 have the character of sample tests and are subject to agreement between the manufacturer and the purchaser.

11 Instrument transformers

11.1 DC current transformer

Requirements for DC current transformers for HVDC applications are defined in IEC 61869-14.

11.2 DC voltage transformer

Requirements for DC voltage transformers for HVDC applications are defined in IEC 61869-15.

11.3 Current transformers in DC filter circuits

DC filter circuits normally include current transformers for protection purposes (for example, to detect harmonic overload). While such applications do not require the measurement of a DC component of current, they nevertheless have special requirements related to the high levels of harmonic current flowing in such current transformers. Requirements for such current transformers are defined in IEC 61869-14.

12 DC insulators and bushings

12.1 Bushings

Requirements for bushings for HVDC applications are defined in IEC/IEEE 65700-19-03.

Additional considerations are:

- subject to agreement between the manufacturer and the purchaser, for gas-insulated bushings, the polarity reversal test can be a type test instead of a routine test and, as a consequence, the DC withstand routine test shall be performed twice, once with positive polarity and once with negative polarity;
- unless agreed between the manufacturer and the purchaser, the bushing under test should preferably be mounted at its intended service angle and the test arrangement should include simulated earth planes representing the floor and other walls;
- for dielectric tests, the dry power frequency voltage test with partial discharge measurement should be preferably performed last or repeated at the end of the test programme.

12.2 Post insulators

12.2.1 General

Test requirements for ceramic or glass post insulators are defined in IEC 60168. For composite post insulators, test methods and acceptance criteria are defined in IEC 62231 and IEC 62217. However, no requirements related to DC applications are given in the above-mentioned standards.

Artificial pollution tests on ceramic or glass insulators exposed to DC conditions are defined in IEC TS 61245. Where insulators are designed in accordance with IEC 60815-4, no artificial pollution test is required. Additional guidance in respect of selection of insulators for polluted conditions is given in IEC 60815-4.

For hollow-core composite insulators, IEC 62772 defines requirements, including for DC conditions. For hybrid post or hollow-core insulators, IEC TS 62896 defines requirements, including for DC conditions. Aging or artificial pollution test requirements for composite insulators are still under development in CIGRÉ.

For DC applications, at least the tests defined in 12.2.2 and 12.2.3 apply. Where agreed between manufacturer and purchaser, the tests defined in 12.2.4 are also required.

12.2.2 Type tests

12.2.2.1 Power-frequency voltage withstand test

The test shall be performed under dry conditions for indoor use or wet conditions for outdoor use.

The test level should be derived from the LIWL and SIWL as defined by the insulation coordination study for the project. The power-frequency withstand level is defined according to IEC 60071-1 and should be consistent with the insulation level defined by the insulation coordination study. Where the level defined from the insulation coordination study is not one of the standard LIWL or SIWL levels defined by IEC 60071-1, it should be rounded up to the next higher level. For outdoor applications, the partial discharge tests may be omitted with the agreement of the purchaser and the manufacturer. For indoor applications, creepage distances are shorter and thus partial discharge is a more critical performance aspect.

12.2.2.2 Direct voltage withstand test

The test shall be performed under dry conditions for indoor use or wet conditions for outdoor use.

The test level, test method and acceptance criteria are as defined for DC wall bushings in 9.4 of IEC/IEEE 65700-19-03:2014. For outdoor applications the partial discharge tests may be omitted with the agreement of the purchaser and the manufacturer. For indoor applications, creepage distances are shorter and thus partial discharge is a more critical performance aspect.

12.2.2.3 Dry lightning-impulse withstand voltage test (LIWV)

The test level should be derived from the system insulation coordination study for the project. For ceramic post insulators, the tests shall be performed in accordance with IEC 60168. For composite post insulators, the tests shall be performed in accordance with IEC 62231 and IEC 62217.

12.2.2.4 Switching-impulse withstand voltage test (SIWV)

The test shall be performed under dry conditions for indoor use or wet conditions for outdoor use.

The test level should be derived from the system insulation coordination study for the project.

12.2.2.5 RIV test

a) Test procedure:

The test is performed generally as described in IEC 60437. A voltage of $1,1 \times$ the applicable rated direct voltage shall be applied to the insulator and maintained for at least 5 min. The voltage shall then be decreased by steps down to $0,3 \times$ the applicable rated direct voltage, raised again by steps to the initial value and finally decreased by steps to $0,3 \times$ the applicable rated direct voltage. At each step, a radio interference measurement shall be taken and the radio interference level, as recorded during the last series of voltage reductions, shall be plotted versus the applied voltage; the curve so obtained is the radio interference characteristic of the insulator. The amplitude of voltage steps shall be approximately $0,1 \times$ the applicable rated direct voltage.

b) Acceptance criteria:

The insulator shall be considered to have passed the test if the radio interference level at $1,1 \times$ the applicable rated direct voltage does not exceed 2 500 μ V.

RIV tests are not applicable to insulators where both terminals operate at <100 kV with respect to earth.

Subject to agreement between the purchaser and the manufacturer, RIV tests may be performed using an AC voltage source as described in IEC 60437, instead of direct voltage. In this case, the RMS value of the AC test voltage shall be the direct test voltage divided by $\sqrt{2}$.

12.2.2.6 Mechanical failing load tests

The mechanical load tests shall include cantilever load, torsional load, compressive load and tensile load. All the load tests will be carried out with the insulator installed in the vertical orientation. The mechanical load requirement for non-vertical installation positions shall be agreed by the manufacturer and the purchaser.

The mechanical falling load tests shall be performed for ceramic post insulators according to IEC 60168 and for composite post insulators according to IEC 62217.

12.2.2.7 Thermal tests

For toughened glass insulators, thermal shock tests shall be performed in accordance with IEC 60168.

12.2.2.8 Dimension check and creepage distance measurement

Dimension check and creepage distance measurement shall be performed as specified in the relevant insulator product standard, where appropriate.

12.2.3 Routine tests

- Dimension check.
- Bending (cantilever) mechanical test: as described in IEC 60168 (for glass or ceramic insulators) or IEC 61462 (for composite insulators). The load shall be applied at the insulator terminal in the two mutually perpendicular directions, in both polarities, i.e. for a horizontally mounted insulator, left, right, up and down. The test load value is the 60 % rated failing cantilever load and the applied time is at least 3 s in each direction.

12.2.4 Special tests (subject to agreement between the manufacturer and the purchaser)

- Artificial pollution tests are mainly relevant to glass and ceramic insulators, tests are defined in IEC TS 61245; for composite insulators there is currently no standard.
- Aging tests are mainly relevant to composite or hybrid insulators. There is currently no applicable standard, but CIGRÉ Technical Brochure No. 442 [8] provides general guidance. In addition CIGRÉ SC A3.29 is conducting further research into this area.
- Polarity reversal test; the test level, test method and acceptance criteria are as defined for DC wall bushings in 9.5 of IEC/IEEE 65700-19-03. The polarity reversal test may be omitted if the direct voltage withstand test is done twice, once for each polarity, with partial discharge measurement.

12.3 Suspension insulators

For suspension insulators on DC-side equipment, IEC 60383 for ceramic or glass insulators and IEC 61466 for composite insulators for overhead lines are generally applicable. However, no requirements related to DC applications are given in these standards.

The electrical test requirements specific for DC applications, as defined in 12.2, are also applicable for suspension insulators.

13 Monitoring equipment for electrode line or dedicated metallic return

Where an HVDC scheme includes the facility for operation in earth return mode, an electrode line is required to connect the land or sea electrodes (which are normally located at some distance away from the converter station) to the converter station.

Various techniques may be used for the protection and monitoring of the electrode line in order that earth faults may be detected. Some of the more common types are described in Clause A.7.

The additional equipment needed for electrode line monitoring and protection is generally covered by the other types of equipment mentioned in Clauses 8, 9 and 11. Typical equipment needed can include the following:

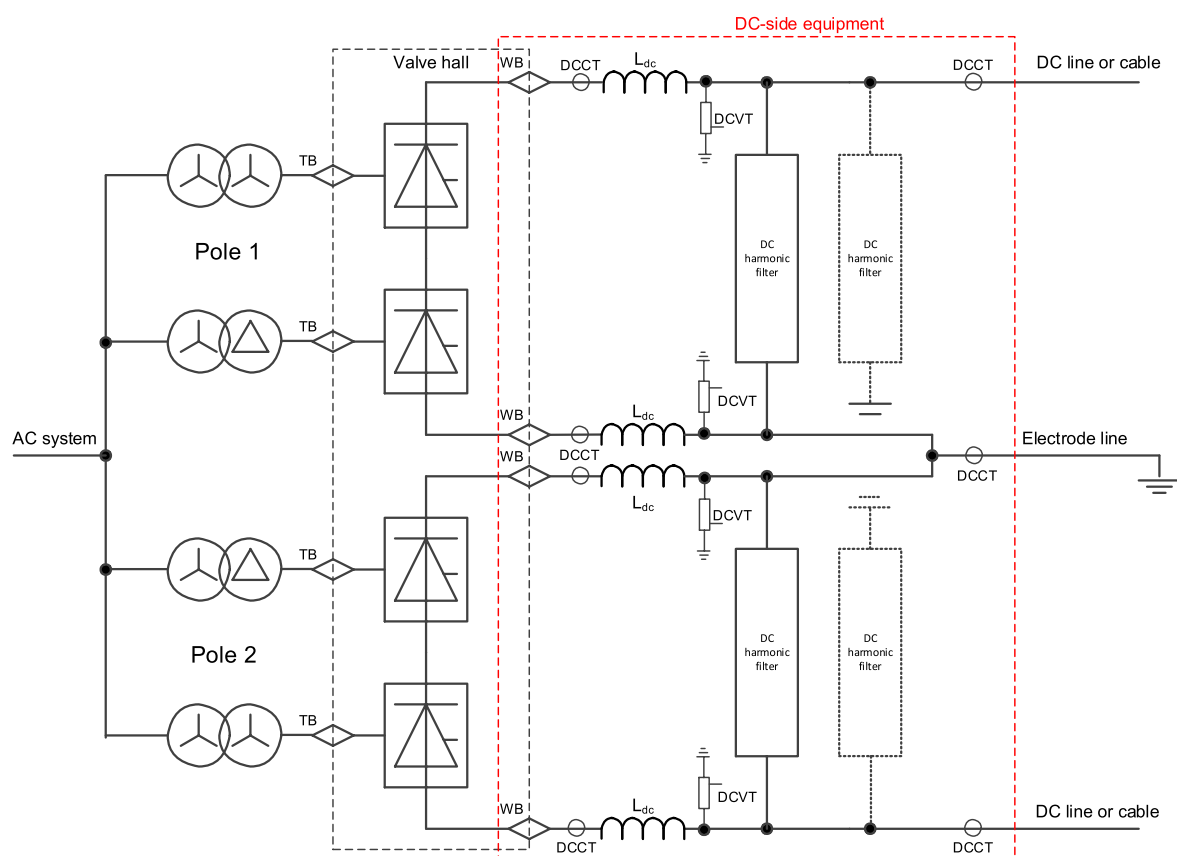
- DC current and voltage transformers to measure the neutral bus voltage and current in the converter station and, in some cases, the electrode line current at the electrode station. These are covered by 11.1 and 11.2.
- DC neutral capacitors used as coupling capacitors for high-frequency or pulse injection systems, together with line traps to contain such signals to the electrode line. These are covered in 8.7.
- AC current and voltage transformers used to inject and/or measure alternating current in the electrode line for fault detection purposes. These are generally quite conventional in design and are similar to instrument transformers used for filter protection (11.3). They are covered by the IEC 61869 series.

Annex A (informative)

Overview of DC-side equipment

A.1 General

As stated in the scope, the term DC-side equipment covers all equipment between the converter DC-side terminals (including DC bushing) and the DC line or cable termination (for transmission schemes) or the DC-side terminals (including DC bushing) of the other converter (for back-to-back schemes). DC-side equipment may be mounted either outdoors or, where pollution concerns are high, in a separate indoor DC yard. Figure A.1 illustrates the typical arrangement of the main items of DC-side equipment on a bipolar scheme, although surge arresters and DC switching devices are omitted for clarity.



