IEC TS 63291-1

Edition 1.0 2023-09

TECHNICAL SPECIFICATION

High voltage direct current (HVDC) grid systems and connected converter stations – Guideline and parameter lists for functional specifications – Part 1: Guideline

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colour inside

High voltage direct current (HVDC) grid systems and connected converter stations – Guideline and parameter lists for functional specifications – Part 1: Guideline

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HIGH VOLTAGE DIRECT CURRENT (HVDC) GRID SYSTEMS AND CONNECTED CONVERTER STATIONS – GUIDELINE AND PARAMETER LISTS FOR FUNCTIONAL SPECIFICATIONS –

Part 1: Guideline

FOREWORD

IEC TS 63291-1 has been prepared by IEC technical committee TC 115: High Voltage Direct Current (HVDC) transmission for DC voltages above 100 kV. It is a Technical Specification.

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

Draft	Report on voting
115/319/DTS	115/328A/RVDTS

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

This Technical Specification is to be used in conjunction with IEC TS 63291-2:2023.

A list of all parts in the IEC 63291 series, published under the general title *High voltage direct current (HVDC) grid systems and connected converter stations – Guideline and parameter lists for functional specifications*, can be found on the IEC website.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

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

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The "colour inside" logo on the cover page of this document indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

In the preparation of this document, special care has been taken to, as far as possible, describe the requirements in a technologically independent way. In order to achieve that, a function of interest is described by a comprehensive set of parameters. The parameters are selected based on a systematic analysis of physical phenomena relevant to achieve the requested functionality.

Reflecting the early stage of technology, the technical parameters need comprehensive explanations and background information. This need is reflected in the dual character of the content, which is presented in the two corresponding parts:

- IEC TS 63291-1, Guideline containing the explanations and the background information in context with the parameter lists;
- IEC TS 63291-2, Parameter lists containing the essential lists of parameters and values describing properties of the AC respectively DC system (operating conditions) and parameters describing the performance of the newly installed component (performance requirements).

IEC TS 63291-1 and IEC TS 63291-2 have the same structure to aid the reader.

At the time of writing there is no real-life multi-national, multi-vendor HVDC grid project to which the guideline and parameter lists can be applied. Practical experiences in the near future are expected to provide input for developing these guideline and parameter lists further.

HIGH VOLTAGE DIRECT CURRENT (HVDC) GRID SYSTEMS AND CONNECTED CONVERTER STATIONS – GUIDELINE AND PARAMETER LISTS FOR FUNCTIONAL SPECIFICATIONS –

Part 1: Guideline

1 Scope

This document contains guidelines on planning, specification, and execution of multi-vendor HVDC grid systems also referred to as HVDC grids. The terms "HVDC grid systems" or "HVDC grids" are used in this document to describe HVDC systems for power transmission having more than two HVDC stations connected to a common DC circuit. The DC circuit can be of radial or meshed topology or a combination thereof. In this document, the term "HVDC grids" is used.

While this document focuses on requirements specific for HVDC grids, some requirements are considered applicable to all HVDC systems in general, i.e., including point-to-point HVDC systems. Existing IEC (e.g. IEC TR 63363-1 [1]), Cigre or other relevant documents have been used for reference as far as possible.

Corresponding to electric power transmission applications, this document is applicable to high voltage systems, i.e. those having typically nominal DC voltages higher than 50 kV with respect to earth are considered in this document.

NOTE While the physical principles of DC networks are basically voltage independent, the technical options for designing equipment get much wider with lower DC voltage levels, e.g. in case of converters or switchgear.

This document covers technical aspects of:

- coordination of HVDC grid and AC systems,
- HVDC grid characteristics,
- HVDC grid control,
- HVDC grid protection,
- AC/DC converter stations,
- HVDC grid installations, including DC switching stations and HVDC transmission lines,
- studies and associated models,
- testing.

Beyond the scope of this document, the following content is proposed for future work:

- DC/DC converter stations.

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 60909 (all parts), *Short-circuit currents in three-phase AC systems*

IEC 61975:2010, *High-voltage direct current (HVDC) installations – System tests*
IEC 61975:2010/AMD1:2016
IEC 61975:2010/AMD2:2022

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

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

IEC 62747:2014, *Terminology for voltage-sourced converters (VSC) for high-voltage direct current (HVDC) systems*
IEC 62747:2014/AMD1:2019

IEC TS 63014-1, *High voltage direct current (HVDC) power transmission – System requirements for DC-side equipment – Part 1: Using line-commutated converters*

IEC TS 63291-2:2023, *High voltage direct current (HVDC) grid systems and connected converter stations – Guideline and parameter lists for functional specifications – Part 2: Parameter lists*

ISO/IEC 25010:2011, *Systems and software engineering – Systems and software Quality Requirements and Evaluation (SQuaRE) – System and software quality models*

3 Terms, definitions and abbreviated terms

For the purposes of this document, the following terms and definitions apply.

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

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

3.1 Terms and definitions

3.1.1
AC/DC converter unit
indivisible operative unit comprising all equipment between the PoC-AC and the PoC-DC, essentially one or more converters, together with interface transformers, control and protection equipment, essential protective and switching devices and auxiliaries, if any, used for conversion

Note 1 to entry: The term "converter transformer" is also used instead of "interface transformer".

[SOURCE: IEC 62747:2014, 7.5, modified – "AC/DC" has been added to the term; the definition has been neutralised with respect to technology (not only VSC converters) and uses the terms PoC-AC and PoC-DC as defined in 3.1.3 and 3.1.4 in this document.]

3.1.2
AC/DC converter station
part of an HVDC system which consists of one or more AC/DC converter units including DC switchgear, if any, DC fault current controlling devices, if any, installed in a single location together with buildings, reactors, filters, reactive power supply, control, monitoring, protective, measuring and auxiliary equipment

[SOURCE: IEC 62747:2014, 9.21, modified – "AC/DC" has been added to the term; the definition has been made specific with respect to AC/DC converter units, differentiating from

DC/DC converter units. Furthermore, only the term "AC/DC converter station" is used in this document; the note to entry has been deleted.]

3.1.3
PoC-DC
point of connection-DC
electrical interface point at DC voltage as shown in Figure 1

3.1.4
PoC-AC
point of connection-AC
electrical interface point at AC voltage as shown in Figure 1

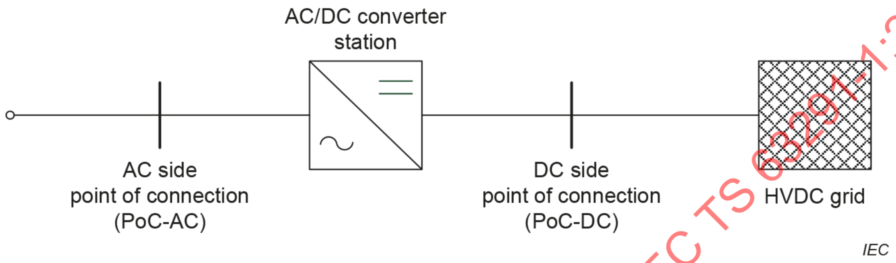


Figure 1 – Definition of the point of connection-AC and the point of connection-DC at an AC/DC converter station

3.1.5
DC/DC converter unit
indivisible operative unit comprising all equipment between the points of connection to the HVDC grid having different nominal DC voltage, essentially one or more converters, together with interface transformers, if any, control equipment, essential protective and switching devices and auxiliaries, if any, used for conversion

Note 1 to entry: The term "converter transformer" is also used instead of "interface transformer".

3.1.6
DC/DC converter station
part of an HVDC grid which consists of one or more DC/DC converter units including DC switchgear, if any, DC fault current controlling devices, if any, installed in a single location together with buildings, reactors, filters, control, monitoring, protective, measuring and auxiliary equipment, if any

3.1.7
DC line power flow controller
device connected in series with a transmission line inserting a DC voltage for the primary purpose of controlling the power flow in a meshed HVDC grid

Note 1 to entry: Series connected devices can also be used to insert into or absorb power from a transmission line for the purpose of compensating the voltage drop along the line or connecting load or generation.

3.1.8
DC grid protection zone
physical part of an HVDC grid with a distinct DC fault handling sequence

3.1.9
DC switching unit
indivisible operative unit comprising all equipment between the DC busbars and the terminals (HV poles and neutral, if any) of one point of connection on the DC side, comprising, if any, one or more switches, control, monitoring, protective, measuring equipment and auxiliaries

3.1.10
DC switching station
part of an HVDC grid with the primary purpose to establish electrical connections between AC/DC converter station and HVDC grid installations, such as transmission lines, DC/DC converter station, including connections to earth, if any, using one or more DC switches, installed in a single location together with buildings, reactors, filters, control, monitoring, protective, measuring and auxiliary equipment, if any

3.1.11
functional software-in-the-loop model
control and protection (C&P) model representing the relevant functionality and performance for testing, running on a simulation environment different from the original C&P equipment hardware

3.1.12
HVDC grid
high-voltage direct current transmission network connecting more than two AC/DC converter stations transferring energy in the form of high voltage direct current including related transmission lines, switching stations, DC/DC converter stations, if any, as well as other equipment and subsystems needed for operation

3.1.13
HVDC station
substation in or connected to an HVDC grid

EXAMPLE AC/DC converter station, DC/DC converter station, DC switching station.

3.1.14
inertia
<in an electric power system> property of a rotating rigid body according to which it maintains its angular velocity in an inertial frame in the absence of an external torque

[SOURCE: IEC TS 62898-3-3:2023, 3.1.18] [2]

3.1.15
meshed HVDC grid
HVDC grid having more than one direct current connection between at least two converter stations

3.1.16
metallic return conductor
insulated conductor between the DC neutral busbars of HVDC stations

3.1.17
NBES
neutral bus earthing switch
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

Note 1 to entry: To describe this type of switch, some standards use the term "neutral bus grounding switch (NBGS)".

[SOURCE: IEC 60633:2019, 9.27, modified – The terms "neutral bus grounding switch" and "NBGS" have been omitted and the note added.] [3]

3.1.18
nominal active power
value of active power used to designate or identify a component, device, equipment, or system

Note 1 to entry: The nominal value is generally a rounded value.

3.1.19
nominal DC current
value of DC current used to designate or identify a component, device, equipment, or system

Note 1 to entry: The nominal value is generally a rounded value.

3.1.20
nominal DC voltage
value of DC voltage used to designate or identify a component, device, equipment, or system

Note 1 to entry: The nominal value is generally a rounded value.

Note 2 to entry: In HVDC grids, the nominal DC voltage can be defined pole-to-earth or pole-to-neutral.

[SOURCE: IEC 60050-151:2001 [4], 151-16-09, modified – The term "nominal value" has been replaced with "nominal DC voltage", voltage used as reference; Note 2 to entry added.]

3.1.21
rated current
current assigned by a manufacturer or other entity to a component, device, equipment, or system to state the maximum value for defined operating conditions

Note 1 to entry: The definition is applicable to AC and DC current. The characteristic of the current value shall be further described, e.g.:

- continuous or transient,
- peak, RMS, average.

3.1.22
rated voltage
voltage assigned by a manufacturer or other entity to a component, device, equipment, or system to state the maximum value for defined operating conditions

Note 1 to entry: The definition is applicable to AC and DC voltage. The characteristic of the voltage value shall be further described, e.g.:

- continuous or transient,
- peak, RMS, average.

3.1.23
rigid bipole
rigid DC current bipolar system
bipolar HVDC system without neutral connection between both converter stations

Note 1 to entry: Since only two (pole) conductors exist, no unbalance current between both poles is possible. In case of interruption of power transfer of one converter pole, the current of the other pole has to be interrupted as well (at least for a limited time to allow reconfiguration of the DC circuit).

Note 2 to entry: See Figure 2 for an example of a rigid bipolar HVDC system.

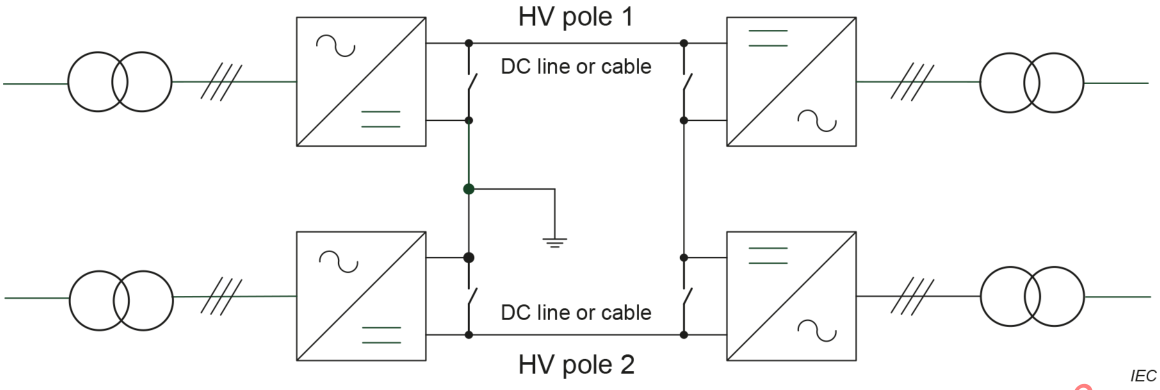


Figure 2 – Rigid bipolar HVDC system

[SOURCE: IEC 60633:2019, 8.9, [3], modified – The term "rigid bipole" added and Note 2 added.]

3.1.24
synthetic inertia
capability of a grid connected converter to emulate the effect of inertia of a synchronous generator to a prescribed level of performance

[SOURCE: IEC TS 62898-3-3:2023, 3.1.39, modified – Domain <in an electric power system> omitted.] [2]

3.1.25
transition station
station providing the connection between different types of transmission line sections

Note 1 to entry: Transition stations are used for connecting e.g. cable and overhead line sections or several cable sections.

3.1.26
HVDC transmission line
part of an HVDC grid providing electrical connection between the DC points of connection located in distant HVDC stations

Note 1 to entry: A transmission line can consist of several line sections. The sections can be air insulated (e.g. overhead lines), solid insulated (e.g. cables) or gas insulated (e.g. gas insulated lines). Different sections are connected by transition stations.

3.1.27
HVDC transmission line section
portion of an electric line bounded by two points which are either terminations of the line or line taps

[SOURCE: IEC 60050-601:1985, 601-02-30, modified – "transmission" added to the term.] [5]

3.1.28
transmission line tap
tee point
point on the multi-terminal electric line where portions (leading, directly or indirectly, to three or more terminations) are joined

Note 1 to entry: Terminations are part of a transmission line and can be connected to e.g. a transition station or the DC point of connection of an HVDC station.

[SOURCE: IEC 60050-601:1985, 601-02-29, modified – "transmission" added to the term, brackets added to the definition and note added.] [5]

3.2 Abbreviated terms

AC/DC	alternating current / direct current (conversion)
BB	bus bar
CB	circuit breaker
CLES	converter local earthing switch
CU	converter unit
C&P	control and protection
DC/DC	direct current / direct current (conversion)
DMR	dedicated metallic return
DPS	dynamic performance studies
DPT	dynamic performance tests
ENTSO-E	European Network of Transmission System Operators for Electricity
ERTS	earth return transfer switch
FCR	frequency containment reserve
FRR	frequency restoration reserve
FSD	fault separation device
GOOSE	generic object-oriented substation events
HSS	high speed switches
HV	high voltage
HVDC	high voltage direct current
MMC	modular multilevel converter
MRTS	metallic return transfer switch
NBES	neutral bus earthing switch
NBS	neutral bus switch
OHL	overhead line
OP	operating point
OVRT	over voltage ride through
PoC	point of connection
POD	power oscillation damping
STATCOM	static synchronous compensator
SRAS	system recovery ancillary service
SU	DC switching unit
T	terminal
THD	total harmonic distortion
TSO	transmission system operator
UVRT	under voltage ride through
VSC	voltage sourced converter

4 Coordination of HVDC grid and AC systems

4.1 About HVDC grids

HVDC grids differ from HVDC systems which are designed as one integrated system.

Integrated HVDC systems act as single controllable entities to meet the requirements at their AC connection points (PoC-AC). As such, individual integrated HVDC systems are optimized for their respective transmission tasks.