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Surge arresters and switching devices are not shown.

Key

- L_{dc} = DC smoothing reactor
- TB = transformer bushing
- WB = wall bushing
- DCCT = DC current transformer
- DCVT = DC voltage transformer

Figure A.1 – Main items of DC yard equipment for a typical HVDC transmission scheme

Most DC-side equipment differs to an appreciable extent from conventional AC substation equipment and many items are found only in HVDC converter stations, having no direct equivalent in AC substations. For this reason, DC-side equipment is generally more specialised than AC equipment and there is less industry experience to be drawn upon in specifying it.

For this reason, this annex and Annex B are intended to provide an informative overview of the main items of specialised DC-side equipment, to explain their roles and main characteristics.

On transmission HVDC schemes, many different types of specialised DC switching devices may be included. These are addressed in Annex B.

A.2 DC smoothing reactor

The DC smoothing reactor is one of the largest and most important items of DC-side equipment. It is connected in series with the converter and the DC line or cable and therefore experiences the same current as those components. The DC smoothing reactor plays many roles in an HVDC scheme, including:

- together with the leakage reactance of the converter transformer and the inductance of the DC line or cable, it helps to minimise the ripple component of direct current;
- linked to the above, it assists in preventing the converter from entering the "intermittent current" operating mode, which can be harmful to some components of the thyristor valves;
- it reduces the peak current and di/dt that flow in response to either a DC line to earth fault or a commutation failure;
- in conjunction with the DC harmonic filters (A.3.1), it reduces the adverse effects of converter-generated harmonics on the DC line (to avoid telephone interference);
- when connected on the high-voltage side of the converter, it helps to protect the converter from the effects of a lightning strike on the DC line.

DC smoothing reactors have three main alternative construction methods:

- oil-immersed iron-cored;
- oil-immersed, air-cored;
- dry-type, air-cored.

Oil-immersed, iron-cored reactors have a magnetic core, are installed in a steel tank and immersed in oil, which provides both cooling and insulation, in much the same way as for an oil-type transformer. Bushings are used to bring the power connections out to the DC line and the reactor winding needs to be insulated for the full DC line voltage with respect to earth. This method was once popular but is now rarely used, partly because of the difficulty in insulating the winding from the increasingly high direct voltages now being used. A further disadvantage is that the inductance falls at high values of current (owing to saturation of the core), reducing the effectiveness of the reactor against limiting fault currents.

Oil-immersed air-cored reactors do not have a magnetic core and hence do not suffer from the problem of saturation at high values of current, but are otherwise similar to oil-immersed iron-cored reactors. Such reactors are still used on some projects.

The most common technique today is to use dry-type air-cored reactors. Such reactors have no iron core and consist of a copper or aluminium conductor wound helically to form a cylindrical coil which is then placed on top of support insulators, relying on natural air cooling. Dry-type reactors are much lighter than oil-immersed reactors (although they are still heavy components, usually weighing over 10 tonnes). With this design, the only insulation requirements for the reactor itself are for the transient terminal to terminal voltages, which occur during DC line faults, commutation failures or lightning strikes. The job of insulating the reactor from earth is achieved by the support insulators, which can be of relatively conventional design.

There is a limit to the maximum inductance that can be provided in a single coil, so in some cases the DC smoothing reactor comprises two or three identical coils in series. A further advantage of this approach is that the reactor coils can be split between the high-voltage and neutral busses. It is necessary to have at least part of the reactance on the high-voltage side in order to protect the converter from lightning strikes, but if the majority of the reactance can be connected on the DC neutral side, the reactor requires less insulation and is therefore less costly.

The most onerous requirements for DC smoothing reactors are generally on overhead line transmission schemes, where the need for protection from lightning strikes, DC line faults and the minimisation of converter harmonics are most important. Requirements on cable transmission schemes and back-to-back installation are less onerous, being concerned mainly with the need to limit the peak current owing to a commutation failure, to prevent operation in intermittent current mode and to minimise cross-modulation of harmonics between the two connected AC systems.

Some back-to-back HVDC schemes have been built without DC smoothing reactors, thereby eliminating a large and costly component from the DC system and allowing the entire DC circuit to be contained within the valve hall. However, in such cases, it is important to ensure that the above constraints on commutation failures, intermittent current and cross-modulation of harmonics are adequately satisfied by the proposed solution.

A.3 Filter equipment

A.3.1 DC harmonic filters

A.3.1.1 General

Line-commutated converters for HVDC generate harmonic voltages on the DC side of the converter, mainly at multiples of $12n$ of the fundamental frequency (the "characteristic harmonics", where $n = 1, 2, 3, \dots$). The first two of these harmonics, 12th and 24th, are usually the most important, although non-characteristic harmonics and higher-order characteristic harmonics can sometimes also be significant.

The harmonic voltages at the DC terminals of the converter will result in harmonic currents in the DC conductor, and if the DC conductor runs close to open-wire telephone systems (especially with overhead line transmission schemes), telephone interference can be a serious problem. Hence, for overhead line transmission schemes, DC harmonic filters are nearly always required in order to reduce the level of telephone interference to acceptable limits. A comprehensive treatment of DC harmonic filters is given in CIGRÉ Technical Brochure No. 92 [9] which is currently being revised by CIGRÉ Working Group B4-68.

Back-to-back HVDC schemes do not require DC harmonic filters and cable transmission schemes usually do not (unless a telephone line is located within a few metres of the DC cable for a significant distance), because the cable capacitance acts as an effective high-pass filter and the cable screen provides effective cancellation of harmonic currents.

A.3.1.2 Passive DC filters

The construction of a DC harmonic filter bank is, in many respects, quite similar to that of an AC harmonic filter bank as described in the IEC TR 62001 series [4]. In both cases, the filter bank is normally connected between the high-voltage AC or DC line and the neutral or earth. It consists of a high-voltage capacitor bank (which makes up most of the cost and space of the filter) in series with one or more tuning components on the lower voltage side. As with AC harmonic filters, DC filter banks may be single-tuned, double-tuned or triple-tuned, with or without damping. A considerable number of different configurations and variations are possible; [4] describes in some detail the most important configurations while Figure A.2 shows three of the configurations most commonly used for DC filters.

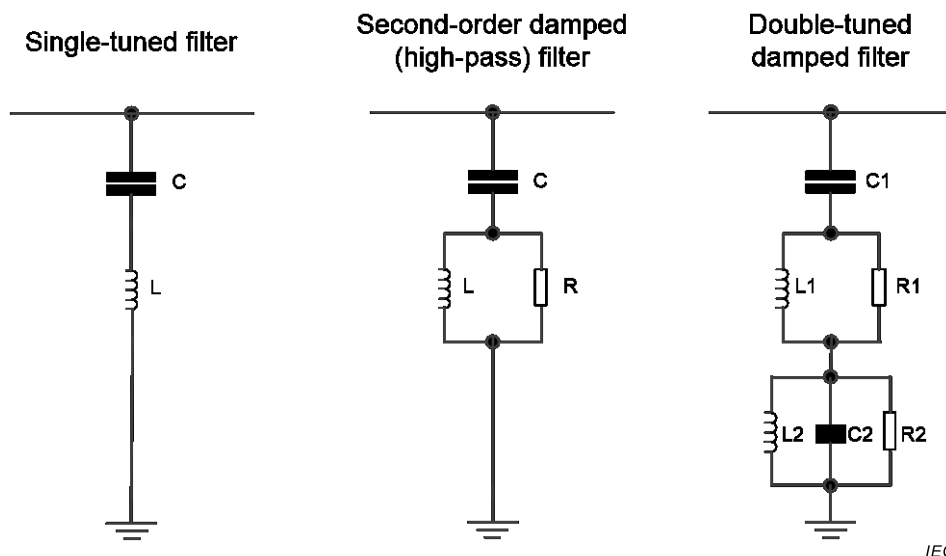


Figure A.2 – Some commonly used DC filter configurations

The characteristic harmonic spectra to be filtered differ between AC and DC filters (characteristic harmonics occur at orders $12n$ for DC filters but $12n \pm 1$ for AC filters). The other main differences between a DC filter bank and its AC equivalent are as follows:

- The DC filter bank is provided purely for filtering. It has no requirement to provide reactive power. Hence, the only currents flowing through the bank are at harmonic frequencies – there is not the large fundamental component of current that characterises AC harmonic filter banks.
- As a result of the above, the main high-voltage DC capacitor tends to be very tall and narrow in shape. In some projects, the main DC capacitor is suspended from an overhead gantry in order to facilitate the mechanical design of such a tall capacitor bank. In principle, a DC filter capacitor bank can be of stacked-type or hanging-type from the gantry. When needed to divide a DC filter C1 capacitor bank into a two-tower arrangement, unsymmetrical splitting of the bank will lead to grading current imbalance, which shall be taken into account in the design of the bank.
- Because reactive power balance is not a consideration for DC filters, there is no advantage to be gained from arranging the DC filter in switched banks. As a result, unlike the case for AC filters, DC filters are often arranged in a single bank, or sometimes separately switchable banks in order to allow for continued, but degraded, performance in the event of outage of one bank.
- The high-voltage main capacitor needs to be designed to withstand direct voltage. The main consequence of this is that the individual capacitor units need to be provided with DC grading resistors (either internally or externally). As the main source of uneven voltage distribution is the leakage current due to pollution in the unit bushings and in the insulators between "floors" in the stack. The pollution is never even in these parts, and the voltage drop in these parts will not be even. Further, the capacitance does not help in evening out the DC voltages. The resistors take a current high enough above the leakage current to ensure an even voltage distribution. The proper design will ensure that the current has to be far larger than the leakage current in the polluted parts.
- Because the main DC filter capacitor bank does not experience any fundamental-frequency component of current, conventional techniques used for detecting individual capacitor element failures on AC capacitor banks (such as unbalance protection) are not effective on DC filter capacitors. However, it is possible that future innovations in protection might change this. Individual element failures can be detected by capacitance measurements in the capacitor bank when the filter is de-energized, for example at maintenance outages. Suitable instruments and measuring procedures should be given in the manufacturer's maintenance manual.

DC harmonic filters are usually connected from the high-voltage DC connection to the DC neutral. However, some converter stations also include filters connected between the high-voltage DC connection and earth because some harmonics (mainly the characteristic harmonics 12th, 24th, 36th etc.) are filtered more effectively by pole-to-neutral filters while others (mainly non-characteristic triplen harmonics) are filtered more effectively by pole-to-earth filters.

In addition to the main DC capacitor, a DC filter bank includes, as a minimum, one tuning inductor (for a single-tuned filter type). For double- or triple-tuned filters, several tuning inductors and auxiliary capacitors are needed, and where a damped filter is required, damping resistors are added. The tuning inductors and capacitors and damping resistors are considerably smaller than the main DC capacitor; also, the auxiliary capacitors, unlike the main DC capacitor, experience only harmonic voltages across their terminals – not a direct voltage – so the constraints about direct voltage sharing do not apply for the auxiliary capacitors. The tuning inductors are almost always dry-type, air-cored in construction, similar to a dry-type DC smoothing reactor but much smaller.

A.3.1.3 Active DC filters

Although almost all HVDC schemes built to date have used passive DC filters, it is possible to use active DC filters. An active DC filter relies on measuring the current distortion on the DC line, feeding this signal into a control system and then controlling a small voltage-sourced power electronic converter (with a power rating of the order of a few kW) to produce a harmonic current at the relevant frequency with a phase shift such as to cancel out the voltage distortion. The output voltage of the converter is coupled onto the high-voltage DC line by the main DC capacitor.

Unlike passive DC filters, active DC filters can be self-adapting and are therefore ideal for dealing with non-characteristic harmonics whose frequencies and amplitudes may vary in an unpredictable way. However, the very small number of active DC filters currently in service suggests that conventional passive filters may be more cost-effective in most circumstances.

A description of various different types of active filters, both DC and AC, is given in IEC TR 62544 [10].