HVDC grids, similar to AC, will consist of HVDC transmission lines connected via DC switching stations through which autonomous AC/DC converter stations and/or DC/DC converter stations are connected. The requirements of the HVDC stations and the HVDC transmission lines are defined at their PoC-DC, PoC-AC or both.

HVDC grids will develop over time as known from the case of AC grids. Attention should be paid to consider foreseeable system developments in the future, such as anticipated additional circuits, loads and generator connections in line with a possible network development and forecasting plan. The corresponding design margins shall be included.

HVDC grids shall stay operable in the event of loss of communication. Coordinating control functions shall be performed by the HVDC grid controller. The interfaces for communication with the grid controller shall be agreed and documented between the involved parties.

System planning studies are required as described in Clause 10 as well as in CLC/TR 50609:2014 [6][1].

Modelling and testing (Clause 10 and Clause 11) are required. Software and model updates are necessary regularly during the entire life of equipment. Appropriate system equivalent models and tests should be standardized for system interaction studies.

System responsibility shall be defined for the individual entities of an HVDC grid in a multi-vendor environment. The split of responsibility should be supported by the standardisation of each individual entity. This document is written to provide a guideline for the entity having the responsibility for the overall system integration.

4.2 HVDC grid structure

The HVDC grid connects several AC/DC converters via their respective PoC-DC to a common DC circuit as shown in Figure 3. The HVDC grid can consist of one or more of the following installations:

- DC switching station,
- HVDC transmission line (OHL, cable or combinations thereof),
- DC/DC converter station.

[1] Numbers in square brackets refer to the Bibliography.

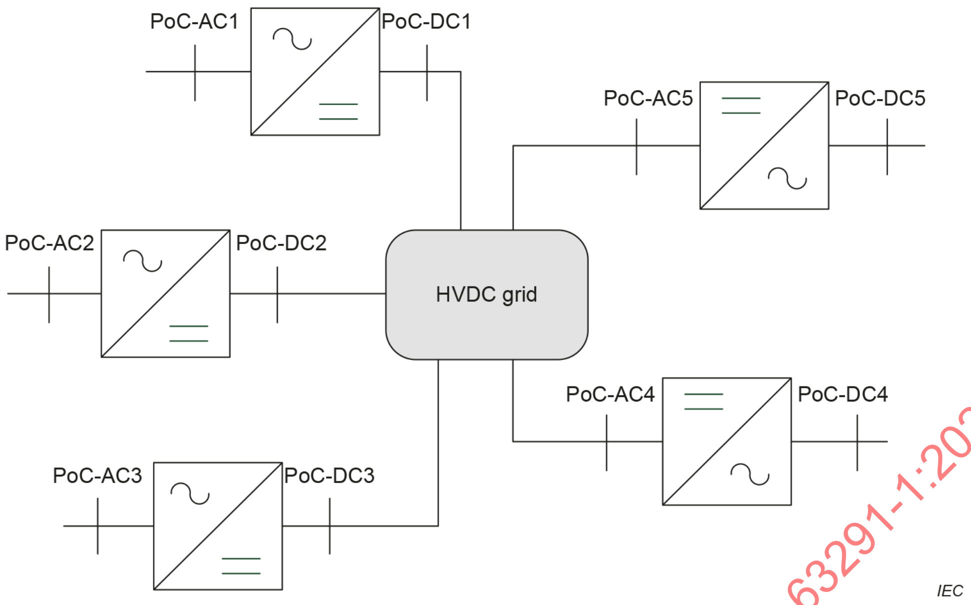


Figure 3 – Schematic structure of an HVDC grid

The topologies of the AC/DC converter stations as well as the various installations of the HVDC grid shall be coordinated and specified as described in 5.1.

Within the boundaries of the given topologies, each AC/DC converter station or HVDC grid installation can be operated in different DC connection modes as described for AC/DC converter stations in 8.4.2.1 DC connection and for DC switching stations in 9.2.3.2.1 DC connection. The individual connection modes and their application shall be coordinated throughout the HVDC grid at all times when operating.

4.3 Purpose of the HVDC grid and power network diagram

To provide an overall understanding of the HVDC grid, the purposes, basic functions and the operational concept of the HVDC grid including all HVDC stations shall be explained.

To explain the AC and HVDC grid structure, a network diagram shall be specified showing the grid topology including the installations and their connections. This diagram shall contain information such as the following:

- AC/DC converter stations,
- DC switching stations,
- HVDC transmission lines (OHL, cable or combinations thereof),
- DC/DC converter stations,
- AC networks showing the connection of each AC/DC converter station to the synchronous areas,
- main circuit data (DC voltage level and DC voltage band),
- topology of HVDC grid and HVDC stations according to the nomenclature given in Table 1,
- DC earthing impedances at each HVDC station,
- FSDs,
- energy storages,
- energy absorbers, e.g., dynamic braking devices typically used for absorbing energy that cannot be delivered to the AC grid.

4.4 AC/DC power flow optimisation

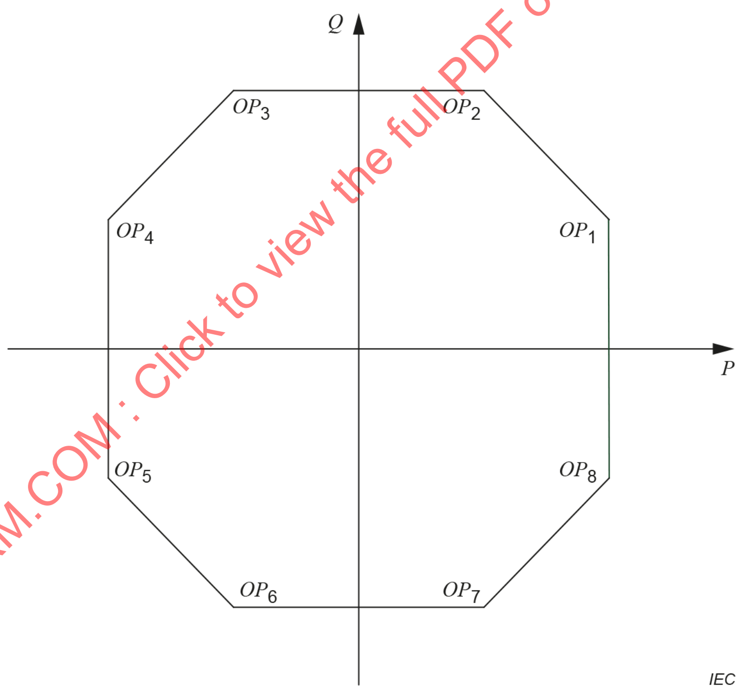
The behaviour of an HVDC grid and its AC/DC converter stations within their AC system environment is typically described in corresponding grid codes for the respective AC systems. Clause 4 of this document describes typical requirements from the AC system perspective with respect to their implications on the design of HVDC grids.

An HVDC grid with more than two HVDC stations in operation requires superordinate coordination of the power flow between the individual HVDC stations. The requirements for such coordination are described in Clause 6.

The steady-state active and reactive power capabilities of an AC/DC converter station are described by the active vs reactive power exchange capability charts depending on the AC voltage (U_{AC}) at the PoC-AC of each station as shown in Figure 4. There can be different boundaries representing normal and temporary conditions or different AC voltage levels.

The specification of the power flow through the AC/DC converter shall be such that power flowing from the PoC-DC into the converter and further on from the converter into the PoC-AC shall have positive sign as defined in IEC 62747:2014/AMD1:2019, Figure 1.

For DC/DC converter stations and DC switching stations, the current directions shall be clearly defined. The current direction shall be selected consistently throughout the entire HVDC grid.



P Active power

Q Reactive power

OP_n Steady-state OP *n*

NOTE The ratio of *P* and *Q* in Figure 4 is indicative only and not necessarily symmetrical with respect to the origin of the diagram.

Figure 4 – Example of a PQ-diagram showing the active vs reactive power exchange capability of an AC/DC converter station for a given AC voltage level

Compared to AC infrastructures, AC/DC converter stations provide the capability to set and control active power flow going through them. The active power set points as well as the control droop parameters have an impact on the global grid power flows (AC and DC). Optimising the static power flow can be aimed at different objectives, e.g., minimizing the overall losses, while remaining below the limits of individual equipment (converters, rated current of lines, etc.) and minimizing the consequences of contingencies such as loss of a line.

4.5 Converter operational functions

4.5.1 General

In this document a general categorization of converter operational functions into basic operation functions during normal operation states, basic operation functions during abnormal operation states and functions for ancillary service provision is provided. Basic operation functions both during normal and abnormal operating state are functions which shall be parameterized since they are basic to the coordination of an HVDC grid with AC systems. Subclause 4.5.2, Subclause 4.5.3 and Subclause 4.5.4 will further outline the converter operational functions.

4.5.2 Basic operation functions – Converter normal operation state

4.5.2.1 General

The AC/DC converter station control has two fundamental degrees of freedom on the AC side:

- active power exchange,
- reactive power exchange.

In general, for active power exchange, reference values can be given for the following control objectives:

- active power control,
- AC frequency control,
- DC voltage control.

The corresponding control objectives for active power exchange cannot be reached independently from one another.

The basic operating functions are specified as follows:

- AC system frequency following a frequency / power droop (s_{PF}),
- DC voltage following a DC voltage / DC power droop ($s_{\mathrm{P\_UDC}}$) or a DC voltage / DC current droop $s_{\mathrm{IDC\_UDC}}$).

For reactive power exchange, reference values can be given for the following control objectives:

- reactive power control.
- AC voltage magnitude control.
- Power factor control (active power to apparent power ratio, cos φ).

These functions are described in 4.5.4.

The corresponding control objectives for reactive power exchange cannot be reached independently from one another. The capabilities and requirements of all AC/DC converter stations connected to an HVDC grid have to be coordinated with the AC system needs on AC voltage control and reactive power.

4.5.2.2 AC system frequency following a frequency / power droop

The AC system frequency following a frequency power droop (s_{PF}) describes the change of active power in response to a deviation of the AC system frequency from its reference value. It is defined by

$$s_{PF} = (\Delta f / f_{nom}) / (\Delta P / P_{nom})$$

where

Δf is the frequency change;

f_{nom} is the nominal AC system frequency;

ΔP is the change of the active power output of the AC/DC converter station;

P_{nom} is the nominal active power of an AC/DC converter station.

There are two extreme cases:

a) scheduled power, $|s_{PF}|->\infty$

In this case, the AC/DC converter station will operate at a power reference value and does not contribute to AC system frequency control.

b) constant AC system frequency $s_{PF}=0$

In this case, the AC/DC converter station will exchange the power needed to keep the AC system frequency constant.

Case b) as well as all other cases with $|s_{PF}|\neq\infty$ require at least one independent source of active power connected to the HVDC grid, such as an asynchronous AC system.

4.5.2.3 DC voltage / DC power droop

The DC voltage following a DC voltage / DC power droop (s_{P_UDC}) describes the change of active power in response to a deviation of the DC voltage from its reference value.

$$s_{P\_UDC} = (\Delta U_{DC} / U_{DCn}) / (\Delta P / P_n)$$

Similarly, the DC voltage following a DC voltage / DC current droop (s_{IDC_UDC}) describes the change of DC current in response to a deviation of the DC voltage from its reference value. It is defined by

$$s_{IDC\_UDC} = (\Delta U_{DC} / U_{DCn}) / (\Delta I_{DC} / I_{DCn})$$

There are two extreme cases:

a) scheduled power, $s_{P\_UDC}=\infty$, $s_{IDC\_UDC}=\infty$

In this case, the AC/DC converter station will operate at a power reference value and does not contribute to DC voltage control.

b) constant DC voltage, $s_{P\_UDC} = 0$, $s_{IDC\_UDC} = 0$

In this case, the AC/DC converter station will exchange the power needed to keep the DC voltage at its terminals constant.

In all other cases, the contributions of an AC/DC converter station to the DC voltage control is specified by corresponding droop values s_{P_UDC}, s_{IDC_UDC} between these two extremes.

The above droop characteristics are the most common. However, there could be others along with all other control modes as defined in 6.2.3.3 where it is explained that droop constants can be a function of active power, DC voltage, etc. Several droop constants $s(P)$ could be used to model dead bands, etc.

4.5.3 Basic operation functions – Converter abnormal operation state

4.5.3.1 General

Abnormal operation states are conditions induced by faults. The specific operation requirements of the converter shall be defined.

4.5.3.2 Network conditions and power flow requirements

In order to maintain the stability of the connected DC or AC system, respectively, the maximum loss of power due to system outages can be defined. The maximum loss of power in MW can differ for outages that are considered frequent events or non-frequent events.

Pre- and post-fault AC system strengths are defined by the minimum and maximum short-circuit currents at the PoC-AC of an AC/DC converter station without considering possible contributions by that particular station, if any.

With respect to maintaining AC and DC system stability, maximum times of interruption of active and reactive power exchange at an AC/DC converter station shall be specified.

Permanent faults can require a reconfiguration of the AC or DC grid, respectively, resulting in different post-fault capabilities of the AC/DC converter stations. This shall be reflected in the post-fault target values for active or reactive power.

During an AC fault, the AC current contribution by an AC/DC converter station shall be specified according to the corresponding AC grid code requirements.

4.5.3.3 Abnormal AC voltage conditions

The operational requirements for abnormal AC voltage conditions are specified by AC undervoltage ride through (UVRT) as well as AC overvoltage ride through (OVRT).

NOTE Instead of overvoltage ride through, the deprecated term high-voltage ride through (HVRT) is also known. Instead of undervoltage ride through, the deprecated term low-voltage ride though (LVRT) is also known.

A generic combined AC under and over voltage ride through characteristic is shown in Figure 5. The x-axis is the time and the y-axis is the RMS voltage at the PoC-AC. This relates to symmetrical faults. AC voltage profiles for asymmetrical faults shall be specified similar to the one for symmetrical faults.

A converter shall maintain controllability of current inside the grey shaped area depicted in Figure 5. Each converter shall withstand a specified number of consecutive voltage disturbances. Outside the grey area the converter can disconnect.

The AC/DC converter station shall remain connected and maintain controllability of current in the event of an AC under or over voltage affecting one phase for a specified period of time as given in Figure 5. The AC voltage vs time characteristics can be different for symmetrical and asymmetrical faults. The AC voltage profile starts from a pre-condition within the normal AC voltage operating range.

Although Figure 5 displays a deterministic number of AC over voltage / time tuples, this number is not subject of specification; it could be any number "n" greater or less than the breaking points illustrated.

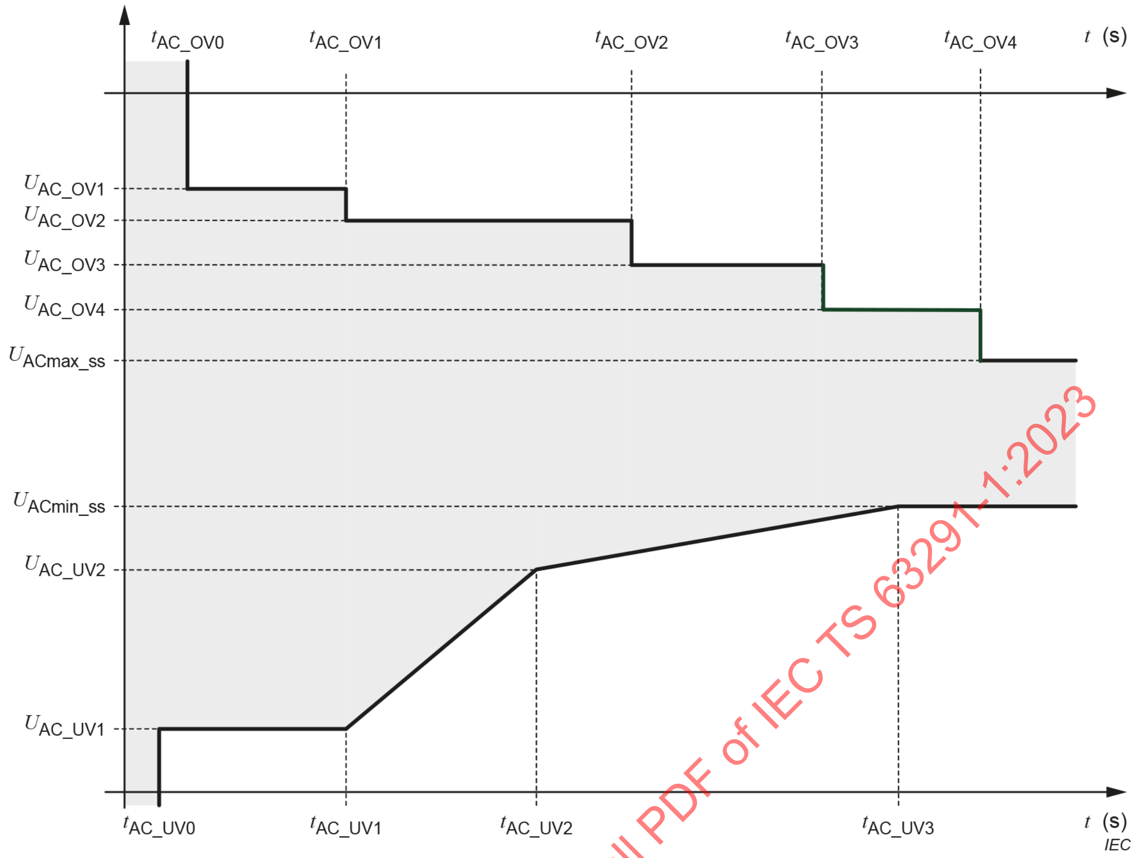


Figure 5 – Generic AC over- and under voltage ride through profile of an AC/DC converter station

4.5.4 Ancillary services

4.5.4.1 General

Ancillary services comprise operation functions which are optional, i.e. they can be activated in order to improve or support the rest of the power system, but they are not mandatory for the operation of the power system. An HVDC grid can provide the following ancillary services to an AC system:

- frequency control related services,
- AC voltage control related services,
- POD service,
- system restoration service.

These categories of ancillary services are further outlined in the following.

4.5.4.2 Frequency control related services

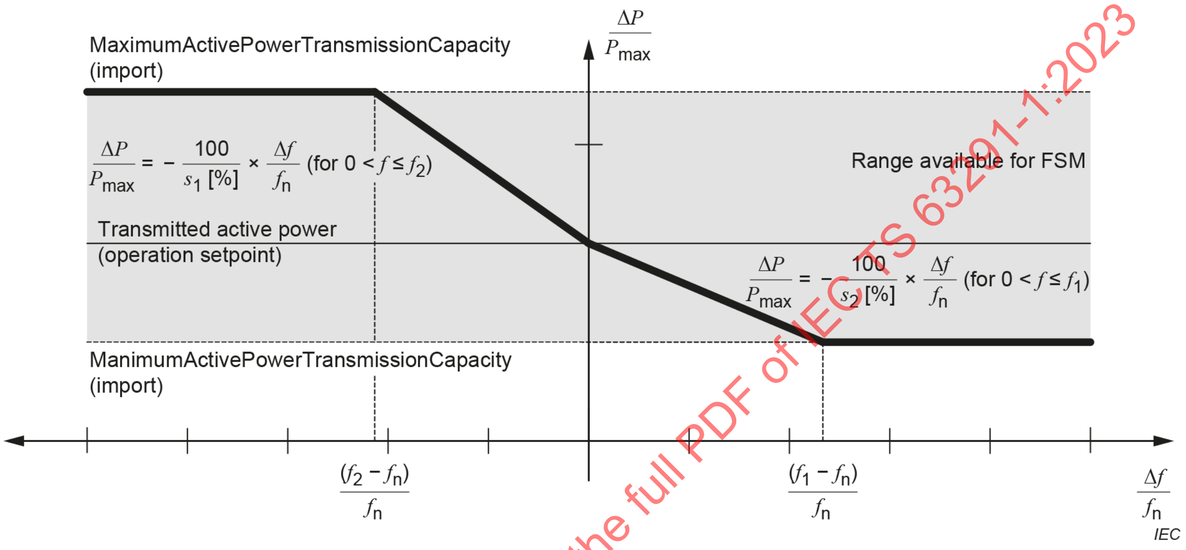
4.5.4.2.1 Synthetic inertia (differential frequency control)

In the absence of commonly agreed principles, the details of such services shall be specified case by case based on applicable grid codes.

4.5.4.2.2 Frequency containment reserve (primary frequency control)

An HVDC grid connecting a minimum of two asynchronous areas can be specified to provide FCR to be transmitted from at least one asynchronous area to another one. If all AC/DC converters of the HVDC grid are connected to the same synchronous area, an independent source supplying or absorbing power within the HVDC grid would be needed.

The corresponding requirements for one synchronous area supported by the primary frequency control can be distributed among all AC/DC converter stations interconnecting the supported synchronous area and the HVDC grid. The contribution of one of the AC/DC converter stations can be specified as shown in Figure 6.



ΔP Change in $P_{SETPOINT}$ triggered by the step change in frequency (MW)

P_{max} Maximum HVDC active power transmission capacity (MW)

f_n Target frequency in the AC network (Hz)

$f_{DEADBAND}$ [f_{min}, f_{max}], Frequency response dead-band (indicative range 0 mHz ± 500 mHz)

s_1 upward regulation "droop" (indicative value ≥ 0,1 %)

s_2 downward regulation "droop" (indicative value ≥ 0,1 %)

f_1 Over-frequency threshold (Hz)

f_2 Under-frequency threshold (Hz)

Frequency response insensitivity: ≤ 30 mHz

[SOURCE: Based on Commission Regulation (EU) 2016/1447, 26 August 2016 [7][2]]

Figure 6 – Example of an active power frequency response capability of an AC/DC converter station in frequency sensitive mode (FSM) with zero deadband and insensitivity with a positive active power setpoint; FSM in this figure shall be understood as FCR

2 Reproduced (from Commission Regulation (EU) 2016/1447, 26 August 2016), with the permission of the European Union, http://eur-lex.europa.eu © European Union, 1998-2023, Responsibility for the adaption and reuse lies entirely with IEC/TC 115/WG 15

Subclause 4.5.2.2 describes an option to define a relation between frequency and power of a specific HVDC converter. To provide this capability as FCR, the following parameters have to be defined by the affected parties for each AC/DC converter station:

- droop value s_{PF}, see 4.5.2.2,
- minimum step response time t_{FCRact}, to coordinate with inertia,
- maximum provision time $t_{FCRprov}$, to coordinate with FRR,
- frequency dead band $f_{DEADBAND}$, to limit the activation to exceptional situations.

In order to support the FCR process of at least one synchronous area, the FCR provision by an HVDC grid adapts the active power infeed from the HVDC grid to at least one synchronous area (receiving area(s)). It further modulates the active power drawn by the HVDC grid from at least one synchronous area (sending area(s)).

The coordination of power associated with primary frequency control shall be specified by the required variation of the output power, which is calculated by:

$$\begin{bmatrix} \Delta P_{SZ,1} \\ \vdots \\ \Delta P_{SZ,i} \\ \vdots \\ \Delta P_{SZ,n_S} \end{bmatrix} = \begin{bmatrix} K_{FCR,1,1} & \cdots & K_{FCR,1,j} & \cdots & K_{FCR,1,n_R} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ K_{FCR,i,1} & \cdots & K_{FCR,i,j} & \cdots & K_{FCR,i,n_R} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ K_{FCR,n_S,1} & \cdots & K_{FCR,n_S,j} & \cdots & K_{FCR,n_S,n_R} \end{bmatrix} \begin{bmatrix} \Delta P_{RZ,1} \\ \vdots \\ \Delta P_{RZ,j} \\ \vdots \\ \Delta P_{RZ,n_R} \end{bmatrix}$$

and

$$\sum_{k=1}^{n_S} K_{FCR,k,j} = -1;\ K_{FCR,k,j} < 0$$

where:

$K_{FCR\ i,j}$ is the FCR-distribution coefficient (dimensionless) indicating the amount of active power drawn from the sending area j and fed into the receiving area i

$\Delta P_{RZ\ j}$ is the active power fed into receiving area j

$\Delta P_{SZ\ i}$ is the active power drawn from sending area i

n_R is the number of asynchronous AC grid zones which are receiving areas

n_S is the number of asynchronous AC grid zones which are sending areas.

4.5.4.2.3 Frequency restoration reserve (secondary frequency control)

The coordination of the FRR among different synchronous control areas will be done by a dedicated superior system controller. If the HVDC grid is supposed to participate in the corresponding load flows, there will be a corresponding change in the converter setpoints.

4.5.4.2.4 Replacement reserves (tertiary frequency control)

The coordination of the frequency replacement reserve among different synchronous control areas will be done by a dedicated superior system controller. If the HVDC grid is supposed to participate in the corresponding load flows, there will be a corresponding change in the converter setpoints.

4.5.4.3 AC voltage control related services

AC voltage control related services can be:

- AC voltage magnitude control,
- reactive power provision as a function of AC voltage magnitude, either manually or automatically.

4.5.4.4 Power oscillation damping services

4.5.4.4.1 General

The POD control function modulates the AC/DC converter station power output to provide damping of low frequency power swings, typically in the range 0,1 Hz to 2,0 Hz. POD can be made by active and/or reactive power modulation.

4.5.4.4.2 Electromechanical oscillations

Electromechanical oscillations can be damped by active power:

- with a small energy storage at each AC/DC converter station,
- by importing and exporting power for a few seconds from a neighbouring synchronous area,
- with DC power transferred within the DC network.

A supplementary control is typically used to provide active and/or reactive power modulation.

4.5.4.4.3 Subsynchronous torsional interactions

HVDC control loops introduce subsynchronous frequencies in the AC network, through the voltages applied on the stator windings of the generator. Electromagnetic torque disturbances (e.g. abrupt change of the topology of the electrical network further to fault elimination) can also initiate the phenomenon of subsynchronous oscillations. The subsynchronous frequencies can then excite those of the turbine generator shaft and produce very high torsional torques.

Further information and mitigation measures can be found in [8], [9].

4.5.4.5 System restoration services

4.5.4.5.1 General

System restoration services are ancillary services intended to re-establish system operation and maintain operational security after blackout state or emergency state. HVDC grids can provide several of these services. A functional specification of these systems therefore includes a description of the provided system restoration services which are presented in 4.5.4.5.2 and 4.5.4.5.3.

4.5.4.5.2 Restoration from blackout

An HVDC grid can be designed to provide AC system restoration services. The corresponding requirements are not HVDC grid specific. This Subclause 4.5.4.5.2 provides the minimum requirements that shall be specified.

AC system restoration services comprise two steps:

1) energisation of a relevant AC/DC converter station from another remote or asynchronous, operational AC system via a DC connection. This step is also referred to as black start;
2) energisation of the black, connected AC system or parts thereof, also referred to as SRAS-AC, SRAS-AC means, the AC/DC converter station providing this service shall be able to maintain the AC voltage and frequency at its PoC-AC within defined limits for defined network configurations.

The start-up of an AC/DC converter station from a connected AC system, DC system or an internal power source like a diesel generator is considered an energisation process and not a system restoration service. Energisation of an AC/DC converter station is described in 8.4.2.5.1.The limits of the AC voltage at the PoC-AC shall be defined based on the AC voltage profile given in 4.5.3.3. The frequency limits shall be defined based on the requirements of the AC system restoration process.

The specification shall cover the following requirements to be coordinated with the design of the AC/DC converter stations:

- provide the active and reactive power demand of the AC network and the connected loads,
- provide the inrush currents of equipment to be energised,
- provide short-circuit currents according to the AC network protection concepts.

For design purposes, a generic AC network with project specific parameterized components shall be specified considering the following aspects:

- philosophy for restoring the real AC network including all relevant scenarios until reaching the normal operating state (see 5.3),
- relevant AC network configurations, e.g. switching states,
- AC system earthing concept,
- equivalent impedances of all relevant AC network elements,
- transient and dynamic characteristics of all relevant AC network elements,
- control characteristics and mechanical data of other generators to be connected to the AC network during the restoration process.

The generic test network shall be sufficient to demonstrate the HVDC grid's capabilities. Therefore, it can typically include models of:

- HVDC transmission lines,
- transformers,
- different types of loads, e.g. industrial and residential loads,
- generators.

Representative test sequences demonstrating the capabilities of the HVDC grid can typically include:

- switching the largest relevant transformer unit,
- switching the longest relevant HVDC transmission line,
- switching a representative load or test load bank.

4.5.4.5.3 Post-AC fault active power recovery

After the clearance of a fault, the magnitude and duration of the recovery of the active power from an AC/DC converter station can be specified using the following parameters.

- $P_{\text{POST-FAULT}}$ Post-fault active power recovery:

(example 90 % of pre-fault active power transmission)

- $t_{\text{POST-FAULT}}$ Time in which to recover P:

(example 0,2 s)

5 HVDC grid characteristics

5.1 HVDC circuit topologies

5.1.1 Availability and reliability

The availability and reliability of the HVDC grid depends on its topology as well as on the availability and reliability of its individual systems, subsystems and components. Redundant components, systems or subsystems have a decisive impact on availability and reliability.

The requirements for availability and reliability of the individual components, systems or subsystems shall be specified according to overall transmission system planning aspects.

5.1.2 Basic characteristics and nomenclature

The HVDC circuit topologies are differentiated regarding attributes characterizing the HVDC grid as well as attributes characterizing an HVDC station (AC/DC converter station, DC switching station or DC/DC converter station).

Attributes characterizing the HVDC grid are:

- number of HV poles,
- DC circuit earthing.

Attributes characterizing an HVDC station are:

- connection to HV poles,
- connection to a neutral return path,
- station earthing.

The DC circuit topology has a fundamental influence on the possible operating modes and fault currents. It determines component rating and the protection system as well as the insulation coordination.

The characteristics of the HVDC grid and an HVDC station are expressed by the nomenclature of the HVDC circuit topologies given in Table 1.

The possible HVDC circuit topologies are listed in Table 2 with respect to the HVDC grid characteristics and Table 3 with respect to an HVDC station characteristics. Figure 7 shows a bipolar, effectively earthed HVDC grid with different AC/DC converter station topologies as an example.