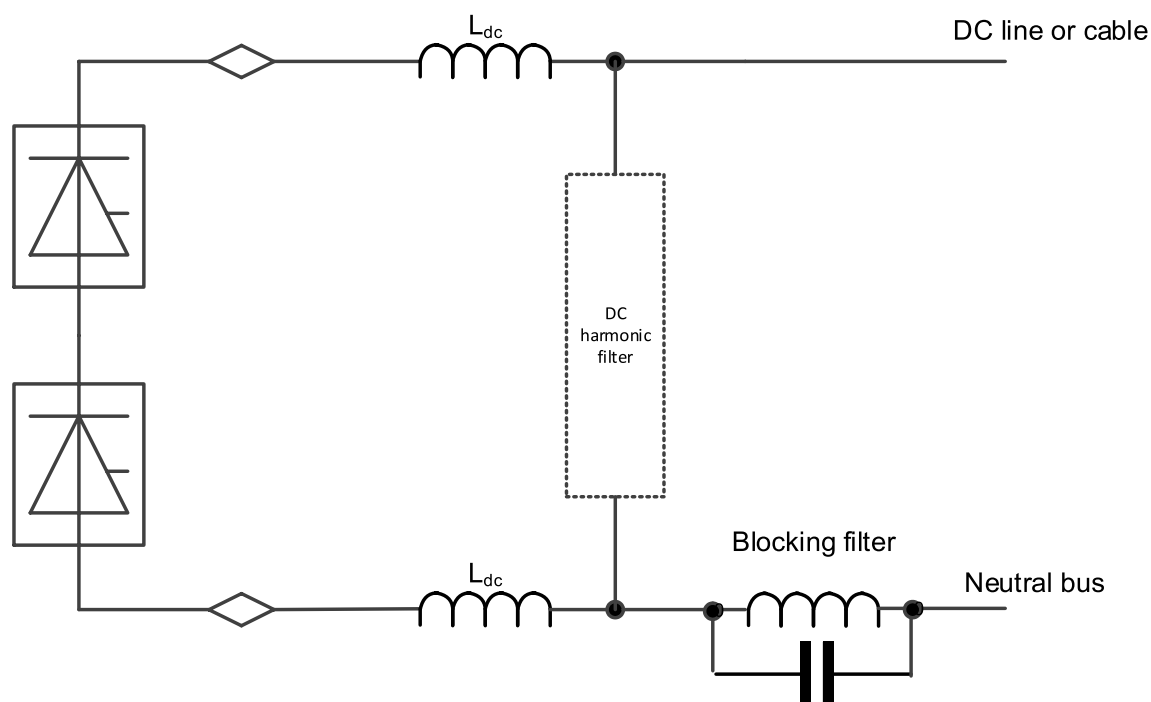
A.3.2 Series DC blocking filters

Although not common, a few transmission HVDC schemes have been built with a series blocking filter in addition to the more conventional shunt DC filters. This requirement typically occurs where the DC transmission line runs in close proximity to AC lines and there is a risk of induced fundamental-frequency voltage in the HVDC connection. The fundamental-frequency current reaching the converter, due to the induced voltage, needs to be limited to an acceptable level in order to prevent DC and second harmonic components of current appearing on the AC side of the converter.

In contrast to conventional DC harmonic filters (which are shunt-connected and designed to present a low impedance at particular frequencies), blocking filters are series-connected and designed to present a high impedance at a particular frequency – usually the fundamental frequency.

The blocking filter consists of a reactor in series with the DC circuit (which could either be part of the DC smoothing reactor or a separate reactor) and a tuning capacitor connected in parallel with it (Figure A.3). Where the blocking filter is designed with the smoothing reactor, typically only a part of the smoothing reactor's inductance is equipped with a tuning capacitor. This part is normally located in the neutral bus of each pole.

Because blocking filters are usually tuned to 50 Hz or 60 Hz, both the capacitor and the inductor tend to be very large. As a result, a blocking filter is a costly item of equipment which should only be specified when absolutely necessary.



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Figure A.3 – Series blocking filter

Blocking filters are equally effective whether installed in the high-voltage or neutral connections, so to minimise insulation requirements they are usually placed in the neutral, between the shunt DC filters and the electrode line or metallic return conductor.

A.4 DC bushings

Bushings are used anytime it is necessary to bring a high-voltage busbar connection through a solid barrier. On the DC side of the converter, this occurs in two main locations: wall bushings to bring the DC connections out of the valve hall or DC hall, and on oil-insulated DC smoothing reactors. The latter are now relatively uncommon in new HVDC schemes, so the main application of DC bushings is for wall bushings. On HVDC schemes with two more independently operable converters per pole, the separate converters are usually installed in adjacent valve halls – which will require wall bushings between adjacent valve halls as well as to the DC yard.

DC bushings are classified mainly according to the type of insulation used. Insulation of bushings may be divided into the insulation of the active part (capacitive grading) and the insulation of the passive part (gap between active part and outer insulation).

The active part is usually oil-impregnated paper or resin-impregnated paper. The rest may be solid, liquid (e.g. oil) or gas (e.g. SF_6). Housings may be of porcelain (more common with older, oil-filled bushings) or composite.

Oil-filled porcelain bushings were widely used on HVDC schemes up until the 1980s but are not commonly used today. The main reason for this is that such bushings have proved vulnerable to flashover as a result of pollution or uneven wetting – particularly at higher direct voltages. Various techniques have been proposed to mitigate such problems, including water spray washing and coating the external surfaces with various types of water-repellant grease or silicone elastomer, but with only limited success. A further disadvantage of such bushings is that the large quantity of oil they contain can create a serious fire risk in the event of a rupture of the bushing.

Composite-housed bushings usually comprise a glass-fibre reinforced polymer structural tube with silicone elastomer sheds applied to the outside. The silicone sheds have proved much more resistant to flashovers under DC conditions than porcelain housings, even under highly polluted conditions.

The internal insulation of such bushings can be either solid (epoxy-resin-impregnated paper) or gaseous. The insulating gas is normally sulphur hexafluoride (SF_6). Solid bushings are used mainly up to around 500 kV DC and gas-insulated bushings above that voltage.

A.5 Instrument transformers

A.5.1 General

Conventional, iron-cored current transformers and voltage transformers cannot be used to measure currents or voltages that contain a DC component because the core saturates. For the DC-side equipment of an HVDC converter station, the only place where conventional instrument transformers could be used is for the protection of the DC filters, where the only currents flowing are AC currents at harmonic frequencies. However, conventional CTs have limited performance at harmonic frequencies.

For all other cases, where measurement of a direct voltage or current is required, special instrument transformers are needed.

A.5.2 Direct voltage measurement

Measurement of direct voltages is normally achieved by a capacitive-resistive voltage divider (Figure A.4).

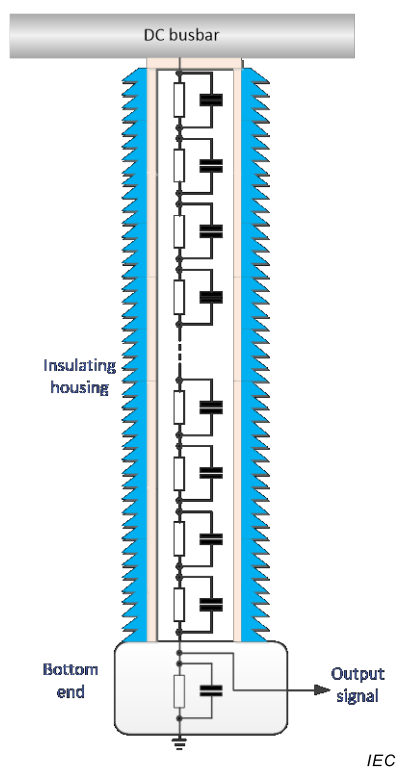


Figure A.4 – Resistive voltage divider for measurement of direct voltage

A resistive voltage divider typically comprises a large number of identical resistance elements in series at the "top end", coupled to a single stage in the "bottom end", across which the output signal is tapped. For voltage measurement of the high-voltage DC bus, voltage ratios are extremely high (typically 50 000:1 or 100 000:1).

DC voltage dividers are very rarely purely resistive because the bandwidth of such a divider would be very poor. Each resistance stage almost always has a grading capacitor in parallel to it, in order to improve the accuracy of the divider at harmonic frequencies and during step responses.

The high-voltage part of the voltage divider is enclosed in a porcelain or composite insulating housing (not unlike that of a bushing) and the internal space is usually filled with oil, epoxy resin or an insulating gas such as SF₆ or dry nitrogen.

In principle, such a resistive voltage divider can step down the full DC bus voltage (typically 500 kV) to an appropriately low voltage to be fed into the control and protection equipment (<10 V). However, this involves transmitting the low-voltage output signal for considerable distances in the switchyard, making induced voltage pick-up a potentially serious problem. To counteract this effect, DC voltage dividers with traditional analogue outputs can use a two-stage voltage division, using an intermediate voltage for transmission to the control and protection equipment, which is stepped down a second time within the control room.

An alternative approach that is becoming more popular is to digitise the low-voltage DC signal directly at the base of the voltage divider. The digital signal can then be transmitted either optically or electrically with far greater immunity to interference. Since modern control and protection systems are invariably digital, any analogue signals would, in any case, need to be converted to digital at some stage. IEC 61850-9-2 defines a sampled-value transmission protocol suitable for substation applications and IEC 61869-9 specifies the digital interface for instrument transformers using IEC 61850-9-2.

A.5.3 DC current measurement

A conventional, iron-cored current transformer uses a primary winding (normally just a length of busbar) passing through a toroidal magnetic core onto which a secondary winding is wound. The secondary winding is connected to a burden resistor whose value is known very accurately. The voltage across the burden resistor is proportional to the current induced in the secondary winding and, therefore, provided conditions leading to saturation of the core are avoided, also the primary current.

However, this approach is not suitable when the measured current contains a DC component, so an alternative approach is needed.

Several possibilities exist but three of the most common methods are listed below:

- zero-flux CT;
- resistive shunt;
- optical measurement.

A zero-flux CT (Figure A.5) is, in effect, an active version of a conventional CT. The difference is that instead of passively relying on the current induced in a secondary winding, the current in the secondary winding becomes the controlled parameter and is continuously adjusted by a suitable power amplifier such that, at all times, the secondary flux (generated by the amplifier) cancels the primary flux and as a result the total magnetic flux in the core is zero. The primary flux always being compensated, the flux created by the secondary winding is proportional to the primary current. Without flux in the core, the core cannot saturate and, as a result, current transformers of this type are capable of measuring signals ranging from pure DC to moderately high frequencies in the range of 30 kHz.