Table 1 – Nomenclature of HVDC circuit topologies

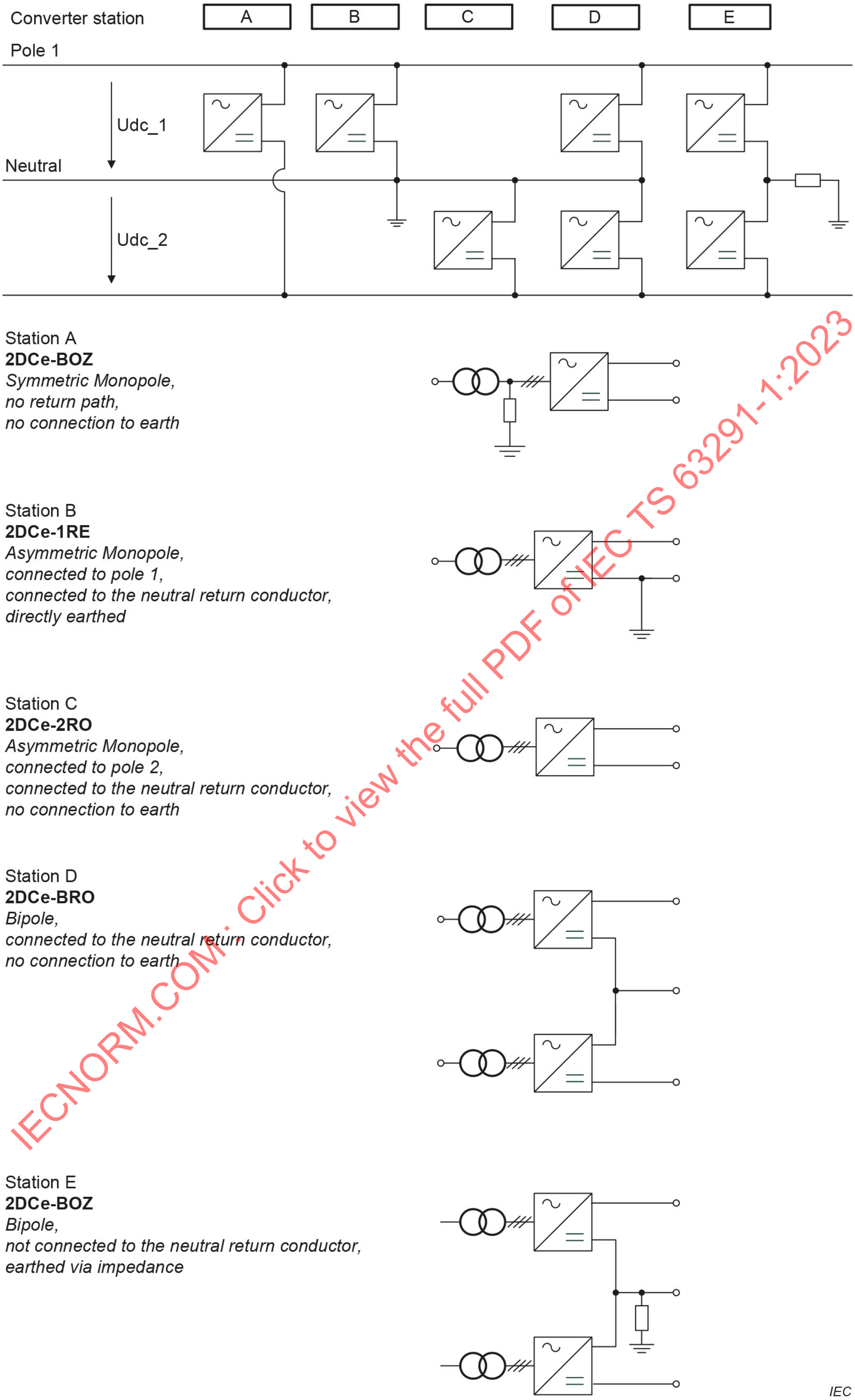
Characteristics of the HVDC grid			-	Characteristics of an HVDC station		
Number of HV poles	type	DC circuit earthing	-	connection to pole	connection to neutral return path	station earthing
1 2	DC	"z" not effectively earthed "e" effectively earthed	-	"1" pole **1** "2" pole **2** "B" both	"O" none "R" return conductor "E" earth electrode	"O" none "Z" impedance "E" direct

Table 2 – HVDC circuit topologies – HVDC grid characteristics

Number of HV poles		**1DC (Monopole)**	**2DC (Bipole)**	
DC earthing		effectively earthed **1DCe**	effectively earthed **2DCe**	not effectively earthed **2DCz**

Table 3 – HVDC circuit topologies – HVDC station characteristics at a PoC

Number of HV poles		**One**	**Two**	**Two**
Connection to HV poles		Pole 1 or pole 2 1DCe-1 or 1DCe-2 (Asymmetric monopole)	Both poles 2DCe-B (Bipole)	Both poles 2DCz-B
Neutral return path	Dedicated return conductor	1DCe-*x*R (Asymmetric monopole with dedicated metallic return, connected to pole *x* (1 or 2))	2DCe-BR (Bipole with dedicated metallic return)	2DCz-BR (Bipole with dedicated metallic return, impedance earthed)
	Earth electrode	1DCe-*x*E (Asymmetric monopole, connected to pole *x* (1 or 2), connected to earth electrode)	2DCe-BE (Bipole, connected to earth electrodes)	
	None		2DCe-BO (Rigid bipole)	2DCz-BO (Rigid bipole or symmetric monopole)
Station earthing	Direct	1DCe-*x*EE or 1DCe-*x*RE (Asymmetric monopole, connected to pole *x* (1 or 2), connected to earth electrode, alternatively neutral return conductor, directly earthed)	2DCe-B*x*E (Bipole, directly earthed; *x*: either connected to earth electrodes, neutral return conductor or no neutral return path)	
	Impedance	1DCe-*x*RZ (Asymmetric monopole, connected to pole *x* (1 or 2), connected to return conductor, impedance earthed)	2DCe-BRZ (Bipole, connected to neutral return conductor, impedance earthed) or 2DCe-BOZ (Rigid bipole, impedance earthed)	2DCz-BRZ (Bipole, connected to neutral return conductor, impedance earthed) or 2DCz-BOZ (Rigid bipole or symmetric monopole, impedance earthed)
	None	1DCe-*x*RO (Asymmetric monopole, connected to pole *x* (1 or 2), connected to return conductor, no connection to earth)	2DCe-BRO (Bipole, connected to neutral return conductor, no connection to earth) or 2DCe-BOO (Rigid bipole, no connection to earth)	2DCz-BRO (Bipole, connected to neutral return conductor, no connection to earth) or 2DCz-BOO (Rigid bipole or symmetric monopole, no connection to earth)



NOTE The DC circuit earthing can also be provided by an adjacent DC switching station.

Figure 7 – Example of an HVDC grid in 2DCe topology with different AC/DC converter station topologies

5.1.3 Attributes of HVDC grids or HVDC grid subsystems

5.1.3.1 Number of HV poles

The topologies of the HVDC grids differ in terms of the number of HV pole conductors. Systems can have:

- one HV pole, so-called monopoles,
- two HV poles, so-called bipoles or symmetric monopoles.

The number of HV poles is counted assuming all converters and connecting lines are available as designed. A system, designed as a bipole, can also be operated with just one of the two HV poles in operation and one of the HV poles or the neutral return path for current return. These possibilities of operation are not reflected in the nomenclature of HVDC circuit topologies.

5.1.3.2 DC circuit earthing

The DC earthing has a fundamental impact on the behaviour of the HVDC grid during faults at one of its HV conductors. It provides a means of maintaining the voltage between conductors and earth within stipulated limits and facilitates the isolation of faulty equipment in fault condition.

The DC circuit earthing is based on the connection of the neutral point(s) in the HVDC grid or subsystem to the earth. In principle, two types of DC circuit earthing exist:

- effectively earthed,
- not effectively earthed.

The two types of DC circuit earthing are characterized by the change of the DC voltage of a non-faulty conductor with respect to earth due to an undisturbed steady-state fault current, i.e., assuming there are no countermeasures limiting the DC fault current. The decisive parameter is the ratio of the non-faulty conductor's DC voltage to earth during the fault to the nominal DC voltage to earth of the same conductor. DC circuits having a DC voltage displacement lower than or equal to a pre-defined level are defined as being effectively earthed. DC circuits having higher DC voltage displacement are defined as being not effectively earthed.

HVDC grids that are effectively earthed are built either in 2DCe topology (so-called bipoles) or in 1DCe, (so-called asymmetric monopoles). A DC circuit in 2DCe topology can be considered to be consisting of two 1DCe circuits having opposite DC voltage polarity to earth. 2DCe HVDC grids or parts thereof can be operated as 1DCe in the event that one DC pole is out of operation.

One special case is the BOZ configuration of an AC/DC converter station, i.e., a so-called symmetric monopole configuration, using one converter between both HV poles and an AC side star point earthing as shown for station A in Figure 7. It should be noted that station A in Figure 7 is connected to an HVDC grid being effectively earthed, which is expressed by the corresponding nomenclature 2DCe. In this case, the DC voltage displacement during a DC insulation fault will be dominated by the earthing of the DC circuit with respect to DC currents. The same would apply, if a BOO AC/DC converter station were connected to a 2DCe grid.

The effectively earthed system will experience high DC fault current stresses due to the low conductor and earth resistances.

A DC pole to earth fault in a not effectively earthed system will result in significant voltage stresses (temporary overvoltages) during the earth fault condition. This increase in the voltage stress on the equipment shall be considered as part of the insulation coordination.

In a system with multiple earthing paths, attention shall be given to the impact on return current distribution within the DC system. This applies also for possible currents through conductive structures in the earth and above, like cable sheaths, pipelines, OHLs, transformers in AC systems or others with respect to magnitude and time.

5.1.4 Attributes of an HVDC station

5.1.4.1 Connection to HV poles

An HVDC station can be connected to:

- HV pole 1 (asymmetric monopole station),
- HV pole 2, (asymmetric monopole station), or
- Both HV pole 1 and HV pole 2 (symmetric monopole station or bipole station).

A bipole station comprises at least two separate CUs connected in series between both HV poles (i.e., Figure 7, station D or E).

A symmetric monopole station connects both HV poles by just one CU (i.e., Figure 7, station A).

An asymmetric monopole station connects to one HV Pole by one CU (i.e., Figure 7, station B or C).

In the case of an non-effectively earthed HVDC grid, the number of series connected CUs shall be specified.

Converters with unidirectional DC current, i.e. type 1 converters as described in 8.2, can be complemented by dedicated switchgear to connect the terminals of the converter to either HV pole of the HVDC grid. This possibility is not reflected in the nomenclature of the converter topologies.

5.1.4.2 Neutral return path

The options for the neutral return path are:

- DMR,
- HV pole conductor used for the return path (metallic return),
- earth electrode,
- no return path.

1DCe topologies can use dedicated metallic return conductors (1DCe-xR) or the earth electrodes (1DCe-xE) for the DC current to return.

NOTE 1DCe-xR: The x represents the connection of the respective HVDC station to the HV poles. The variable x can be 1 or 2.

In the case of 1DCe-xR any current through the return path will result in a corresponding DC voltage drop at the return path impedance. This DC voltage drop leads to a steady-state DC voltage displacement with respect to earth which has to be taken into account for the specification of the steady-state DC voltage operating band of all poles and the neutral points (see 5.4.3). When the DC voltage displacement exceeds tolerable limits, the operation concept of the grid with respect to unbalanced operation and the location of the earthing point has to be determined. Lower return path resistances or multiple earthing points can be considered.

In the case of 1DCe-xE all relevant HVDC stations have to be equipped with or connected to appropriate earth electrodes. These electrodes are often located at some distance from the stations or other AC substations in order to avoid negative effects due to earth potential rise. The corresponding electrode lines are considered part of the connection between HVDC station neutral point and electrode and are not reflected in the nomenclature of the HVDC station topologies.

In order to avoid uncontrolled currents through the earth path in 1DCe-xR configurations, only one HVDC station within the DC circuit shall be earthed.

If earth path currents are permissible, multiple earthing points are an option to reduce the DC voltage drop on the return conductor in asymmetrical operation. Provision shall be made to keep earth return current within the given earth current limits through control actions of converters or use of other equipment.

The DC circuit topologies described for 1DCe apply to 2DCe as well. In addition, 2DCe can be built in 2DCe-BO configuration (so-called "rigid bipoles" or "symmetric monopole"), where there is no neutral return path. During contingencies, i.e., one of the two pole converters out of operation in a 2DCe-BO configuration, one pole can be operated in so-called "metallic return" using the other HV pole conductor. Under these conditions, the HV pole conductor has to be disconnected from the rest of the HVDC grid at both ends and be connected to the neutral point of the related HVDC stations. This possibility is not reflected in the nomenclature of the station topology.

5.1.4.3 Station earthing

The options for earthing an HVDC station are:

- direct earthing,
- impedance earthing,
- no connection to earth.

The neutral point of an HVDC station can be directly connected to earth. HVDC stations operated using earth electrodes are always directly earthed.

The location of the earthing point shall be selected considering conductive structures in the earth and above, such as cable sheaths, pipelines, OHLs, transformers in AC systems or others with respect to magnitude and time. This can require the earthing point to be located outside the physical boundaries of an HVDC station and to be connected by a dedicated HVDC transmission line.

If more than one HVDC station is directly earthed in a subsystem, provision shall be made to keep earth currents within the given earth current limits through control actions of converters or other equipment.

The neutral point of an HVDC station can be connected to earth via impedance. The impedance can be ohmic, inductive, capacitive or a combination thereof. Nonlinear impedances like arresters can be used as well.

5.2 Connection modes

Within the boundaries of the given topologies, each HVDC station or HVDC transmission line and transition stations, if any, can be operated in different DC connection modes as described for AC/DC converter stations in 8.4.2.1 and for DC switching stations in 9.2.3.2.1 . The individual connection modes and their application shall be coordinated throughout the HVDC grid at all times when operating the grid.

5.3 Grid operating states

5.3.1 General

The operating states of the grid and their relation to one another are shown in Figure 8.

5.3.2 Normal state

Normal state means a situation in which the system is within operational security limits. In this state, no transmission system element is unavailable due to occurrence of an unplanned event.

5.3.3 Alert state

Alert state means a situation in which the system is within operational security limits, but a contingency has been detected. Under this contingency, countermeasures are recommended to bring the system back to a normal operating state in order to avoid entering an emergency state. This can include limited operation due to:

- AC system constraints,
- HVDC grid constraints.

5.3.4 Emergency state

Emergency state means a state in which one or more operational security limits are violated.

5.3.5 Blackout state

Blackout state means the state where the operation of part or all the transmission system has stopped.

5.3.6 Restoration

Restoration means the transition in which the objective of all activities in the transmission system is to bring the system back to normal state after blackout state or emergency state.

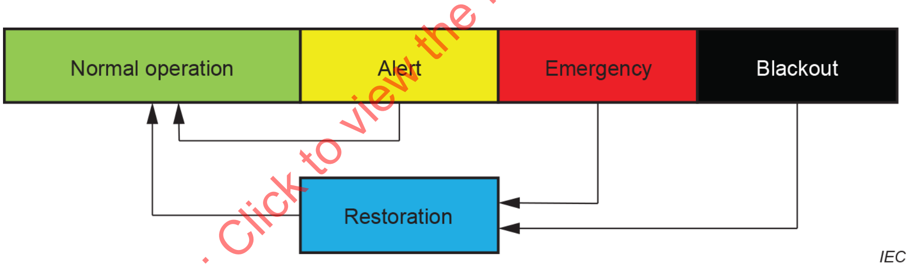


Figure 8 – Operating states

5.4 DC voltages

5.4.1 General

One of the main parameters of an HVDC grid is its nominal DC voltage. Furthermore, steady-state, temporary and transient DC voltage limits have to be defined.

It should be noted that terminal-to-neutral and terminal-to-earth voltages can differ depending on the topology of the HVDC grid, operating conditions and the resistances of dedicated metallic return conductors or earth electrode lines, respectively. Therefore, the definition of DC voltages requires the reference neutral or earth to be stated.

5.4.2 Nominal DC system voltage

So far, DC voltages of HVDC pole lines are chosen with respect to the requested power transmission capacity of the DC system versus the current carrying capability of the equipment. Moreover, various economic factors, such as evaluation of power losses, cost of material, etc., influence the selection of the nominal DC system voltage. In HVDC grids additional aspects such as load flow control and potential extension of the grid shall be considered. The nominal DC system voltage is defined as the DC voltage between HV pole and earth.

5.4.3 Steady-state DC pole voltage

In no-load operation, i.e., operation without any DC current flowing, all nodes share the same DC voltage. With increasing load, AC/DC converter stations acting as rectifier with power import to the HVDC grid increase the DC voltage, and AC/DC converter stations acting as inverter with power export from the HVDC grid decrease the DC voltage because of resistive voltage drops across HVDC transmission lines and other elements connected in series.

Therefore, a steady-state operating band shall be defined. This band shall be wide enough to cover all target OPs of the HVDC grid.

Also, the maximum DC voltages applicable to the neutral bus, dedicated metallic return conductors and electrode lines shall be defined. Both the DC pole voltage to earth as well as the DC neutral voltage to earth shall be considered when defining the DC voltage across the converter. Operation at reduced DC voltage levels can be considered taking into account reduced DC insulation capabilities, e.g., due to harsh weather and/or air pollution conditions, having impact on type and/or design of converters.

5.4.4 Temporary DC pole voltage

Unbalances of power import and export, e.g., caused by trip of AC/DC converter stations, faults in the DC or the connected AC systems, energisation or switching of elements of the DC system can cause the DC voltage to deviate temporarily from the steady-state range.