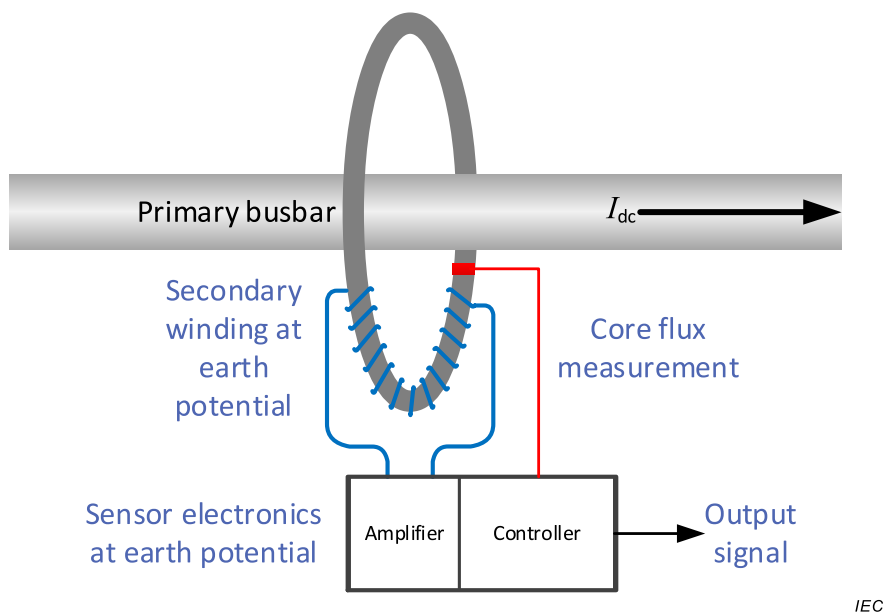
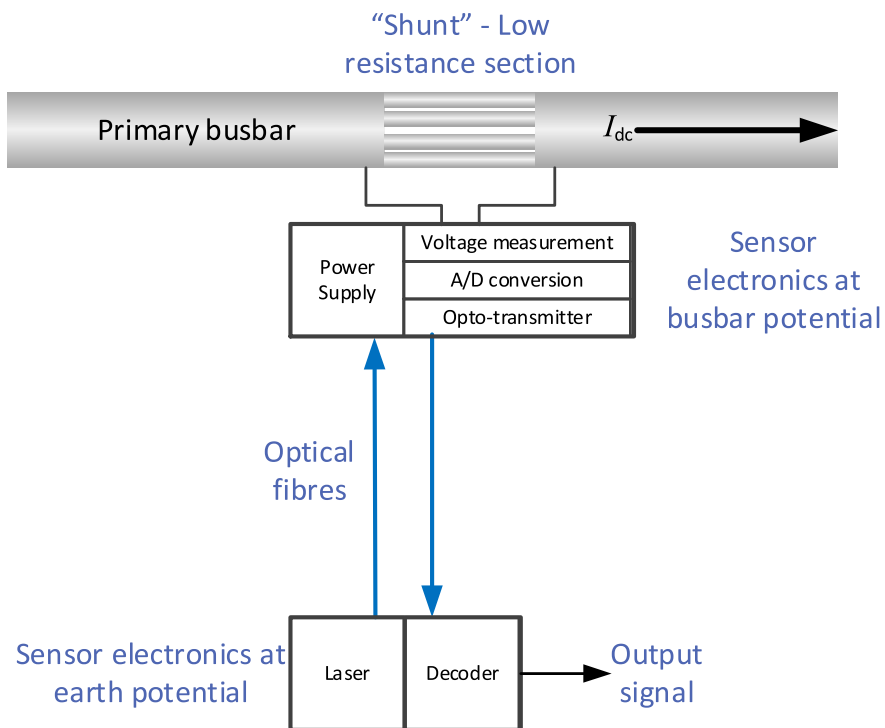


Figure A.5 – Operating principle of zero-flux CT (simplified)

In zero-flux CTs, the core and secondary winding are at earth potential. The insulation between the primary busbar and the secondary is provided as for conventional CTs:

- ring-type CTs can be used, either creating an adequate air clearance (for lower voltage), or by using insulation given by other equipments (cables or bushings);
- a suitable HV insulation is provided by different techniques, resin, oil-impregnated paper or gas such as SF₆, generally together with an insulator for air insulation.

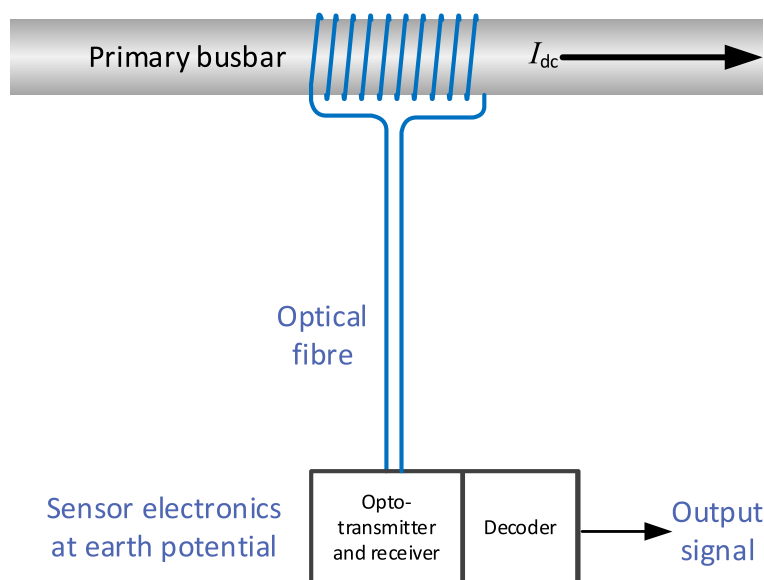
Another technique is to insert a low-value resistance (a "shunt") directly into the primary current path and to use the voltage developed across the resistor as a current measurement. However, this method is not as simple as it seems, because the shunt is always at HV potential that is different to that of the control and protection equipment into which the signal is to be fed. So the output signal needs to be transmitted from very high potential (up to the full pole direct voltage) to the control and protection electronics at earth potential. This leads, in turn, to the problem of how to provide power to the electronics at the busbar potential. With developments in opto-electronics, it is now possible to use a laser power source at earth potential, coupled into an optical fibre, which is coupled at the high-voltage end to a photovoltaic cell. With this arrangement (illustrated in Figure A.6) the interface between the high-voltage electronics and earth consists of only two optical fibres, with the result that this technique is very easy to extend to very high voltages.



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Figure A.6 – Current measurement by resistive shunt using optical powering

The third common technique is to use optical current measurement. This makes use of the "Faraday effect", whereby the plane of polarisation of light is rotated under the influence of a magnetic field. With this technique (Figure A.7), a single optical fibre is passed from earth potential up to the busbar whose current is to be measured, is wound around the busbar a number of times and then returned to earth potential. Comparison between the polarisation plane of the outgoing and incoming signals provides a direct measurement of primary current.



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Figure A.7 – Optical current measurement

Like the optically powered shunt, this technique is very simple to extend to very high voltages because of the minimal insulation requirements between primary and secondary, and has the further advantage that no electronic equipment is required at the high-voltage side. All the electronic equipment can be kept within the safe environment of the control room.

A.6 Surge arresters

Surge arresters are used for overvoltage protection of key equipment within the HVDC converter station, in much the same way as they are used for protecting AC equipment. IEC 60071-5 provides a detailed description of the insulation coordination process for an HVDC converter station and IEC 60099-9 includes general requirements for DC surge arresters.

One of the defining characteristics of DC arresters is that the voltage existing between the terminals of the arrester in steady state has a different character when compared with AC arresters. AC arresters normally experience only sinusoidal AC voltage between their terminals but DC arresters experience a combination of a DC component of voltage, an AC component (on the valve arresters) and notches and high-frequency transients caused by the firing and recovery of the valves in the bridge.

Since surge arresters are highly non-linear, a small increase in voltage results in a disproportionate increase in current, and therefore heating. The safe working voltage of a surge arrester therefore depends almost entirely on the peak of the applied voltage rather than its RMS value alone. However, in DC applications, the presence of high-frequency transients cause by valves turning on and off means that it is necessary to distinguish between two types of peak voltage:

- The peak values of those parts of the operating voltage that are fed by a low-impedance source (the AC power system). Because the source impedance is very low, the surge arrester will have no mitigating effect on such voltages and the applied voltage source (which is essentially the AC voltage of one or more phases of the converter transformer valve winding) can be considered as an ideal voltage source. The peak voltage arising from such low-impedance sources is referred to as the crest continuous operating voltage (CCOV).
- The peak values of those parts of the operating voltage that are fed by a high-impedance source. This primarily refers to the commutation transients resulting from turn-off (and to a lesser extent, turn-on) of the valves. The high source impedance of these transients means that the arrester exerts an appreciable "clipping" action on these transients, which means that the peak voltage experienced by the arrester is lower than it would have been had the arrester not been there. The energy fed into the arrester as a result of such transients is therefore less than from a voltage of the first type with the same amplitude and duration. The peak voltage arising from such high-impedance sources is referred to as the peak continuous operating voltage (PCOV). In addition to continuous voltage stresses, temporary/transient overvoltages also need to be considered for the arrester design.

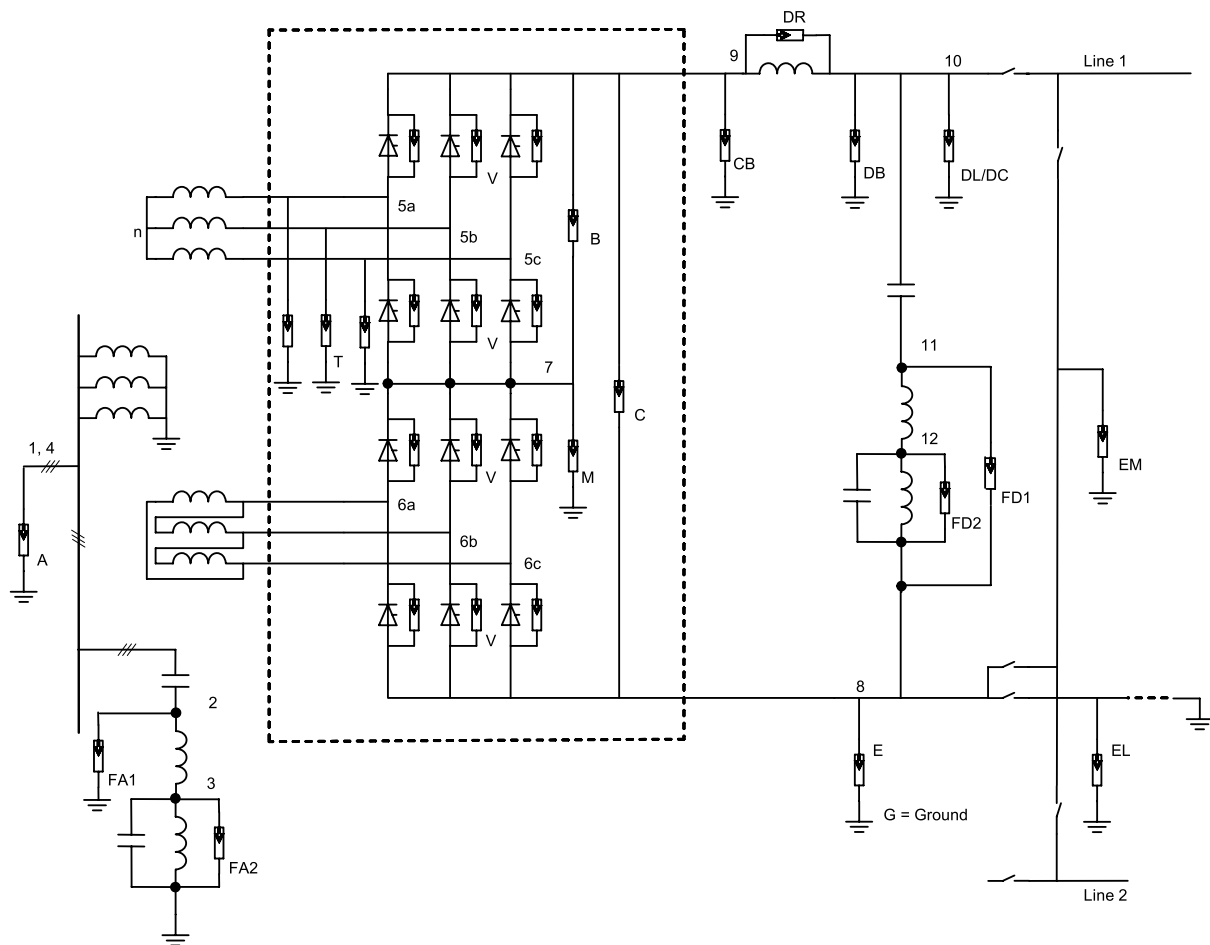
Typical locations of surge arresters in an HVDC converter station are illustrated in Figure A.8. Not every arrester shown in Figure A.8 will necessarily be required on every project and not all of the arresters shown in Figure A.8 are in the scope of this document, but the following DC-side arresters are always needed on transmission schemes:

- Across each valve (type V). This is one of the most critical types of arrester, as well as being the most numerous (since each converter station commonly contains 24, and sometimes 48, valves). The protective level of the valve arrester is a very important parameter and should preferably be as low as possible without risking thermal overload of the arrester, since it has a direct influence on the number of thyristor levels in the valve, and hence on the cost of the valve. The valve arresters are normally mounted inside the valve hall, close to the valves, and therefore benefit from the clean, dry environmental conditions of the valve hall.