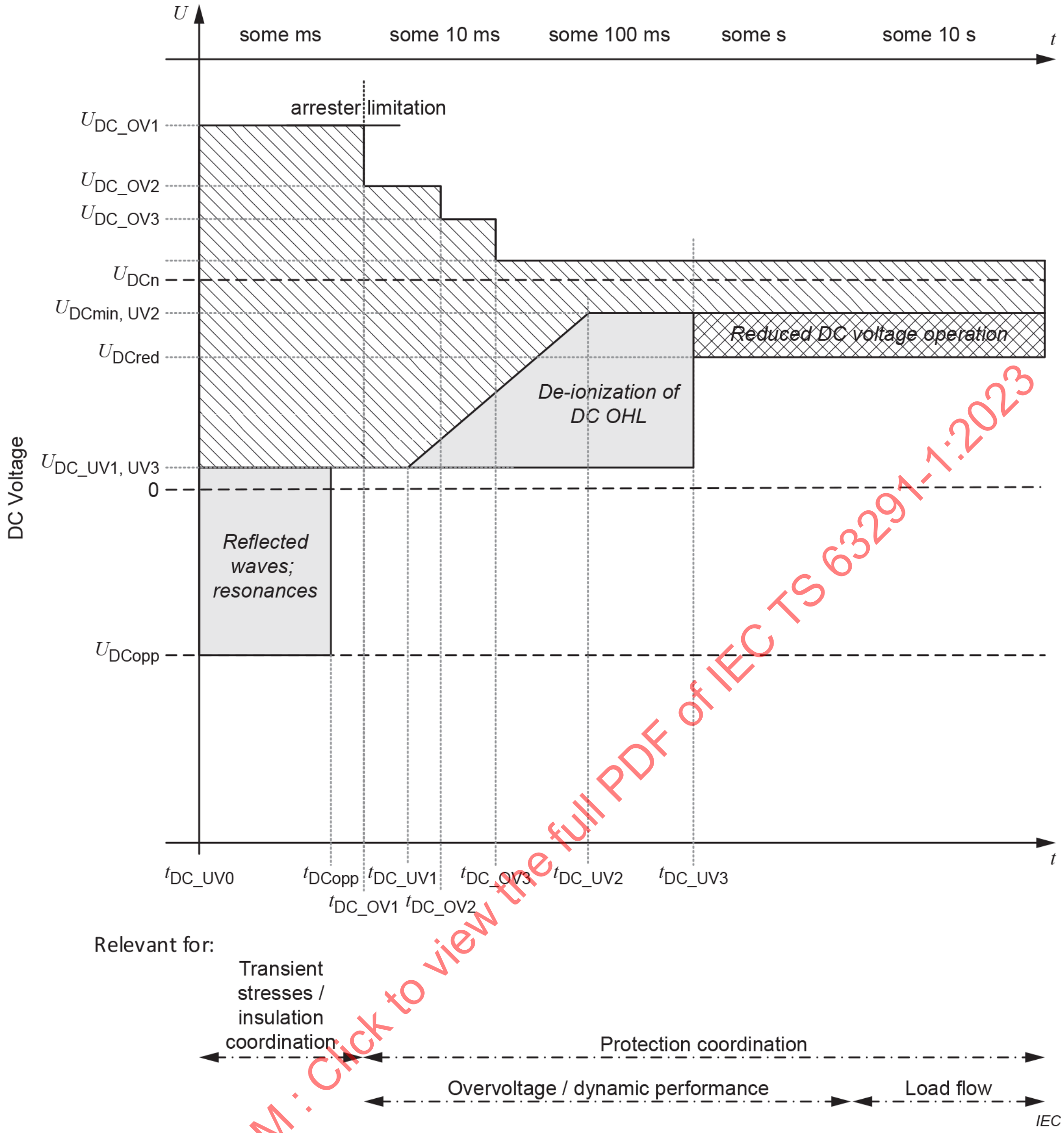
The limits for the temporary DC voltage excursions vs time are defined by the DC voltage band as shown in Figure 9. Beyond these DC voltage bands, the HVDC grid equipment protection would be allowed to reduce the operational performance of the grid, e.g., by blocking or tripping grid subsystems or components.

The following example of a temporary voltage profile for the DC voltage shown in Figure 9 is based on Cigre Technical Brochure 657 [10]. In order to derive a specific representation several aspects are to be considered, such as:

- AC and DC system power flow changes;
- AC and DC system harmonics;
- AC system transients and fault scenarios, including margins for emergency voltage control (e.g., $U_{\mathrm{DC\_OV2}}$, $U_{\mathrm{DC\_OV3}}$, U_{DCmax} in Figure 9;
- DC system transients and fault scenarios, including margins for emergency voltage control (e.g., $U_{\mathrm{DC\_OV2}}$, $U_{\mathrm{DC\_OV3}}$, U_{DCmax} in Figure 9;
- de-ionization and potential fault clearing for faults at OHLs.

The time and DC voltage limits depend on the technology and topology of the HVDC grid. The scales in Figure 9 are used for illustration only.

Diagrams as shown in Figure 9 can be used to specify the voltage withstand capabilities of the equipement as well as the operational performance of an HVDC station with respect to voltage.



[SOURCE: Based on Cigre Technical Brochure 657 [10] [3]

Figure 9 – Generic temporary DC pole to earth voltage profiles in HVDC grids

5.4.5 DC neutral bus voltage

This Subclause 5.4.5 refers to the return conductor or electrode line, if any, as well as HVDC stations that include a neutral bus. Deciding on the neutral bus voltages, the influence of the entire HVDC grid shall be considered.

The design of the neutral bus and any neutral bus connected equipment shall take into account the maximum steady-state neutral bus DC voltage as well as any temporary overvoltage and voltage distortion. The steady-state neutral bus DC voltages depend on the topology and the concept of operation of the neutral return path as described in 5.1.4.2.

3 Reproduced (from Cigre Technical Brochure 657), with the permission of Cigre.

As the steady-state neutral bus DC voltage is mainly driven by the current through metallic return conductors or across electrode lines and through electrodes, power limitations can be necessary in order to keep neutral bus voltages within their limits.

Owing to the considerably lower DC voltage level at the neutral bus compared to a HV pole conductor, temporary overvoltages and voltage distortions will influence the design of the neutral bus and connected equipment more significantly.

The voltage distortion of the neutral bus voltage at certain locations will be affected by the DC circuit impedances and can be influenced by dedicated neutral reactors or blocking filters.

The following scenarios shall be considered when defining the temporary overvoltage profile for the neutral bus:

- all relevant fault scenarios, such as:
  - neutral bus faults,
  - pole, return or electrode line faults,
  - faults within converters,
  - faults of converter transformers and reactors;
- operation of DC switches, such as MRTS, ERTS, NBS and NBES for all relevant DC system configurations and reconfiguration sequences;
- temporary ground currents, if any.

Compared to a point-to-point HVDC system, in an HVDC grid there are more scenarios (e.g., application of different AC/DC converter station types according to 8.2) that make it more complex to define the voltage profile. Moreover, the headroom that would be required for future expansion of the HVDC grid has to be taken into account.

Neutral bus voltages shall be coordinated between the different HVDC stations under consideration of all connection modes as described in 8.4.2.1 and 9.2.3.2.1 for DC switching stations, including transfers between the modes. Furthermore, earthing point(s) in the HVDC grid can change to different locations.

An example of a voltage profile is given in Figure 10. It shows different time spans where the voltage is defined by:

- arrester protective level,
- the maximum permissible voltage excursions during switching actions,
- maximum steady-state voltage level defined by the DC voltage and peak value of voltage distortion.

The neutral bus voltage profiles can be different for different HVDC stations or parts of the HVDC grid.

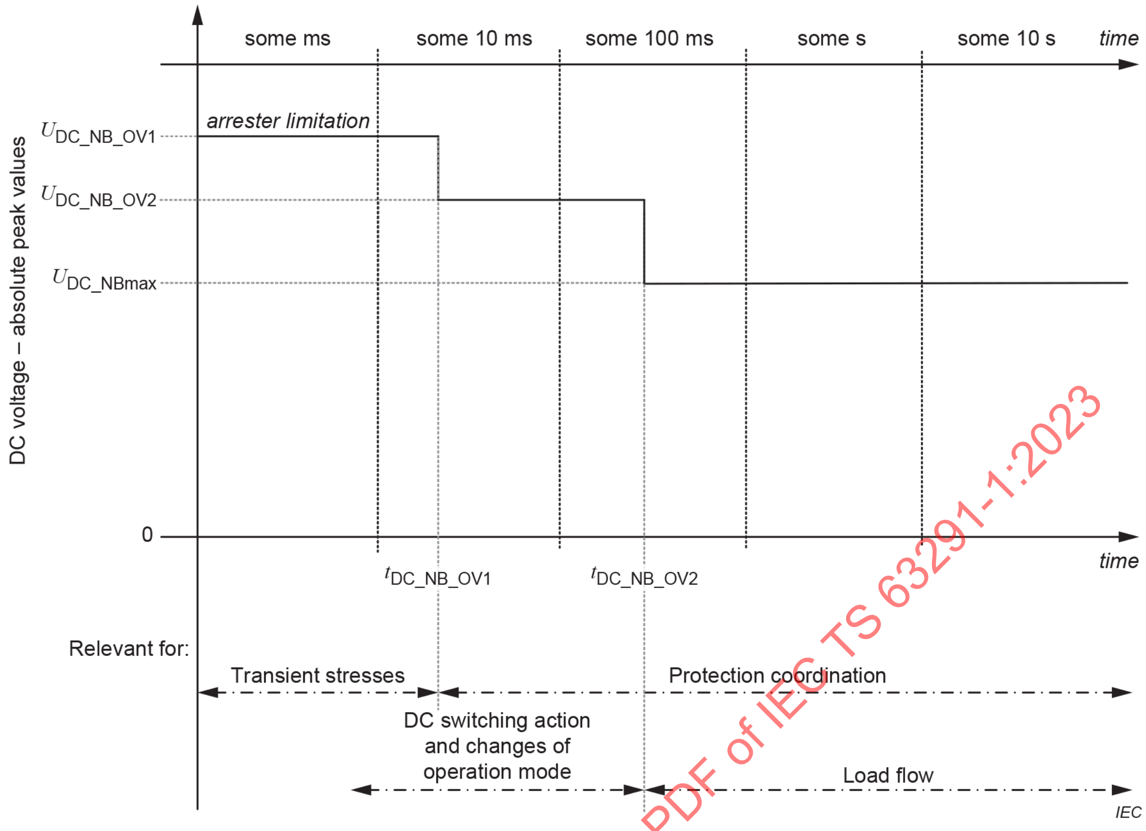


Figure 10 – Generic neutral bus voltage profile

Further guidelines can be found in IEC 62344 [11].

To design the HVDC grid equipment insulation, appropriate voltage withstand levels for switching and lightning type overvoltages shall be defined. These levels shall be coordinated throughout the HVDC grid.

5.5 Insulation coordination

To design the HVDC grid equipment insulation, appropriate voltage withstand levels for switching and lightning type overvoltages shall be defined. These levels shall be coordinated throughout the HVDC grid.

The voltage profile along HVDC transmission lines during transient events or due to voltage and current distortions shall be considered [12].

5.6 Short-circuit characteristics

5.6.1 Calculation of short-circuit currents in HVDC grids

Short-circuit currents of DC networks will expose the installed DC components to time-dependent stresses. In general, maximum short-circuit currents have to be considered for the assessment of mechanical and thermal stresses, whereas the minimum short-circuit current can be relevant for the setting of the system protection. The amplitude of the minimum and maximum currents depends on the topology and the operation of the system as well as on the components of the short-circuit path.

The short-circuit current characteristics shall be specified at each PoC-DC.

The calculation of short-circuit currents can be performed according to the following principles:

- calculation of defined short-circuit currents due to characteristic values for example maximum converter current or discharge current of lines;
- calculation of the transient behaviour of the short-circuit current after fault initiation taking into account the control and protection system of the HVDC stations as well as the data of the complete system (topology, line configuration, operational DC voltage, etc.).

The short-circuit currents at the fault location consist of four different parts:

- discharging of OHLs and cables,
- discharging of filters/capacitors,
- contribution of the HVDC stations,
- contribution of parts of an HVDC grid that are connected via a short-circuit current limiting device.

In general, the conditions after the initiation of short-circuit will be largely influenced by:

- type of the HVDC station, i.e., AC/DC types 1, 2, 3, 4, 5, as described in 8.2;
- short-circuit current limiting devices;
- earthing of the DC circuit in the event of line to earth short-circuits.

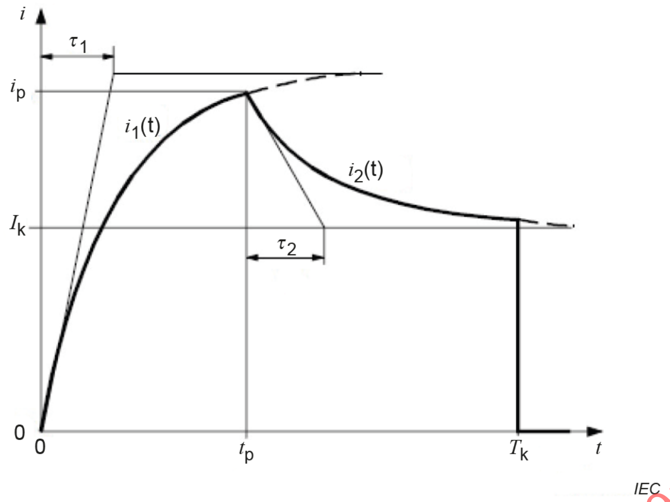
The damping of the discharge current is influenced by the resistance of the short-circuit path and the resistance depends on the frequency of the oscillation.

The amplitude of the short-circuit current in the event of line to earth faults depends on the earthing of the system. The following steps have to be considered in detail for the determination of short-circuit currents:

- selection of a typical DC system (layout), including earthing and used components which will lead to the maximum/minimum short-circuit current;
- configuration of OHLs and cables (resistance, reactance and capacitance for the calculation of minimum and maximum short-circuit currents);
- definition of system installations or components respectively which contribute to the short-circuit currents (filters, capacitors, etc.);
- behaviour of converters during a short-circuit: short-circuit current depending on the fault time (control of the HVDC stations);
- operating conditions (DC voltage, DC current, power flow) in the HVDC grid;
- definition of fault types (single pole, pole-to-poles or intersystem faults).

The total short-circuit current at the short-circuit location is the result of the contribution of several different sources.

Considering future system expansion during the lifetime of equipment the short-circuit current level can change. Therefore, it is recommended to consider such developments in the specification of the short-circuit-current requirements.



I_k steady-state short-circuit current

i_p peak short-circuit current

T_k short-circuit duration

t_p time to peak

τ_1 rise-time constant

τ_2 decay-time constant

[SOURCE: IEC 61660-1:1997, [13] Figure 2]

Figure 11 – Standard approximation function

By calculating the characteristic quantities for the time variation of the short-circuit current according to Figure 11, the mechanical and thermal short-circuit stresses can be ascertained.

5.6.2 Short-circuit current design requirements

Parameters defining the design of the HVDC grid with respect to short-circuit currents shall be specified according to the standard approximation function demonstrated by the wave shape shown in Figure 11, for each part of the HVDC grid.

5.7 Steady-state voltage and current distortions

5.7.1 Emissions and impacts

Power electronic converters are designed to generate voltages and currents of predefined characteristics. Owing to their principles of operation, real power electronic converters, besides their target voltage and current wave shapes, generate unwanted content which can include conducted as well as radiated electromagnetic emissions. In terms of the HVDC grid characteristics, this Subclause 5.7 addresses voltage and current distortions in the frequency range below 9 kHz. These distortions can lead to impermissible emissions, adverse interactions between different HVDC grid installations or interference with other technical systems. To ensure safe and undisturbed operation of the HVDC grid, tolerable limits of voltage and/or current distortions shall be specified.

Voltage and current distortion frequencies can include the fundamental frequencies of the connected or coupled AC networks and their harmonics which are defined as conducted low frequency phenomena (compare e.g., IEC 61000-1-2 [14] and IEC 60050-161:2014, 161-01-26 [15]).

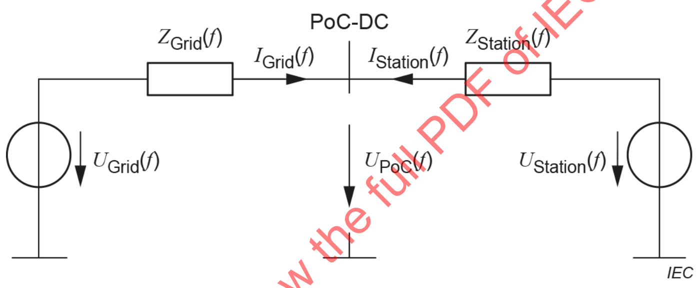
Further voltage and current distortions can occur without direct correlation to the AC system frequencies. These distortions are caused by converter operation or other technical installations and depend on the applied technology.