- Across each 6-pulse bridge (types B and M). In schemes with a single 12-pulse bridge per pole, an arrester is usually connected directly across the upper bridge (type B) but the lower bridge is protected by an arrester from the DC midpoint to earth (type M). The bridge and mid-point arresters are normally set with protective levels slightly above that of the valve arresters, and are normally mounted inside the valve hall, close to the valve arresters.
- From the high-voltage DC bus to earth (types CB, DL, DB, DC). The DC bus may be protected in several different locations, including at the converter terminals (CB), the line side of the DC smoothing reactor (DB) and at the cable or line termination (DL or DC). Not all are necessarily required on a given project but there is always at least one such arrester and frequently two. These arresters are located outside the valve hall.
- From the DC neutral bus to earth (types E, EL, EM). Depending on the neutral bus arrangement, the DC neutral bus is normally protected by arresters to earth directly at the converter neutral potential, outside the valve hall (type E), on the electrode line side of the MRTS (type EL) and on the metallic return side of the ERTS (type EM). These arresters are located outside the valve hall.

In addition, the DC smoothing reactor is often (but not always) protected by a parallel-connected surge arrester (DR). The auxiliary (tuning) components of the DC filters are also protected by several surge arresters (FD) but the arrangement of those surge arrester varies greatly according to the arrangement of the filters themselves.

On back-to-back HVDC schemes, the arrangement of DC arresters is greatly simplified and normally only the valve, bridge and midpoint arresters (V, B, M) are needed. As a result, all arresters are located within the valve hall.



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Key

A:	AC bus arrester	EM:	metallic return arrester
M:	mid-point bridge arrester	EL:	electrode line arrester
E:	DC neutral bus arrester	B:	bridge arrester (6-pulse)
V:	valve arrester	C:	converter unit arrester
T:	transformer valve winding arrester	DB:	DC bus arrester
DR:	smoothing reactor arrester	DC:	DC cable arrester
DL:	DC line arrester	FD1, FD2:	DC filter arresters
FA1, FA2:	AC filter arresters		

T is unnecessary if the combination of M and V protects the secondary circuit of converter transformers.

DR is required depending on smoothing reactor insulation design

CB: converter bus arrester

Figure A.8 – Typical arrangement of surge arresters in a converter station with one 12-pulse bridge per pole (only one pole shown)

Requirements for energy ratings for DC-side surge arresters should be defined by system studies/ insulation coordination.

A.7 Electrode line monitoring and protection equipment

On HVDC transmission schemes using earth return, the earth electrode is always located at some distance from the converter station and connected to it via a medium-voltage electrode line. Commonly, two separated lines are provided in parallel, for redundancy. Monitoring and protection of the electrode line can be quite complex, especially since the electrode site is usually chosen to be in a remote area where availability of auxiliary power supplies may be limited. Furthermore, the current at the electrode line can vary in a range from 0 p.u. (bipolar balanced operation) to full load current (monopolar operation) and since the HVDC converters act as current sources, the fault current is of comparable magnitude to the electrode line current.

In order to prevent risk of injury to humans and livestock, it is important to be able to detect faults on the electrode line. Such faults can include an open circuit conductor, a short-circuit from a conductor to earth and a high-impedance earth fault. [11] presents an overview of the main detection techniques, the main findings of which are summarised below.

Some types of fault can be detected using measurements only at the converter station end. A commonly used solution measures the current in each of the separated electrode line conductors and detects asymmetrical current sharing between the two conductors as a fault condition. Alternatively, by measuring the direct voltage and current at the converter station neutral bus, calculating from this the resistance of the electrode line and comparing the calculated resistance with the expected line resistance (which may need to be compensated for temperature), it is straightforward to detect open-circuit faults anywhere on the line, and short-circuit earth faults at some distance from the electrode. Open-circuit faults result in an impedance that is higher than expected (i.e., the neutral bus voltage becomes unexpectedly high for the current that is flowing); short-circuit faults well away from the electrode, by comparison, result in lower than expected impedance.

By comparing the current in the two electrode line conductors, it may also be possible to detect an increase of leakage current from the insulators of one of the conductors; however, short-circuit faults close to the electrode and high-impedance faults are difficult to detect accurately by this method.

If auxiliary power supplies are available at the electrode station, together with a reliable communication medium between the electrode station and converter station, then differential current protection can detect a wider range of types of fault than the simple impedance-based method described above. The principles are similar to those used for differential protection of AC lines except that the current transformers need to be suitable for measuring DC (see A.5.3). Nevertheless, on bipolar schemes the accuracy of such schemes is severely limited by the fact that the typical electrode line current in bipolar mode is comparable with the measurement accuracy of the transducers (of the order of 1 %). The use of dual-range DC current transformers could be considered as a method of improving the detection accuracy in such circumstances.

It may also be necessary to include systems for determining the location of the fault. One technique that has been proposed for this is to include coupling capacitors to earth at both ends of the electrode line with current transformers to measure pulse currents flowing in the capacitors. When a short-circuit fault occurs, it results in a voltage step that travels along the electrode line in both directions at a predictable velocity. When the voltage step reaches one of the coupling capacitors, it results in a short current pulse. With accurate GPS clocks at both ends to record the timing of such current pulses, the location of the fault can be determined to within a few hundred metres. However, this too requires auxiliary power supplies at the electrode station and communications between there and the converter station.

If power supplies are not available at the electrode station, reliable detection of all types of fault is very difficult. One method that has been used is to inject a medium-frequency AC voltage onto the electrode line at the converter station, fit line traps tuned to that frequency at both ends of the line to be protected (Figure A.9) and measure the AC current flowing in the electrode line. Under normal operating conditions, the line traps present a high impedance at the injected frequency and, as a result, very little current flows. In the presence of an earth fault however, a return current path is opened up back to the converter station, resulting in an increase of current. However, the choice of injection frequency needs to be made with care in order to avoid unwanted interference due to converter-generated harmonics, and the technique is impractical for very long electrode lines.

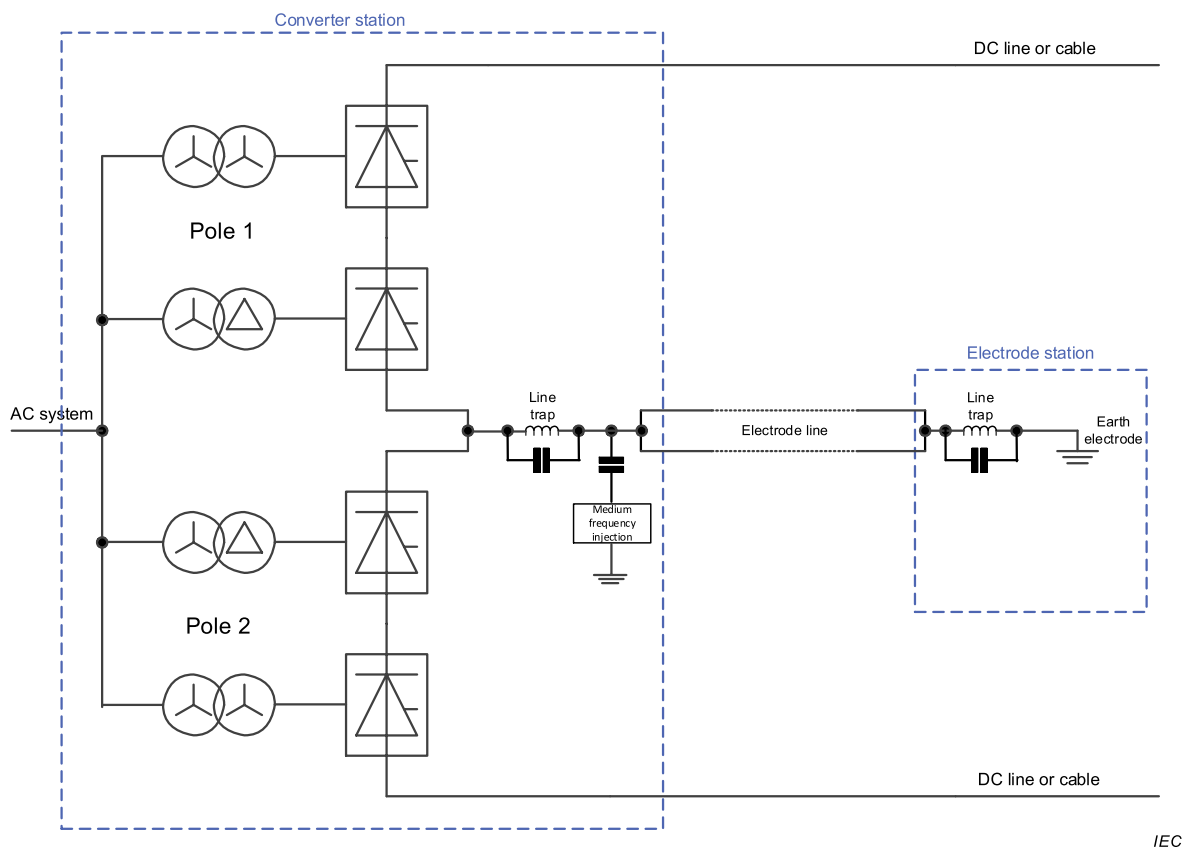


Figure A.9 – Electrode line monitoring by AC current injection

A variant of the injected current method involves fitting additional AC current transformers at the remote end and applying differential protection principles as for a conventional AC system. This technique has been used successfully on at least one HVDC scheme but, like some other methods, requires power supplies at the remote end and communications between ends.

A further alternative is to use a pulse echo technique with time-domain reflectometry. This involves injecting a single high-frequency pulse into the converter-station end of the line and analysing the strength and timing of the reflected signal. However, while quite effective on short electrode lines, this technique becomes ineffective on very long lines because of the high attenuation of the signal.

The voltage and current measurements used for detection of electrode line faults need to be digitised and fed into a controller of some type. Depending on the application, this controller could either be part of the main protection and control system of the HVDC link, or could be a separate programmable logic controller (PLC).

Annex B (informative)

DC switching devices for HVDC converter stations

B.1 General

Transmission HVDC schemes commonly include several quite specialised types of DC switching device on the DC side of the converter. DC switching device types that fall within the scope of this document lie in three categories: DC disconnectors, earthing switches and various types of DC commutation switch. CIGRÉ JWG A3/B4.34 [12] presents a comprehensive overview of all types of DC switching devices for HVDC systems.

NOTE DC circuit-breakers designed to interrupt fault currents are excluded from the scope of this specification. Although they are likely to form an important part of future DC multi-terminal systems, at the time of writing, the technology is not sufficiently mature to warrant standardisation.

DC disconnectors perform the same function as their counterparts in AC substations and are used in much the same way – to isolate other items of equipment so that maintenance or repair activities may be carried out. The main respect in which such disconnectors differ from their AC counterparts is that the insulating gap and the insulation to earth need to withstand direct voltages, often for long periods of time. The same comments apply also to earthing switches. [13] discusses the requirements of DC disconnectors and earthing switches in some detail.

DC commutation switches, however, are more complex. A number of different functions may be required, depending on the type of HVDC scheme, and the arrangements of converters and DC conductors. [14] discusses the requirements and duties of the most common types of commutation switch in some detail and only an overview is given here. Each different function has its own set of special characteristics. The clauses that follow provide an overview of the main characteristics for the more commonly-used types of DC commutation switch.

Commutation switches are so-called because their main role is to commutate current out of one conducting path and into another in parallel with it (which might have higher impedance). Hence, although they do have a requirement to open while current is flowing, they do not actually interrupt the current.

A second important requirement of commutation switches is that, having commutated current into the alternate path, they then have to withstand a transient voltage followed by a direct voltage afterwards. The severity of current commutation duty and subsequent direct withstand voltage vary according to the application; the cases requiring the highest commutating duty generally need only a modest direct voltage requirement (tens of kilovolts) but there are some applications requiring more modest commutating duty followed by full-rated direct line voltage. Likewise, the operating speed requirements vary according to the application.

Back-to-back HVDC schemes and monopolar transmission schemes with only a single converter bridge per pole generally do not require any DC commutation switches. DC commutation switches are normally used on the following types of HVDC scheme:

- bipolar schemes, where four different types of switch (metallic return transfer switch, earth return transfer switch, neutral bus switch and neutral bus earthing switch) are commonly used (Figure B.1);
- schemes where two or more, independently operable, 6-pulse or 12-pulse valve groups are connected in each pole. In such cases a "bypass switch" is used in parallel with each valve group (Figure B.2);

- schemes where additional HV conductors are provided and there is a requirement to connect or disconnect them in parallel with (or instead of) the main pole HV conductors while the scheme is running. In such cases, one or more "paralleling/de-paralleling switches" may be needed (Figure B.3).

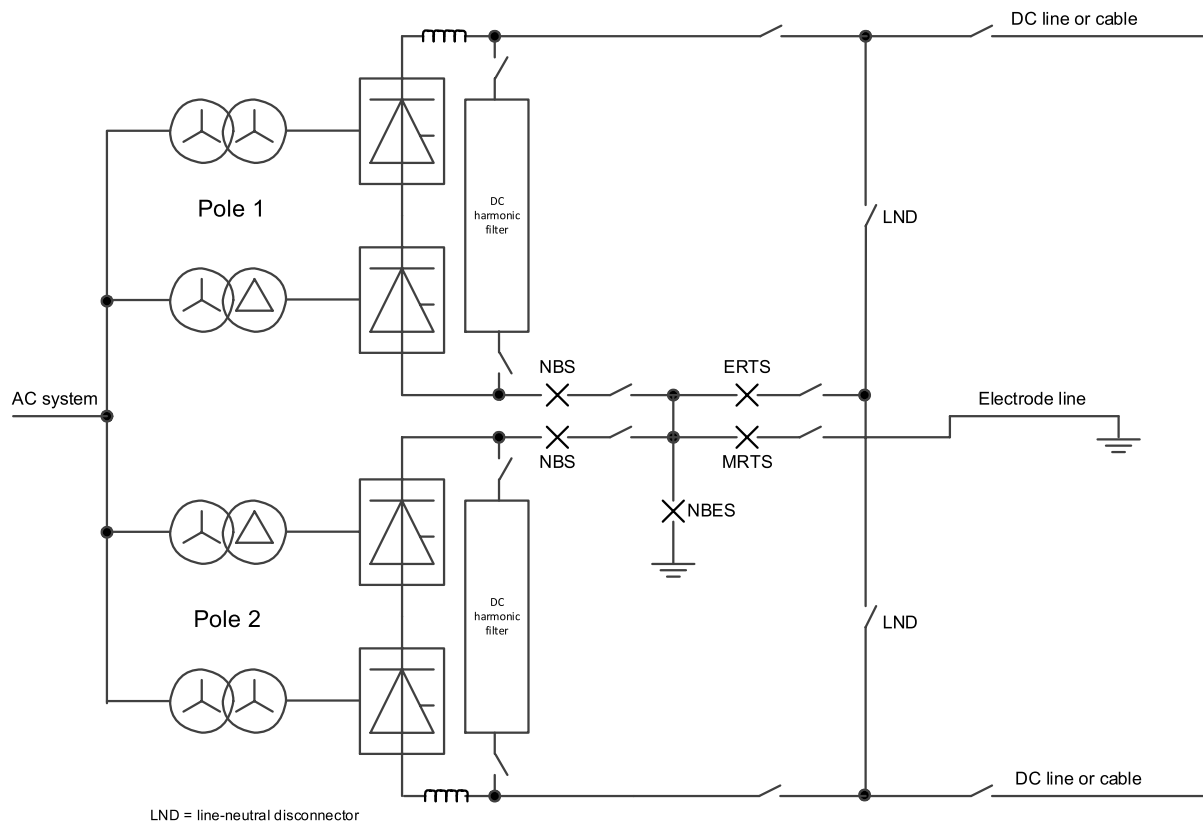
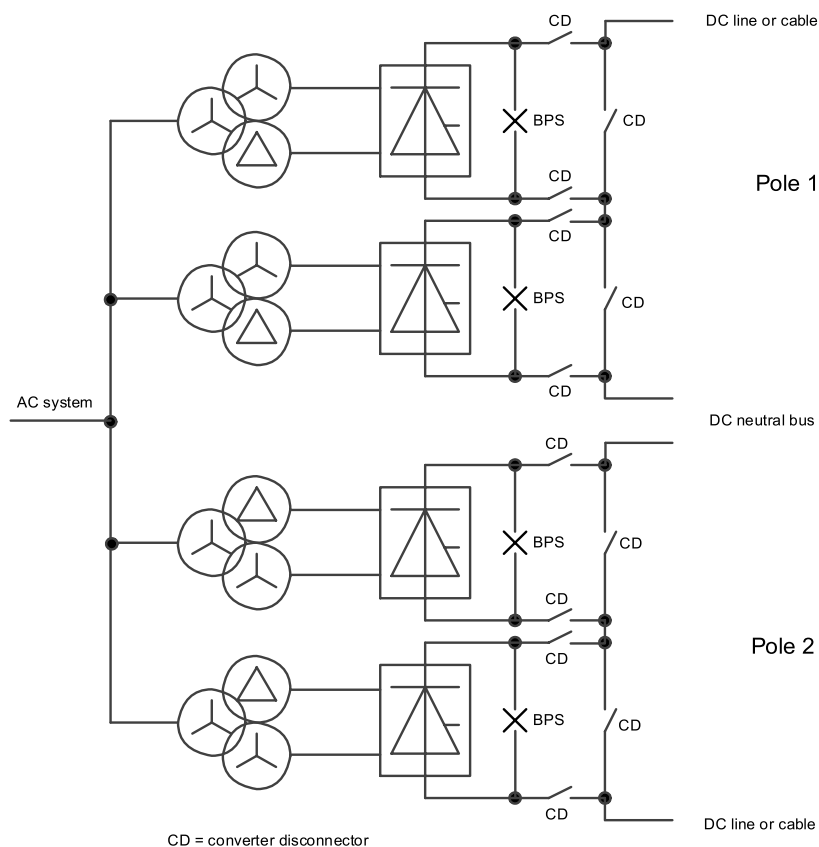
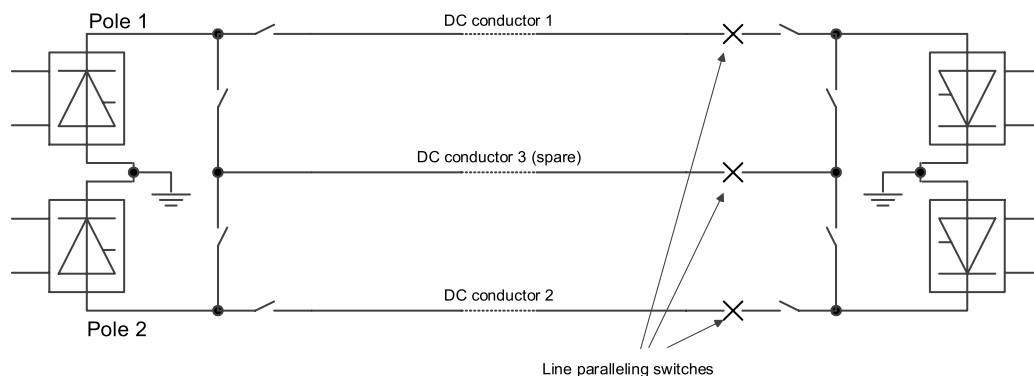


Figure B.1 – Typical arrangement of DC switching devices for a bipolar transmission scheme with one 12-pulse bridge per pole



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Figure B.2 – Typical arrangement of bypass switches and disconnectors for a bipolar transmission scheme with two 12-pulse bridges per pole



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Figure B.3 – Example arrangement of line paralleling switches for a bipolar HVDC transmission scheme

B.2 Typical DC switching device applications

B.2.1 Metallic return transfer switch (MRTS) and earth return transfer switch (ERTS)

On bipolar transmission HVDC schemes equipped with earth return, it is common to allow one of the pole conductors to be used instead of earth return in cases where a converter in one pole is out of service. Operating the scheme in this "metallic return" mode avoids using up the operating life of the earth electrodes and avoids the associated environmental risks, such as drying out of the soil and corrosion of underground metallic structures. However, it requires changeover switching devices to force the return current out of the earth path and into the metallic return path. The metallic return transfer switch (MRTS) is a commutation switch placed in series with the electrode line. Its function is to provide a commutating EMF high

enough to force the DC return current out of earth and into the available pole conductor. The earth return transfer switch (ERTS), also known as the ground return transfer switch (GRTS) is connected in series with one of the pole conductors via a disconnecter. The ERTS plays the opposite role to the MRTS, transferring current out of the metallic return path and into the earth path, and the two switches are normally controlled as a complementary pair. It is unnecessary to provide an MRTS and ERTS at both ends of the scheme, so usually only one end is so equipped, but the MRTS and ERTS should be located at the same converter station.

NOTE The MRTS and ERTS are also referred to as MRTB (metallic return transfer breaker) and ERTB (earth return transfer breaker) although these terms can be confusing since these switches have no ability to interrupt fault current.

The sequence of events for a transfer from earth return to metallic return is as follows:

- ensure that the converter(s) at both ends of the pole whose conductor is to be used as the metallic return, are isolated from the DC line and neutral bus;
- close the high-voltage line-neutral disconnecter (reference LND in Figure B.1) in the out-of service pole at each end of the scheme;
- close the ERTS: earth return and metallic return are now connected in parallel although the higher resistance of the metallic return means that most current is still flowing in the earth path;
- open the MRTS: this creates a commutating EMF of some tens of kilovolts which forces the current out of the earth path and into the metallic return path;
- open the disconnecter in series with the MRTS.

The sequence of events for a transfer from metallic return to earth return is as follows:

- ensure that the electrodes and electrode lines at each end of the scheme are healthy;
- close the disconnecter in series with the MRTS;
- close the MRTS: earth return and metallic return are now connected in parallel, most of the current will flow in the earth but some current will continue to flow in the metallic return;
- open the ERTS: this creates a commutating emf of some tens of kilovolts which forces the current out of the metallic return path and into the earth path;
- open the high-voltage line-neutral disconnecter (reference LND in Figure B.1) in the out-of service pole at each end of the scheme;
- reconnect the high-voltage line to the converter;
- if required, the previously-de-energised converters can now be re-energised, allowing bipolar operation to resume.

The MRTS and ERTS are usually constructed from modified AC circuit-breakers. The main differences with respect to conventional AC circuit-breakers are that the breaker contacts usually have to withstand a direct voltage of some tens of kilovolts in the open position (which may require some changes of materials or geometry in the switching unit) and additional components are needed to help create a current zero in the interrupting chambers so that the current may be transferred to a parallel-connected surge arrester. The auxiliary components used to create the current zero are typically an inductor and a capacitor, which form a resonant circuit, as discussed further in B.3 below.

Of the two applications, the MRTS is usually the more demanding because it has to commutate current from a low impedance to a higher impedance and the direct voltage to be withstood in the open position is higher (in steady state, it is equal to the resistive volt drop along the metallic return conductor. Transiently a higher voltage is needed to ensure a rapid commutation or to withstand the higher resistive volt drop due to overcurrents, such as those arising from commutation failures).

Although the MRTS and ERTS are most commonly used with bipolar schemes provided with earth return, they may also be used on bipolar schemes even where a dedicated metallic return conductor is provided. There are several ways of using an MRTS for changing the return current path between the dedicated metallic return and the pole conductor. Such an arrangement could be used in monopolar mode (when the converter(s) of one pole are unavailable), to:

- connect the dedicated metallic return conductor in parallel with an un-used pole conductor (to reduce the power losses), or
- use the pole conductor instead of the dedicated metallic return in the event of damage to the latter.

Similarly, if a monopolar scheme is equipped with both dedicated metallic return and earth return (for example, so that earth return can be used in emergencies), an MRTS and ERTS may be needed for the same purposes as on bipolar schemes.

The main important design parameters for the MRTS and ERTS are described in Table B.1.

Table B.1 – Summary of main parameters affecting specification of MRTS and ERTS

Parameter		Description of main factors to be considered
Current carrying capability in closed position	Permanent	Full load current of the HVDC scheme
	Short duration	Temporary overload current
Current commutating ability		Full load current plus temporary overload
Maximum operating voltage	Between open terminals	Equal to voltage drop in current path to which current has been commutated – typically some tens of kV (higher for MRTS than ERTS) continuously
	To earth	Voltage drop to earth of current path where the respective switch is located (low – typically <50 kV continuously)
Operating speed		Not critical. Times of 50 ms to 100 ms are usual but longer times could be acceptable.