Voltage and current distortions are related to each other by the effective impedances at the particular frequency as shown in Figure 12. Voltage or current distortion limits shall be specified at the PoC-DC as a superposition of the voltage and current distortions caused by the converter station as well as the pre-existing distortions in the grid.

The equivalent network impedances will be different for different system configurations, e.g. bipolar vs monopolar conditions, return path configurations, HVDC station impedances including passive as well as controlled parts. The equivalent network impedances for different system configurations can for distinct frequency ranges be aggregated into equivalent impedance sectors.

The equivalent HVDC station impedances will be different for different configurations of the HVDC station including passive as well as controlled parts, e.g. different number of converter units in bipolar vs monopolar conditions, return path configurations.

NOTE Converters with dominating current source characteristics can be re-calculated into an equivalent voltage source.



$U_{PoC}(f)$ voltage at the PoC at frequency f

$U_{Grid}(f)$: pre-existing voltage distortion at frequency f in grid

$I_{Grid}(f)$: distortion current flowing in the grid feeder to the HVDC station at frequency f

$Z_{Grid}(f)$: DC-grid equivalent impedance as seen from the PoC-DC into the grid at frequency f

$U_{Station}(f)$: voltage generated by the converters in the station at frequency f

$I_{Station}(f)$: distortion current flowing in the grid feeder to the grid at frequency f

$Z_{Station}(f)$: HVDC station equivalent impedance as seen from the PoC-DC into the HVDC station at frequency f

Figure 12 – Equivalent circuit, defining the relationship between voltage and current distortions

5.7.2 Rights and obligations of a connectee

An HVDC grid can develop over time, with additional HVDC stations or other network elements being added, each possibly belonging to a different entity and possibly using different technologies. Each connectee shall have certain rights and obligations with respect to voltage and current distortions, in a way which is analogous to those of connectees to a normal AC grid.

In this context, the term "connectee" would apply to the owner of any source generating voltage and current distortions, such as an AC/DC converter where the grid connects to the AC network, but also a DC/DC converter or DC line power flow controllers embedded within the network. It could also be extended to apply to a new passive element within the network, such as a cable, which could be considered as a resonant element, capable of modifying the frequency behaviour of the grid.

The rights of a connectee, both existing and new, should include:

- the connectee's equipment, if designed according to appropriate standards, should not be damaged or its functionality adversely affected;
- the connectee's converter control systems should be able to function correctly and not be adversely affected by excessive distortions in the DC side ambient current or voltage.

The obligations of any connectee should include:

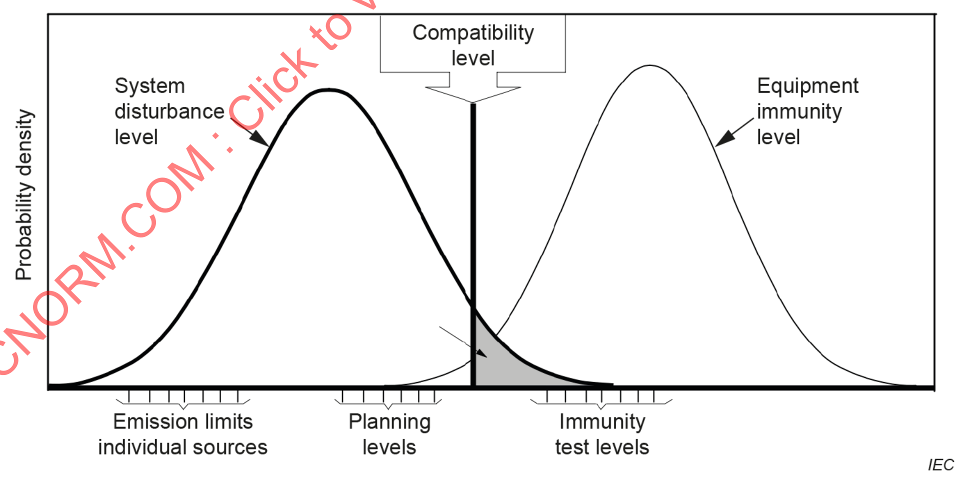
- to limit voltage and current emissions to values defined by an appropriate standard or grid code;
- to limit the impact of new equipment on existing DC system resonance, such that any amplification of pre-existing distortion is limited to values defined in an appropriate standard or grid code;
- to limit electromagnetic emissions from converter equipment or transmission cables or lines to values which will not cause unacceptable interference.

The above implies that relevant standards or grid codes will be required, in order to permit fair access for any entity and for multi-vendor equipment.

5.7.3 Similarities between HVDC grids and AC networks

While voltage and/or current distortion limits for AC-systems have been defined and have become well established over the last decades (IEC/TR 61000-1-4 [16]), such definitions and limits do not yet exist for HVDC grids.

The definition of relevant limits is between the poles of technical feasibility and commercial acceptability while providing safe and undisturbed operation of the HVDC grid itself and other relevant systems in the environment. Thus, for HVDC grids the definition of limits can follow the concept described by IEC/TR 61000-1-4 and depicted in Figure 13.



[SOURCE: IEC TR 61000-1-4 [16]]

Figure 13 – Disturbance level

Regarding voltage and current distortions, an HVDC grid is similar in many ways to a normal AC grid, and a useful starting point for considering voltage and current distortion issues is with reference to normal practice for AC systems. The salient points with respect to harmonics in AC networks are as follows:

1) Any connection to the network which either produces voltage and current distortions, or affects pre-existing distortions due to resonance, or both, is subject to a regulatory code.

2) Maximum harmonic voltage distortion levels are defined, which shall not be exceeded at any point in the network. These are usually called "planning levels" (Figure 14).

3) "Compatibility levels" are also defined, being higher by a margin than planning levels, and being the maximum distortion to which any equipment connected to the network should be immune (Figure 14).

4) In AC systems, these restrictions are normally applied in terms of individual harmonic voltage magnitude, THD, and sometimes a psophometric weighted total distortion, applicable for limiting induced interference to audio frequency telephone systems for onshore sections of the DC grid.

5) The overall maximum limits are divided among connectees according to certain rules, which differ among standards, but in general tend to reflect the relative size of the connection.

6) Where a new connectee is to be added to an existing network, the pre-existing level of distortion on the network is measured, and the difference between this and the planning level is called the "headroom", as shown in Figure 14. The new connectee is then allocated a proportion of this headroom, leaving some remaining headroom for future connections.

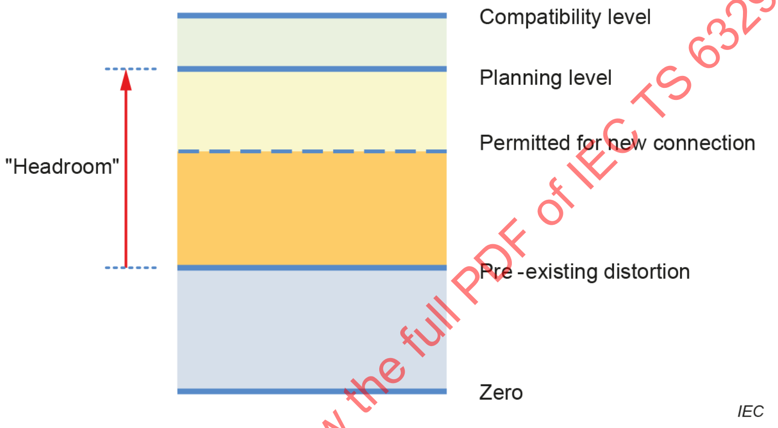


Figure 14 – Planning level and headroom

7) The impact of voltage and current distortions from a new connectee is considered, not only at the local connection bus, but also at remote buses where amplification can occur, using calculated transfer impedances or "coupling factors".

8) Restrictions can also be placed on the current distortion emissions as well as voltage distortion.

9) The contributions from different connectees to voltage and current distortions are assumed to be accumlated according to certain rules, for example the general summation law of IEC TR 61000-3-6:2018 [17], which take into account the likely phase diversity of different sources.

All these points are, in principle, applicable to HVDC grids. The main difference between a standard AC network and an HVDC grid is that an AC network typically hosts very many harmonic-producing connectees compared to DC grids.

5.7.4 Voltage and current distortion limits

When specifying voltage distortion limits in HVDC grids, the following shall be considered:

- limiting dielectric stresses on HVDC cables; a limit on total voltage distortion is sometimes specified by cable manufacturers for this reason;
- providing a sufficiently low-distortion DC side voltage such that any connected HVDC converter can function as designed, without maloperation, reduction of power transmission capability, or excessive losses;
- limiting transfer of voltage distortions to the AC sides, due to cross-modulation through the converters.

When specifying current distortion limits, the following shall be considered:

- limiting resistive losses in the cable core and sheath;
- limiting losses in HVDC station equipment;
- where the HVDC grid has a land route in proximity to an audio-frequency telephone cable, limiting the psophometrically weighted induced noise on the telephone system.

Suitable numerical limits for voltage and current distortions should be developed to satisfy the above requirements of this Subclause 5.7.4, while not placing excessive restrictions on connectees.

The emission of voltage and current distortions from a particular converter station can cause voltage distortion not only at the PoC to the grid, but possibly even at amplified levels at other busbars within the grid, due to system resonances. This effect shall be taken into account by specifying appropriate transfer impedances (or coupling factors) between remote buses and the PoC-DC and then limiting the permitted distortion at the connection bus so that the relevant limits are not exceeded at the remote bus.

5.7.5 Allocation of limits to individual connectees

The individual users of the HVDC grid, such as AC/DC converter stations, shall receive appropriate headroom for electromagnetic emission by the grid owner for their connection points. This can consider the different characteristics of different installations and should also consider rules for adding up contributions from different sources (e.g., general summation law of IEC TR 61000-3-6:2018 [17]).

For the evaluation of the adherence of specified limits, measured values shall be related to the effective impedances as seen from the PoC-DC into the HVDC grid as well as into the HVDC station considered. The limits shall either be defined as voltage and/or current limits.

The definition of limits for distortions is based on definitions given by grid codes or a dedicated limiting standard.

In IEC 61000-4-7 [18] describing procedures for the assessment of limits a frequency step of 5 Hz is recommended to keep measurement time and frequency resolution within acceptable limits. For HVDC grids, suitable steps shall be specified.

For the definition of individual limits for a new installation the following approach is recommended:

- define a PoC-DC;
- measure or simulate pre-existing voltage distortions at PoC-DC;
- evaluate the HVDC grid impedances as seen from the PoC-DC and of the unit to be connected (define and consider different grid conditions/states);
- define headroom of voltage distortions for each frequency (bandwidth) and dedicate it to the installation;
- assess magnification of pre-existing voltage distortion and additional contribution to the disturbance by connecting the new installation.

5.7.6 Frequency-dependent DC system impedance

The frequency-dependent impedances of the HVDC grid as seen from the PoC-DC of the new installation shall be specified for the relevant frequency range and frequency step width.

Alternatively, for small HVDC grids, the frequency-dependent impedances of the individual elements of the HVDC grid together with the topology and potential operational configurations of the grid can be specified. This would enable a comprehensive study of the behaviour of the whole grid, identifying potential with respect to voltage and current distortion issues at any point of the grid, rather than just at the PoC-DC.

Each active device connected to the grid shall be represented as a frequency-dependent impedance as well as a source of voltage or current distortions, taking into account the influence of different OPs as appropriate.

The upper frequency limit of the required range of frequency-dependent impedances and harmonic distortion shall be defined by the grid code with consideration of potential interferences but also of the achievable accuracy of the data for higher frequencies.

5.8 DC system restoration

5.8.1 General

In the event of a fault in the HVDC grid, the affected line or grid section has to be disconnected from the unfaulty part of HVDC grid according to assigned DC fault separation concepts in 7.2. Depending on the fault separation concepts, post-DC fault recovery strategies can require SRAS on the DC side, also referred to as SRAS-DC, by the AC/DC converter stations.

5.8.2 Post-DC fault recovery

In the event of a fault in the HVDC grid, the faulted line or grid section shall be removed from the HVDC grid. The fault separation process including fault detection, fault localization and fault clearing follows the procedures according to the defined DC grid protection zones as described in 7.4. After this process the previously affected line or grid section shall be recovered, if the fault is non-permanent (e.g., after a short-circuit on an OHL). This means that the previously disconnected line or grid section is going to be connected again to the HVDC grid.

Depending on the capabilities of the involved converter(s) and the assigned protection concept (7.4), post-DC fault recovery can contain the following options:

- energization, adaptation of DC voltages and re-connection of the disconnected HVDC stations, e.g., according to 8.6.5; this applies if the involved HVDC stations were de-energised and disconnected from the HVDC grid;
- adaptation of DC voltages and re-connection of the disconnected HVDC stations; this applies if the involved HVDC stations were not blocked but just disconnected from the HVDC grid;
- recovery of the DC voltage after fault separation or recovery of the full insulation capability; this applies if the involved HVDC station can limit and control the fault current by a counter voltage (e.g. using proactive breakers or type 5 converter);
- re-connection and energisation of the faulted line.

The requirements for post-DC fault recovery shall be specified for each DC grid protection zone individually.

5.8.3 Restoration from blackout

Major disturbances within the HVDC grid can result in a blackout of the entire HVDC grid. In these cases, the post-fault recovery strategies (see 5.8.2) are not applicable. The HVDC grid has to be restored from an AC system. The procedure is also referred to as SRAS-DC. It follows the procedure described in 8.4.2.7. Thereby the HVDC grid will be restored and the DC voltages will be adapted subsequently section by section. The priority of energisation and connection to the HVDC grid shall be agreed by the involved system operators.

6 HVDC grid control

6.1 Closed-loop control functions

6.1.1 General

The operation of an HVDC grid requires the active power exchange with the connected AC grids to be balanced. The active power equilibrium of the HVDC grid is represented by the stability of the DC voltage. Temporary power unbalances are absorbed by the effective capacitance of the DC circuit. This capacitance is decisive for the dynamic requirements on the DC voltage controls.

The effective capacitance can be complemented by:

- dedicated energy storages,
- dedicated energy absorbers, e.g. dynamic braking devices.

Depending on their relevance for the HVDC grid operation, the DC-side closed-loop control functions are generally divided into:

- core control functions,
- coordinating control functions.

6.1.2 Core control functions

These functions are essential for HVDC grid operation. They are based on information locally available to the power controlling devices, e.g., in AC/DC converter stations and DC switching stations.

The control targets are typically:

- meeting the local control set point, i.e. DC voltage, DC power or DC current respectively,
- maintaining the operational limits of the respective device.

These functions shall be independent of communication to the coordinating control functions or to other HVDC stations in the HVDC grid.

6.1.3 Coordinating control functions

Coordinating control functions typically use communication, e.g., from a central HVDC grid controller to HVDC stations or to remote measuring points. Therefore, they have longer response times than the core control functions.

If communication of the HVDC grid control to one part of the HVDC grid, such as an AC/DC converter station, is lost, the coordinating control functions will not be fully available.

These functions allow for optimising the HVDC grid operation regarding various aspects, as there are:

- optimisation of power losses,
- fast adaptation of DC power and DC voltage set points,
- coordination of ancillary services as described in 4.5.4, like POD, coordinated frequency support, etc.

The core and coordinating control functions are structured further by different layers of control in a hierarchical order.