B.2.2 Neutral bus switch (NBS)

The neutral bus switch (NBS) is provided on bipolar schemes, between the neutral end of the converters for each pole, and the neutral bus. Its function is to allow monopolar operation to continue (using either earth return or dedicated metallic return), in the event of a line to earth fault on one pole or the neutral bus during bipolar operation.

Usually, four NBSs are provided, one per pole per end. In normal bipolar operation all four NBSs are closed and the MRTS is closed in order to allow the "spill" current (the difference in current between the two poles, normally small) to flow into the earth. In the event of an earth fault on one pole, a transfer from bipolar mode to monopolar mode with earth return needs to be made quickly. To achieve this, the faulted converter and the corresponding healthy converter at the opposite end of the same pole are blocked and de-energised. However, under some conditions, a conducting path in the de-energised pole can remain, causing the load current to continue to be fed into the earth fault by the healthy pole. To counteract this effect, the NBS opens to transfer the load current into the return path (electrode line, pole conductor or dedicated metallic return). Like the MRTS and ERTS, the NBS is a commutation switch whose function is to transfer current from its own path into another path in parallel with it. Its characteristics and construction are normally similar to those of the MRTS and ERTS.

The main important design parameters for the NBS are described in Table B.2.

Table B.2 – Summary of main parameters affecting specification of NBS

Parameter		Description of main factors to be considered
Current carrying capability in closed position	Permanent	Full load current of the HVDC scheme
	Short duration	Temporary overload current
Current commutating ability		Full load current plus temporary overload
Maximum operating voltage	Between open terminals	Low – typically <50 kV continuously
	To earth	
Operating speed		Not critical. Times of 50 ms to 100 ms are usual but longer times could be acceptable.

B.2.3 Neutral bus earthing switch (NBES)

In bipolar schemes with earth or dedicated metallic return, a possibility exists for an open-circuit failure on the return line. This could give rise to damaging overvoltages on the neutral bus. To minimise damage from such events, a neutral bus earthing switch may be provided. The NBES is normally open but is ordered to close upon detection of such an open-circuit fault, creating a connection between the neutral bus and the station earth mat. The primary function of the NBES is therefore to close rapidly when commanded to do so.

The station earth mat is usually not designed to withstand full DC load current for prolonged periods of time, so the NBES is used only as an emergency measure for relatively short periods. In order to prevent damage to the station earth mat, the earth current should be reduced to the minimum possible (if operating in bipolar mode) or the scheme should be tripped (if operating in monopolar mode). If operation continues in bipolar mode with the earth current reduced to the minimum, the neutral line can be isolated by disconnectors. Repair carried out with the HVDC scheme continuing to run. After repair, normal earth return mode can be re-instated by opening the NBES to transfer the current back into the neutral line. For this reason, the NBES, like the MRTS, ERTS and NBS, needs to be a commutation switch although the current to be commutated is normally only a small fraction of normal load current.

On monopolar schemes with earth return, the NBES is not usually needed because with such schemes there is no alternative but to trip the complete scheme in the event of an open-circuit electrode line.

The main important design parameters for the NBES are described in Table B.3.

Table B.3 – Summary of main parameters affecting specification of NBES

Parameter		Description of main factors to be considered
Current carrying capability in closed position	Permanent	Low – a few % of load current (equal to the unbalance current in bipolar mode)
	Short duration	Full load current plus temporary overload
Current commutating ability		Low – typically < 10 % of full load current
Current making capability		Full load current plus temporary overload, in the case where a bipolar scheme was operating in monopolar mode (the scheme will normally be tripped soon afterwards). The rate of change of current can be very high since it is limited only by stray inductances around the loop from the NBGS to the neutral bus surge arrester
Maximum operating voltage	Between open terminals	Normally equal to voltage drop along return path, typically a few tens of kV, continuously. During faults, will be equal to neutral bus arrester protective level until NBES closes.
	To earth	Low – typically < 50 kV continuously
Operating Speed	Closing	Critical – closure within a few tens of milliseconds is needed to avoid excessive energy dissipation in neutral bus arrester.
	Opening	Not critical. Times of 50 ms to 100 ms are usual but longer times could be acceptable.

B.2.4 Bypass switch (BPS)

Although the majority of modern HVDC schemes only use a single 12-pulse converter bridge per pole, some HVDC transmission schemes have two or more separate 12-pulse converter bridges per pole. This measure limits the size of the converter transformers (which may be an important consideration because of transport restrictions) and reduces the amount of transmitted power that can be lost as a result of a single equipment outage. With this arrangement, a fault in one converter bridge allows the affected pole to continue operation at 50 % of normal direct voltage (assuming two 12-pulse bridges in series per pole), hence on a bipolar transmission scheme only 25 % of the nominal power is lost.

Similarly, older mercury-arc HVDC schemes were usually built with two, three or even four separate 6-pulse converter bridges per pole and were designed to operate with some of these bridges unavailable. This was necessary because of the high maintenance requirements of mercury arc valves.

On such schemes, a bypass switch (BPS) is provided in parallel with each independently operable converter bridge. The bypass switch is normally open but is commanded to close in response to a fault (or planned shutdown) of one converter bridge. The primary function of the bypass switch, like the NBES, is therefore to close rapidly when commanded to do so.

Closing of the BPS may take place at almost zero voltage (if a bypass pair of conducting valves has been formed in the bridge that is to be taken out of service) or at a high voltage approaching the peak valve-winding line to line voltage (if the converter bridge is operating at $\alpha = 90^\circ$). The rate of change of current in the BPS may therefore vary over a wide range.

Once the BPS has closed, a disconnecter connected in parallel with it is also closed to avoid the need for the BPS to carry the DC current for an extended period of time. Two other disconnectors, one each side of the converter, allow the faulted converter to be isolated for repair – see Figure B.2.

Compared with the commutation switches described in the four sub-clauses above, the BPS has only a modest opening (commutating) duty. The main requirement is fast closing – which may be required after a very prolonged period of time (years) in the open position with the entire bridge direct voltage between its open contacts. One of the most important design criteria for the BPS is therefore that it is safely capable of withstanding such direct voltage

stresses for long periods of time. This may affect the geometry and the choice of some insulating materials in the switch.

Nevertheless, the BPS has a modest commutating duty as well, which is experienced when a previously out-of-service converter group is being brought back into operation. The converter group is initially with zero voltage order and with a current order such that the load current is transferred from the BPS to the converter. The BPS is then required to commutate the residual DC current (mainly due to measurement errors) out of the BPS and into the converter. This duty is made easier by the fact that the BPS will experience a significant AC component of current, at 6th or 12th harmonic.

The main design parameters for the BPS are described in Table B.4.

Table B.4 –Summary of main parameters affecting specification of BPS

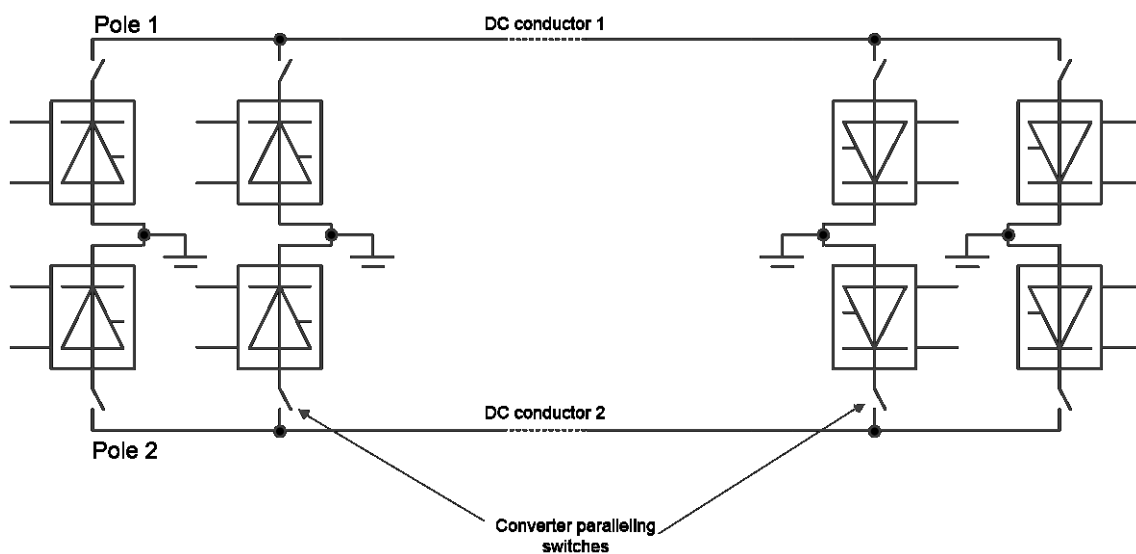
Parameter		Description of main factors to be considered
Current carrying capability in closed position	Permanent	Full load current of the HVDC scheme
	Short duration	Full load current plus temporary overload
Current commutating ability		Low – typically < 10 % of full load current
Current making capability		Full load current plus temporary overload. The rate of change of current may vary from very low to very high depending on whether the converter bridge being taken out of service was operating in bypass mode or at $\alpha=90^\circ$.
Maximum operating voltage	Between open terminals	High – equal to direct voltage of the converter unit across which it is connected (typically 250 kV to 400 kV continuously)
	To earth	High – equal to the direct voltage across the converter groups connected between the BPS and earth (for example, with two converter groups per pole, this is half the total pole voltage), continuously.
Operating Speed	Closing	Critical – closure within a few tens of milliseconds. is needed to avoid damage to faulted valve group
	Opening	Not critical. Times of 50 ms to 100 ms are usual but longer times could be acceptable.

B.2.5 Converter paralleling switch

On some HVDC transmission schemes, typically where two bipoles run in close proximity, it is advantageous to be able to connect converters in parallel onto a common DC transmission line. Sometimes the scheme is designed to operate in this way from the beginning (with the DC line rated to carry the entire power of both bipoles), as illustrated in Figure B.4, or in other situations it could be that the transmission lines for the two bipoles are normally separate but in the event of a line outage on one bipole, the converters of that bipole are connected to the remaining, healthy bipole.

In such cases, DC switches need to be connected in series with each converter unit to isolate the converter from the common DC line. The requirements of such switches depend on how the purchaser of the HVDC scheme intends to operate the converters, but in the majority of cases the switching duty is quite modest and, where operating speed is not a priority, can usually be handled by conventional disconnectors. In some designs, operating speed requirements may dictate that modified AC circuit-breakers are used as fast disconnectors.

There is normally no significant commutating duty because firing angle control of the converter to be switched on or off ensures that the switching takes place at almost no current – similarly to the case for the bypass switch.



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Figure B.4 – Example arrangement of converter paralleling switches for a bipolar HVDC transmission scheme

The main important design parameters for the converter paralleling switch are described in Table B.5.

Table B.5 – Summary of main parameters affecting specification of CPS

Parameter		Description of main factors to be considered
Current carrying capability in closed position	Permanent	Full load current of the HVDC scheme
	Short duration	Full load current plus temporary overload
Current commutating ability		Not required
Maximum operating voltage	Between open terminals	High – equal to pole direct voltage; normally continuously, although may be only for limited duration if separate disconnector is provided in series with the switch.
	To earth	Full pole direct voltage, continuously
Operating speed		Not critical. Times of 50 ms to 100 ms are usual but longer times could be acceptable. In some circumstances a conventional disconnector may be acceptable.

B.2.6 Line paralleling switch

Some HVDC transmission schemes may include more than two high-voltage conductors, typically in order to increase the availability of the scheme or sometimes to allow for higher overload capability. Many such configurations are possible and Figure B.3 illustrates one way of achieving this. In the arrangement shown in Figure B.3, the scheme is provided with three high-voltage conductors – one that is normally used for pole 1, one that is normally used for pole 2, and a spare. By the addition of appropriate DC switching devices, it is possible to arrange the spare conductor to be connected in parallel with or instead of one of the two main conductors. If both of the main high-voltage conductors are available, then the spare conductor can be connected in parallel with one of them to decrease the overall transmission losses. Noting that the thermal time-constant of the conductor can be quite long (especially with cables), it might also be advantageous to be able to switch the spare conductor alternately between pole 1 and pole 2. In this way, it is possible to obtain up to 50 % overload capability as long as the spare conductor is switched frequently enough for the other conductors not to reach thermal equilibrium.