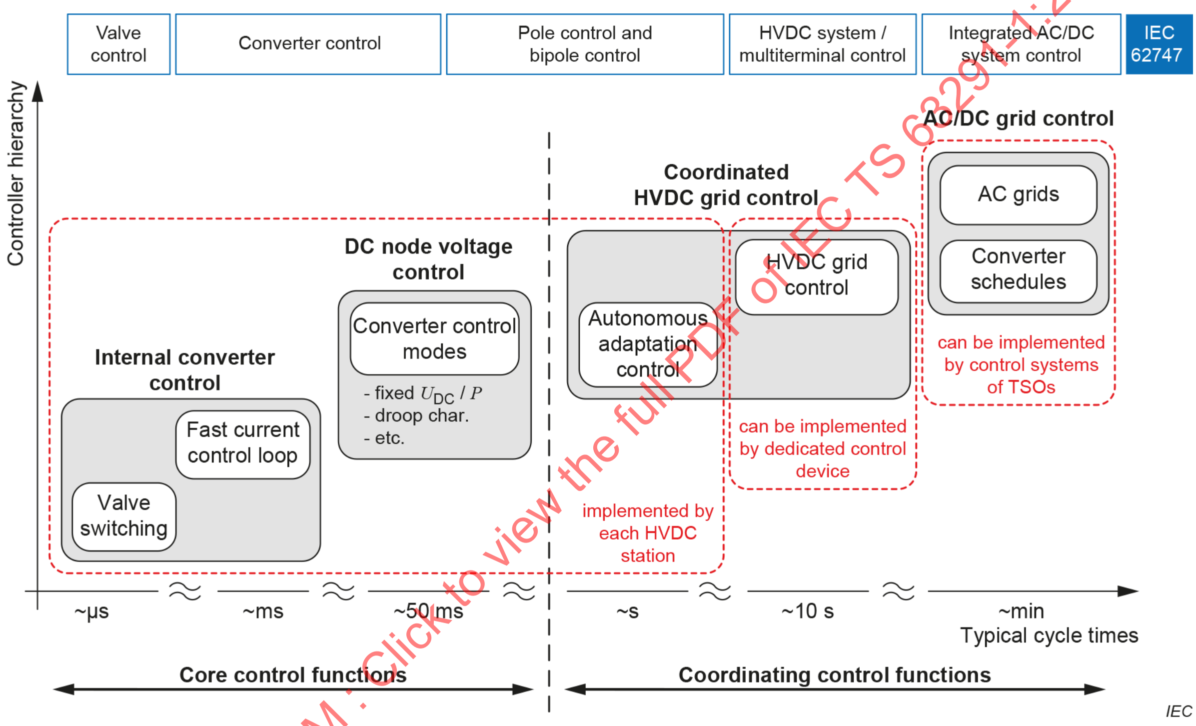
6.2 Controller hierarchy

6.2.1 General

The hierarchy of the control functions is chosen according to the locus of effect, i.e., which parts of the HVDC grid will be affected. The hierarchy has consequences on:

- time range in which control actions should be effectuated,
- priority of operation during normal and abnormal operations,
- available data (i.e. local or global measurements),
- actuator (i.e. local, distributed or centralized device).

Figure 15 illustrates the controller hierarchy.



NOTE The reference to IEC 62747 given at the top of the figure shows the hierarchical structure of an HVDC control system. It is included to show the difference to the controller hierarchy as described here for applications in HVDC grids.

Figure 15 – General controller hierarchy with typical time ranges of operation

From Figure 15 the hierarchy differentiates the four functional layers:

1) internal converter control,
2) DC node voltage control,
3) coordinated HVDC grid control,
4) AC/DC grid control.

The internal converter controls and DC node voltage control define the core control functions. The coordinated HVDC grid control and the AC/DC grid control define the coordinating control functions.

It is important that the time ranges of the individual control layers do not overlap to ensure stability of the control system.

As Figure 15 relates to "layers" in terms of control functionality, the break-down to the actual control implementations in terms of devices/locations is illustrated by three boxes with dashed red lines. Note that this emphasizes that autonomous adaptation controls (if present) have to be realized directly by the HVDC stations themselves, although they conceptually belong to the coordinated HVDC grid control. For the other two boxes, the given locations are only examples, i.e., the actual physical implementations can be located elsewhere.

6.2.2 Internal converter control

The internal converter control represents the lower-most part of this hierarchy scheme and is typically highly specific for each converter technology and HVDC equipment vendor. From the perspective of the AC and DC grids, these controls are expected to regulate the respective quantities at the PoCs of an HVDC station.

The operation of the internal controls shall not adversely interact with the internal controls of other AC and DC grid equipment. The interactions are to be addressed by appropriate studies (see 10.2.3).

6.2.3 DC node voltage control

6.2.3.1 Function

The functions of the DC node voltage control layer are:

- to achieve the desired power flow in the HVDC grid,
- to maintain the DC voltage within its operational limits throughout the HVDC grid.

This layer is continuously in operation during all normal as well as disturbed grid conditions. As its output, it provides reference values to the internal converter control.

6.2.3.2 Targets of control

Targets of the DC node voltage control can be the following quantities:

- at the PoC-DC:
  – DC voltage
  – DC current
  – DC power
- at the PoC-AC:
  – AC active power
  – AC frequency.

NOTE Instead of controlling the DC voltage at the PoC-DC, the DC voltage at a remote point can be controlled.

The desired target of control shall be met within the steady-state and temporary operational limits of the HVDC station.

6.2.3.3 Converter control modes

Depending on the desired target of control or combinations thereof, the following converter control modes can apply. They can be identified by integer numbers (1 to 5):

1) fixed DC voltage control: complies with definition of $s_{\mathrm{P\_UDC}} = 0$ from 4.5.2.3;
2) fixed AC power, DC power or DC current control: complies with definition of $s_{\mathrm{P\_UDC}}\to\infty$ or $s_{\mathrm{IDC\_UDC}}\to\infty$, respectively, from 4.5.2.3;

3) DC voltage/AC power, DC voltage/DC power or DC voltage/DC current droop control: as defined in 4.5.2.3 (one or more sections with constant droop k per section I or continuously changing droop $k(U_{DC})$ in the U_{DC}-P_{AC}, U_{DC}-P_{DC} or U_{DC}-I_{DC} diagram);

4) fixed AC frequency control: complies with definition of s_{PF} = 0 from 4.5.2.2;

5) AC frequency / power droop control: as defined in 4.5.2.2.

An illustration of a typical converter control mode characteristic is shown in Figure 16.

The control modes of all individual HVDC stations shall be coordinated such that the energy balance in the HVDC grid is maintained and stability is maximized (see 6.2.4.3).

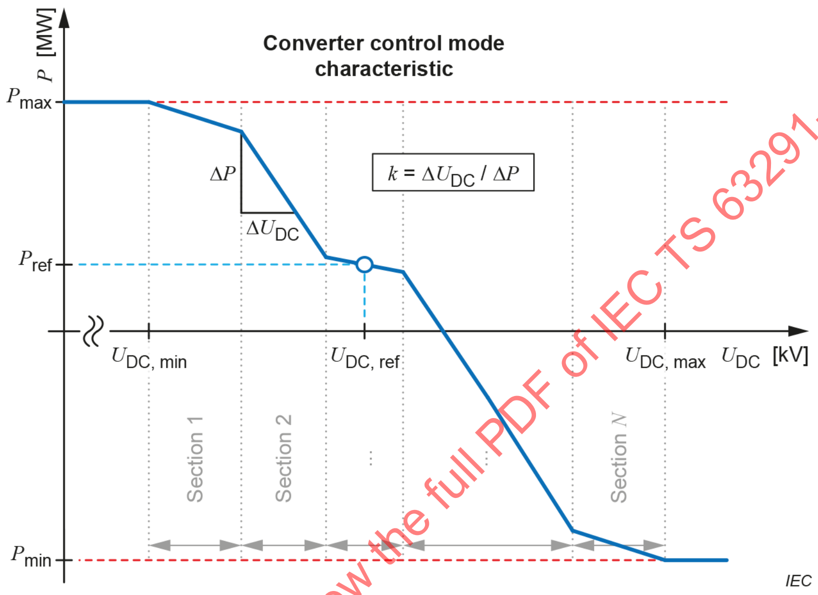


Figure 16 – Typical DC node voltage control modes (illustration in DC voltage/power plane)

6.2.4 Coordinated HVDC grid control

6.2.4.1 General

The coordinated HVDC grid control comprises two sublayers, differing in their speed of response and level of information about the HVDC grid. These two sublayers are:

- autonomous adaptation control,
- HVDC grid control.

6.2.4.2 Autonomous adaptation control

6.2.4.2.1 Function

The function of the autonomous adaptation control sublayer is to detect alert or emergency states and to provide fast, locally based responses predefined by a set of rules. These rules shall be set consistently for the whole HVDC grid and be made available in advance at each HVDC station.

Typically, the autonomous adaptation control does not rely on communication with remote control devices (e.g. HVDC grid controller) but will act based on local measurements available. However, more elaborate rules can be defined when remote measurements are also available.

6.2.4.2.2 Composition of each rule

- Detection/identification criteria
- Related countermeasure(s) to be triggered
- Priority level

6.2.4.2.3 Detection and identification

To detect alert or emergency states, defined observation variables have to be compared to defined thresholds. These observation variables can be:

- measurement signals (local or remote),
- status signals (local or remote).

For a more elaborated identification of unscheduled events, a pattern based on multiple observation criteria shall be evaluated.

If alert or emergency states are detected or identified for a predefined "holding time", the rule becomes effective and its associated countermeasure(s) are triggered.

6.2.4.2.4 Countermeasures

The triggered countermeasures will typically be applied locally (e.g. change of control mode, set points of an HVDC station).

Any autonomous countermeasure has to be reported to the upper control layers such that it can be accounted for in future dispatch cycles.

6.2.4.2.5 Priority

For selectivity purposes and to avoid conflicts, all rules are to be sorted by their priority.

The effective rule with highest priority is the rule whose countermeasure(s) are considered.

6.2.4.3 HVDC grid control

6.2.4.3.1 General

The HVDC grid control layer represents a central interface for getting information on the power flow conditions and accessing all electrical nodes in the HVDC grid.

The HVDC grid control layer continuously receives and transmits status and command messages to and from any high voltage equipment necessary for HVDC power transmission. Based on this information, the HVDC grid control provides modifications on the dispatched converter schedules in order to properly respond to changing external conditions according to desired optimisation targets.

The position of the HVDC grid control layer within the hierarchy (see Figure 15) is characterized by:

- receiving and executing commands from the AC/DC grid control (e.g. converter schedules);
- close interaction with autonomous adaption control layer.

The HVDC grid control layer can either be realised by a single dedicated control unit (central controller) or several controller devices (distributed) for redundancy purposes.

6.2.4.3.2 Function

The main functions of the HVDC grid control are:

- continuous processing of initial converter schedules dispatched by the AC/DC grid;
- managing the control modes of all HVDC stations in the DC node voltage control layer ensuring a secure steady-state operation of the HVDC grid within defined safety limits (i.e. consistency checks, set value modifications, etc.).

Additional, desirable functions of the HVDC grid control can be:

- optimising DC network operation (e.g. after unscheduled events) and reacting to deviations from the anticipated power exchange with new converter control mode and/or settings;
- providing mitigation strategies in case of malfunctioning of individual installations or information inconsistencies;
- provision of operational simplifications for the HVDC grid by "default scenarios" (e.g. pre-defined energisation sequences, response to usual/frequent contingencies, etc.);
- supporting the dispatch process to set up a consistent power schedule for the HVDC grid (e.g. by pre-computed information for the AC/DC grid control);
- monitoring the HVDC grid and the states of all high-voltage equipment;
- coordination of ancillary services for the connected AC grid(s);
- post-processing of DC faults (e.g. more complex analysis algorithms for fault location);
- coordination of HVDC grid earthing, e.g. NBES;
- coordination of neutral bus switches, such as MRTS, ERTS.

6.2.4.3.3 Inputs and outputs

Within the HVDC grid, the HVDC grid control requires information from:

- relevant and accessible nodes in the HVDC grid:
  - voltage of DC nodes
  - currents of DC lines
  - status of DC switching devices
- HVDC stations:
  - operational status
  - active converter control mode
  - active set points (DC voltage, DC current, DC power)
  - limitations / remaining capabilities (active/reactive power)
  - measurements (DC voltage, DC current, DC power).

The HVDC grid control will output modified references to:

- relevant and accessible nodes in the HVDC grid:
  - commands to DC switching devices (open / close)
- HVDC stations (relevant only if an HVDC station comprises corresponding functionalities):
  - orders for converter control mode
  - orders for set points (DC voltage, DC current, DC power)
  - restrictions for operational limits (due to external effects).

6.2.5 AC/DC grid control

6.2.5.1 Function

This layer represents the highest level of control due to availability of information and range of effect (see Figure 15). The AC/DC grid control defines the interaction between the relevant TSOs of the connected AC grids and the interconnecting HVDC grid.

The agreement on the scheduled power transmission for the next dispatch cycle is done according to:

- global, mixed AC/DC power flow optimisation (minimizing losses, maximizing stability, etc.),
- local optimisation(s) for one or more TSOs (e.g. special contractual obligations),
- renewable generation forecasts,
- pricing/market conditions,
- installation constraints.

6.2.5.2 Inputs and outputs

The inputs of the AC/DC grid control layer are the desired active and reactive power request of the relevant TSOs / operators of all HVDC stations.

The outputs of the AC/DC grid control layer are the dispatched initial converter schedules containing reference values for all HVDC stations. These are valid until the next dispatch cycle.

Although the AC/DC grid control layer appears "open-loop" in nature, it should be noted that the control loop is closed by continuous monitoring of the actual power flow situation in the connected AC grids and the HVDC grid and subsequent corrections in the next cycle.

6.3 Propagation of information

Regarding the hierarchy described in 6.2, the safe propagation of all essential information through the control layers is crucial.

In the top-down direction, this information is organized by means of "converter schedules" for single HVDC stations. These schedules include:

- control modes,
- additional control-mode parameters (if any),
- active power reference values (i.e. OP in terms of active power and DC voltage),

for the DC node voltage control layer. In addition, reference values for the AC voltage set points or reactive power support can be incorporated here as well.

As shown in Figure 17, initial converter schedules are periodically dispatched from the top-level AC/DC grid control. If no contingencies are detected and the initial converter schedules fulfil the HVDC grid's operational constraints, these data are simply propagated to the respective DC node voltage controls in the HVDC stations.

In the event of disturbances or other unscheduled events, appropriate modifications of these schedules are applied by the coordinated HVDC grid control layer in order to generate the final converter schedules that meet all optimisation criteria while keeping operational margins.

It should be emphasized that the propagation of converter schedules from the HVDC grid control implies a distribution from one instance to N instances, namely, the HVDC stations.

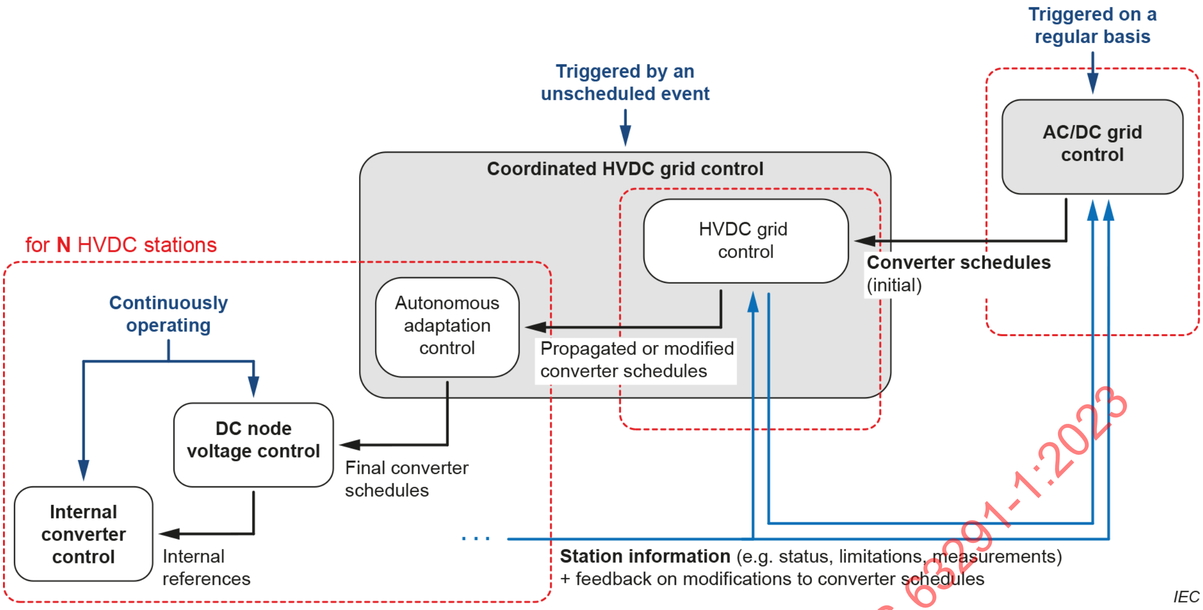


Figure 17 – Generation of final converter schedules including converter control modes and its parameters

The final converter schedules, on the other hand, have to be reported back to the HVDC grid control and AC/DC grid control layers in a bottom-up manner. This is necessary to allow for an automatic consideration of contingencies within the HVDC grid for the next dispatch cycle.