This type of DC switch, referred to here as a line paralleling switch, is a commutation switch with a function similar to that of the MRTS and ERTS. The main difference lies in the fact that all of the active components of the switch, including any auxiliary components (such as inductors and capacitors) have to be at DC pole potential.

The main design parameters for the line paralleling switch are described in Table B.6.

Table B.6 – Summary of main parameters affecting specification of LPS

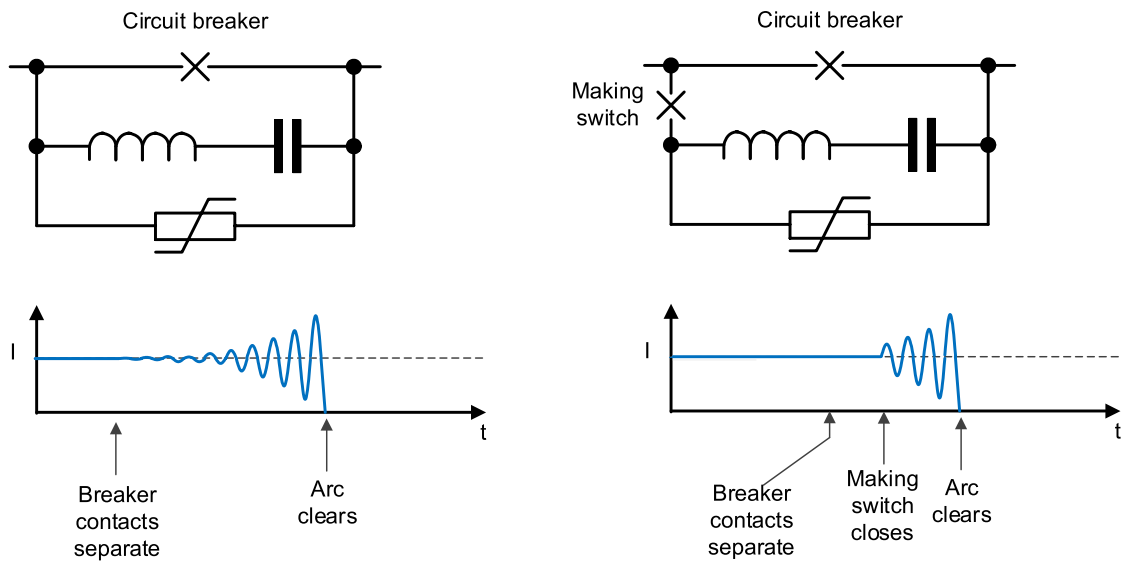
Parameter		Description of main factors to be considered
Current carrying capability in closed position	Permanent	Full load current of the HVDC scheme
	Short duration	Temporary overload current
Current commutating ability		Full load current plus temporary overload
Maximum operating voltage	Between open terminals	Equal to voltage drop in current path from which current has been commutated – typically some tens of kV, continuously
	To earth	Full pole direct voltage, continuously
Operating speed		Not critical. Times of 50 ms to 100 ms are usual but longer times could be acceptable.

B.3 Design

Most DC commutation switches used in LCC HVDC are modified standard AC circuit-breakers. Modifications may be required as a result of the need to withstand direct voltage between the open contacts for prolonged periods of time (this being the case especially for the BPS).

For applications where full load current has to be commutated (particularly the MRTS and ERTS), the most important modifications are concerned with the mechanism for creating a current zero so that the switch can commutate current into an alternative path. Usually this is done by creating a current oscillation superimposed upon the DC load current such that the total current in the breaker passes through zero.

The current oscillation may be created in several ways. One method (Figure B.5) involves placing a resonant inductor-capacitor (LC) circuit in parallel with the contacts of the breaker. The LC components might be purpose-built discrete components [15] but in some cases [16], switches of this type have been successfully built by using only the grading capacitors of the breaker chambers and the natural stray inductance.



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Figure B.5 – Commutation switch based on the divergent current oscillation method, without (left) and with (right) making switch

As illustrated in more detail in Figure B.6, when the contacts of the switch first separate, an arc is drawn between them. As with all electrical arcs, the voltage-versus-current characteristics are non-linear, voltage tending to fall as current increases. In other words, the slope resistance dU/dI is negative, an effect which is mathematically equivalent to a negative resistance. A negative resistance placed in parallel with an LC circuit will result in negative damping, which means that a current oscillation will slowly develop and grow, eventually becoming large enough (if the LC components are chosen with low stray resistance) to exceed the value of current being commutated, at which point the arc in the switch is able to extinguish.

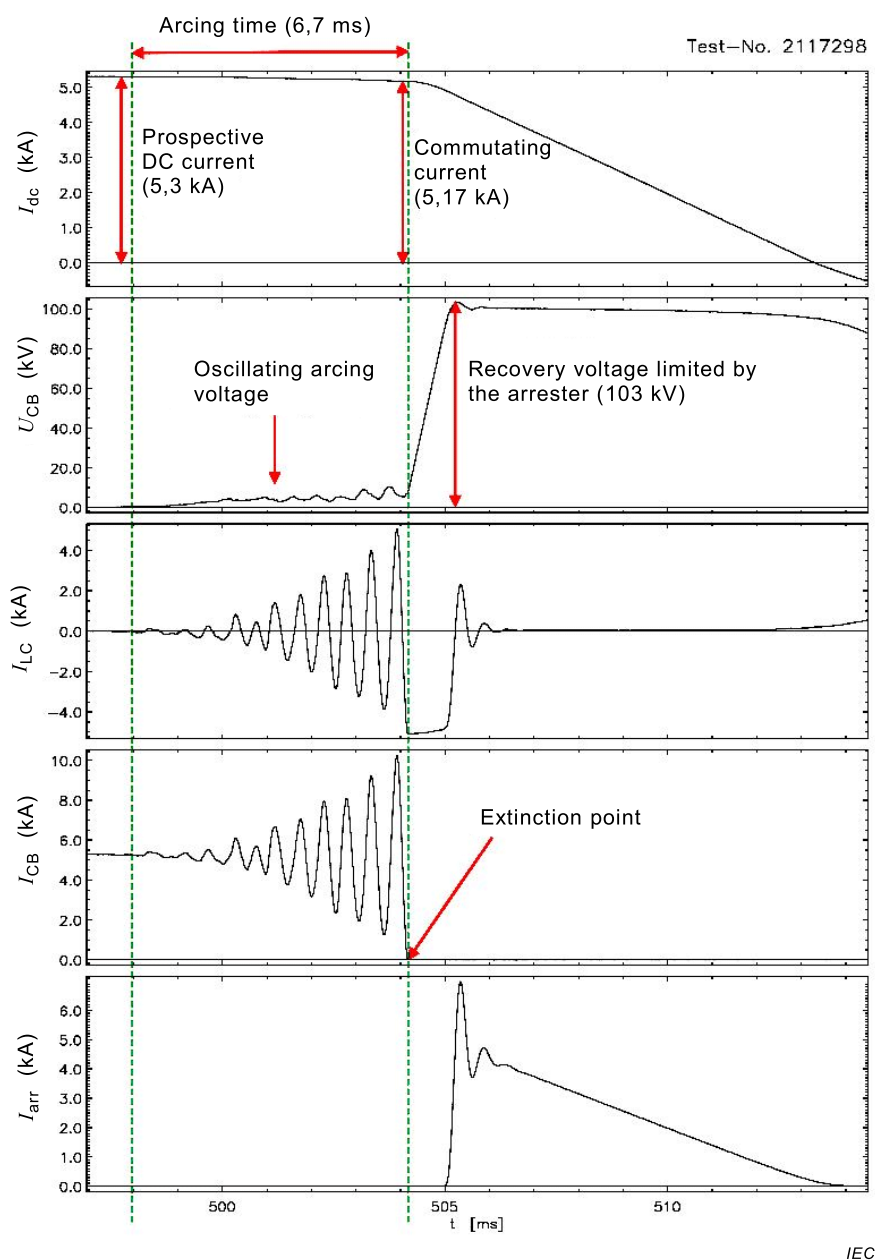


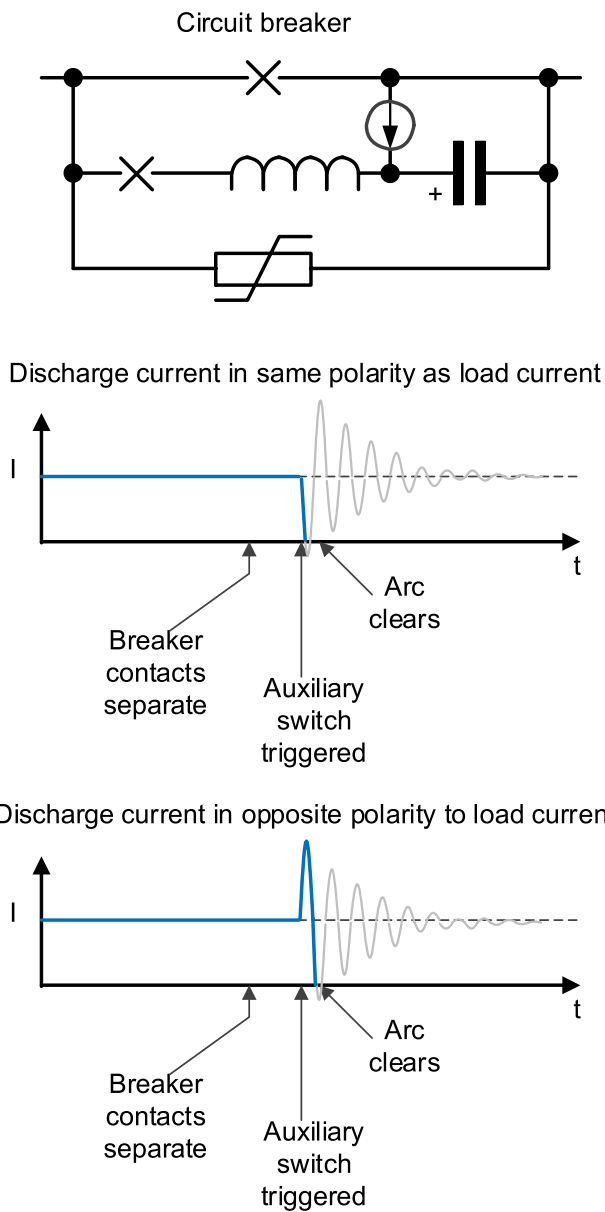
Figure B.6 – Oscillogram of a commutation event

The divergent current oscillation method described above requires fewer components than other alternatives but has the disadvantage that the time required for the oscillation to build up is both long (several milliseconds) and non-deterministic.

A minor variant of the above is to include a second, normally-open, circuit-breaker in series with the LC circuit (outside the main current path). The second breaker (or "making switch") is closed shortly after the main breaker contacts open so as to create a sudden step change of voltage in the resonant circuit, which helps to establish the current oscillation.

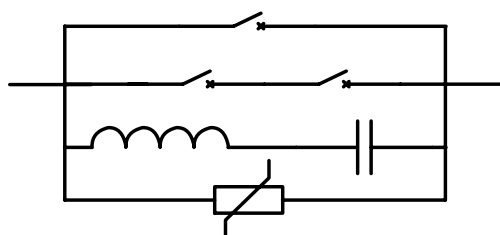
Much faster and more predictable clearing of the arc can be achieved if the capacitor in the LC circuit is pre-charged, since this can result in a current zero being reached in the first quarter-cycle of current oscillation (Figure B.7). The shorter arc duration keeps the erosion of the arcing zone within the switch lower than the case without a making switch. However, this approach is more complex and requires a pre-charging circuit.

In some projects with very high DC current ratings, a parallel arrangement of switches has been used (Figure B.8).



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Figure B.7 – Commutation switch with pre-charged capacitor



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Figure B.8 – Parallel arrangement of switches used at very high current

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