In a similar manner, status, measurements and limitations from the core control functions are collected at HVDC station level and propagated bottom-up by means of "station information" data.

In order to provide open and extensible systems, the control architecture as indicated in Figure 17 should be based on standardized communication protocols wherever possible. For example, International Standards as the IEC 61850 series [19] and the GOOSE framework described in this document could be the basis for this.

If the DC node voltage control (operating continuously at HVDC station level) loses communication with the HVDC grid control, the final converter schedules have to be set manually (see 8.6.2 for AC/DC converter stations).

In addition to the dispatching of the power flow-related set values in the converter schedule, the propagation of switching commands is performed in a similar way as depicted in Figure 18.

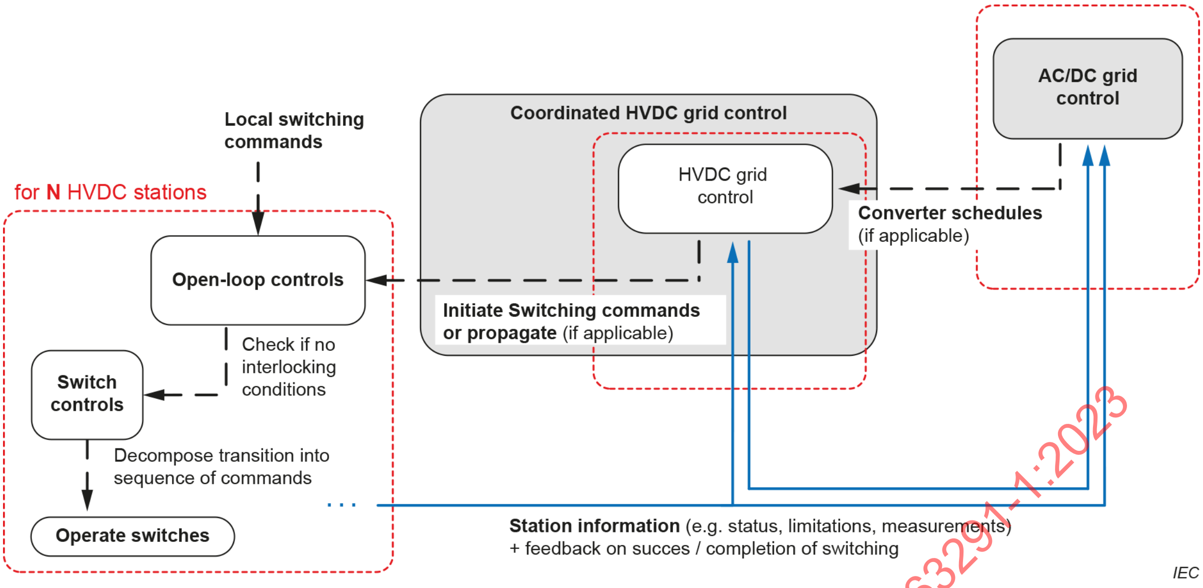


Figure 18 – Propagation of switching commands to individual HVDC stations

As can be seen in Figure 18, switching commands for any HVDC station should be initiated by the central HVDC grid control as this can provide a high degree of coordination. Depending on the design of the HVDC grid, the switching commands can also be received directly from the top-level AC/DC grid control.

Regardless of this, it shall always be possible to request local control from the HVDC grid control so that switching commands can also be controlled locally at each HVDC station (if required).

Any interlocking conditions shall be checked by the local open-loop controls in the respective HVDC station and manually with the relevant remote HVDC station if automatic communication is not available. Only then shall the open/close commands for the relevant switches be put into effect.

The respective HVDC station shall decompose the requested transition from the current to the next switching state into the sequence of individual steps and shall initiate all required steps, depending on its current and next connection mode.

Information on the effective connection and earthing modes shall be transmitted to the higher-level controls by the "station information".

6.4 Open-loop controls

6.4.1 Coordination of connection modes between HVDC stations and their PoC-DC

Important aspects of open-loop controls in the HVDC grid are the proper connection of HV and neutral conductors, if any, as well as the system earthing. Considering restrictions due to HVDC station design or operating conditions and the actual voltage levels at the respective PoC-DC, not all connection modes can be available at each point in time.

In order to establish valid and safe connections, all corresponding switching operations shall therefore be coordinated by the relevant controls at the involved HVDC stations. Refer to 9.2.3.2.1 for illustration of possible connection modes. Sufficient time has to be allowed and shall be specified by the maximum overall duration of a transition sequence.

In cases where an HVDC station loses communication with the coordinating control functions, changes in the connection modes have to be coordinated manually (see 8.6.2 for AC/DC converter stations).

6.4.2 Operating sequences for HVDC grid installations

The fundamental operating sequences of HVDC grids describe the transition between the individual operating states of an HVDC grid, subsystem or installation.

It should be emphasized that operating states and thus also respective sequences always relate to single devices (e.g. switch), units (e.g. AC/DC converter units) or installations.

Typical operating sequences are listed below:

- preparing to energise (from "NOT ready" to "ready to energise"),
- energising (from "ready to energise" to "energised"),
- adapting DC voltages (from "energised" to "ready to connect"),
- connecting (from "ready to connect" to "no-load operation"),
- loading (from "no-load operation" to "on-load operation"),
- de-loading (from "on-load operation" to "no-load operation"),
- disconnecting (from "no-load operation" to "ready to connect"),
- stopping adaptation of DC voltages (from "ready to connect" to "energised"),
- de-energising (from "energised" to "ready to energise"),
- shutting down (from "ready to energise" to "NOT ready"),
- emergency shutting down (from any state to "NOT ready").

An illustration of operating states and sequences is given in Figure 19.

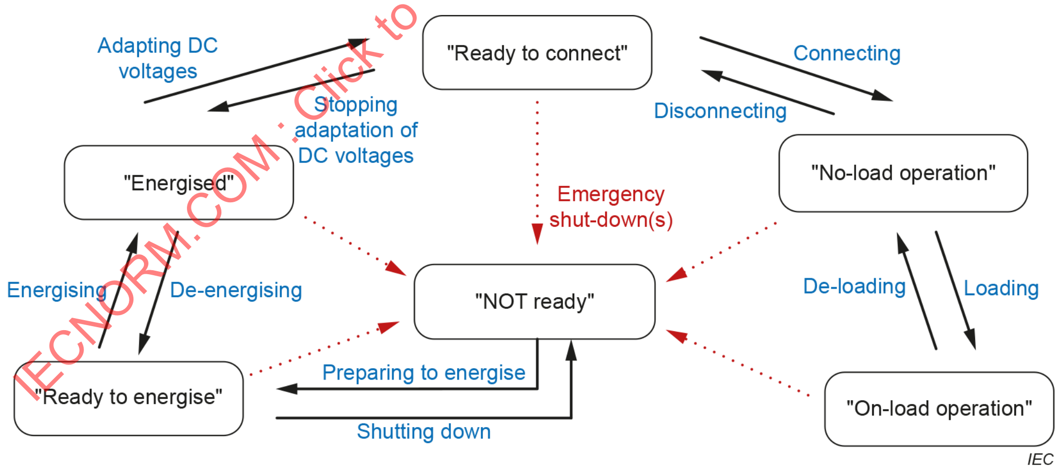


Figure 19 – Typical operating sequences for transitions between operating states of HVDC grid, HVDC grid subsystem or HVDC grid installation

6.4.3 Post-DC fault recovery

After DC insulation fault clearing in the HVDC grid (i.e. after a temporary stop P, see 7.4.4), the controls shall be designed such that:

- DC voltage is properly recovered,
- active power flow restoration is enabled.

AC/DC converter stations affected by the DC insulation fault can continue operation in STATCOM mode (i.e. provision of reactive power), if they do not trip their connection to their AC grids.

Regarding Figure 22, the first action of the control system requires a coordinated ramping of the DC voltage to its pre-fault values (e.g. nominal DC system voltage). The voltage ramp-up has to be provided by one or more HVDC stations set to either DC voltage control or DC droop control mode (see 6.2.3). This can only be started after the DC fault current has been extinguished.

Therefore, it can be necessary to temporarily adjust the control mode of the HVDC station associated with the faulty DC line.

Assuming faults by flashovers on air-insulated OHLs, crucial parameters are given by:

- the time required for a deionisation of the surrounding air volume after arcing,
- the ramp rate (i.e. speed) of the DC voltage restoration.

Once the target DC voltage band is reached, the active power recovery can proceed.

7 HVDC grid protection

7.1 General

The protection algorithms shall be selective and shall operate for a fault within an HVDC grid protection zone as well as not operate for faults outside the same protection zone.

An HVDC grid consisting of several converters requires greater emphasis for selectivity in the DC protection than a two-terminal transmission system. The selectivity is required to allow both identification and subsequent removal of a faulty part and to permit continued operation of the remainder of the HVDC grid.

Faults and consequential protection actions could cause a change of power flow in the transmission system. The power flow changes are handled by the control system described in 6.4.3. Furthermore, recovery actions are also handled by the control system.

The primary concern regarding protection in an HVDC grid is the response to DC side insulation faults.

All other faults, such as HVDC station internal faults or AC side faults, are treated as in the case of a two-terminal system. Such faults can be detected and isolated by the converter protections and DC switches as in the case of two-terminal transmission systems.

The amplitude of fault currents and transient voltages are dependent on the topology, circuit impedances and earthing of the HVDC grid as well as the behaviour of the fault current breaking devices.

Insulation faults on the DC side differentiate regarding their frequency of occurrence as well as their duration. There are faults that are non-permanent, and the insulation properties can restore after the fault current was interrupted, such as flashovers on OHLs, which can be caused by thunderstorms and lightning strikes. There are faults that are permanent, such as insulation breakdown on cables.

Non-permanent faults such as air insulation faults are typically more frequent. HVDC grids including DC OHL could therefore be prone to pole-to-earth faults and require higher performance with respect to system recovery of the control and protection systems.

7.2 DC fault separation

The treatment of DC side insulation faults comprises two phases:

- time between fault inception and fault separation,
- time between fault separation and power flow recovered in the non-faulty and reconnectable part of the system.

Fault separation is handled by the protection system. Fault separation occurs when the fault current is extinguished, and power flow recovery can start in the unfaulty and reconnectable part of the system.

The recovery process is handled by the HVDC grid controls (see 6.4.3).

The term "separation" can also be used to describe the situation where an HVDC grid protection zone affected by a fault, e.g. an HVDC transmission line or a subsystem, gets separated by devices having high impedance from other HVDC grid protection zones, while the fault itself still persists. The power flow in the unfaulty HVDC grid protection zones can thus continue or recover while the fault clearing is still ongoing in the faulty HVDC grid protection zone.

Since the fault current extinguishing will not necessarily be performed by a device which will provide a galvanic isolation (e.g. semiconductor DC breaker or DC/DC converter) the fault will not necessarily be isolated until opening a mechanical isolation switch. The term "separation" is used in a technology-independent way.

Fault separation in the HVDC grid can be provided by DC/DC converters or DC switchgear. DC/DC converters can have breaking capabilities. The DC switchgear can have either DC breaking capability or a disconnecting function only.

The DC fault current contribution from the AC system can be interrupted by the AC/DC converter station.

7.3 Protection system related installations and equipment

7.3.1 AC/DC converter station

There are different types of AC/DC converter stations defined as type 1 to 5 in 8.2.

Each of the AC/DC converter stations connected to an HVDC grid shall have its own independent set of protections. In this context the AC/DC converter station is defined as having a single PoC-DC to the HVDC grid, similar to a PoC-AC as shown in Figure 3.

From the protection point of view, in an effectively earthed symmetric topology the individual poles are treated independently from one another.

The requirement for independent protection can also apply to AC/DC CUs connected in parallel.

The requirements on the AC/DC converter station protections can be summarized as follows:

1) They shall be able to distinguish between internal and external faults (e.g. faults within the HVDC grid as well as faults in other HVDC stations).
2) Except for DC insulation faults within the AC/DC converter station, where fault currents are fed from the DC side, a AC/DC converter station shall be self-protected. For the exceptional case, additional protection has to be provided by the HVDC grid (e.g. HVDC breaker trip) or other HVDC stations (e.g. fault current limitation) in order to stop the fault current from the DC side.
3) The AC/DC converter station shall be self-protected against AC system faults.

7.3.2 HVDC grid topology and equipment

The design of the protection system requires detailed information on the DC circuit topology including the system earthing as well as the installations and their location. Additionally, as described in 4.3, the following list shall be considered in the design of the protection concept as applicable:

- AC/DC converter stations
- DC switching stations
- HVDC transmission lines:
  - OHL, cables or combinations thereof
  - transition stations, e.g. between a cable and OHL
- FSDs:
  - AC breakers
  - HVDC breakers:
    - mechanical HVDC breakers
    - semiconductor HVDC breakers
    - hybrid HVDC breakers (combination of mechanical and semiconductor breaking device)
  - disconnecting switches:
    - HSS, i.e. mechanical breakers
    - disconnectors and earthing switches
  - DC/DC converter stations:
    - with DC fault current breaking capability
    - without DC fault current breaking capability
- surge arresters
- reactors, e.g. to limit di/dt of DC currents
- measurement equipment
- dynamic braking devices.

This information shall be provided as a single line diagram and data sheets of equipment as far as relevant and available.

7.4 HVDC grid protection zones

7.4.1 General

When designing an HVDC grid protection system, one of the basic aspects is the definition of HVDC grid protection zones. The HVDC grid protection zones are defined differently from AC protection zones as the selectivity is mainly not time- or impedance-dependent but more depending on the fault separation concepts. Figure 20 shows an example network illustrating the concept of HVDC grid protection zones.

The FSD (e.g. a breaker, a disconnector or a converter) can be located:

- in an AC/DC converter station on the AC or DC side,
- in a DC/DC converter station,
- in a DC switching station.

For faults in each of these zones the fault behaviour of the transmission system at all PoC-AC and PoC-DC shall be specified.

The fault behaviour shall be specified by a protection zone matrix including the zones and the PoCs on its axis. Table 5 shows an example of a protection zone matrix. At each PoC-DC, the voltage operating conditions during the fault and fault clearing shall be defined according to 5.4.4.

Depending on the capabilities of converters and other equipment in the grid, five concepts for the behaviour at a PoC during faults are to be considered. The five basic concepts are shown in Table 4.

A single PoC can be assigned to different behaviour depending on the fault location (HVDC grid protection zone). When selecting the required fault behaviour, the system stability of the connected AC systems shall be considered. This applies in cases where two or more AC/DC converter stations are connected to the same AC system. The temporary loss of active and reactive power can have different effects and shall be differentiated.

Table 4 – DC fault separation concepts of HVDC grids or parts thereof defined at a PoC-AC or PoC-DC respectively

Fault separation concepts	Definition of the concept
Continued operation	The exchange of active and reactive power remains controllable at all times during the fault and the fault separation.
Temporary stop P	The exchange of active power can be temporarily interrupted while reactive power remains controllable at all times during the fault and fault separation. The interruption of active power is short enough to prevent the transmission system from entering into alert, emergency or blackout state.
Temporary stop PQ	The exchange of active and reactive power can be temporarily interrupted during the fault and fault separation. The interruption is short enough to prevent the transmission system from entering into alert, emergency or blackout state.
Permanent stop P	The exchange of active power can be interrupted due to the fault. The transmission system can enter into alert, emergency or blackout state.
Permanent stop PQ	The exchange of active and reactive power can be interrupted due to the fault. The transmission system can enter into alert, emergency or blackout state.

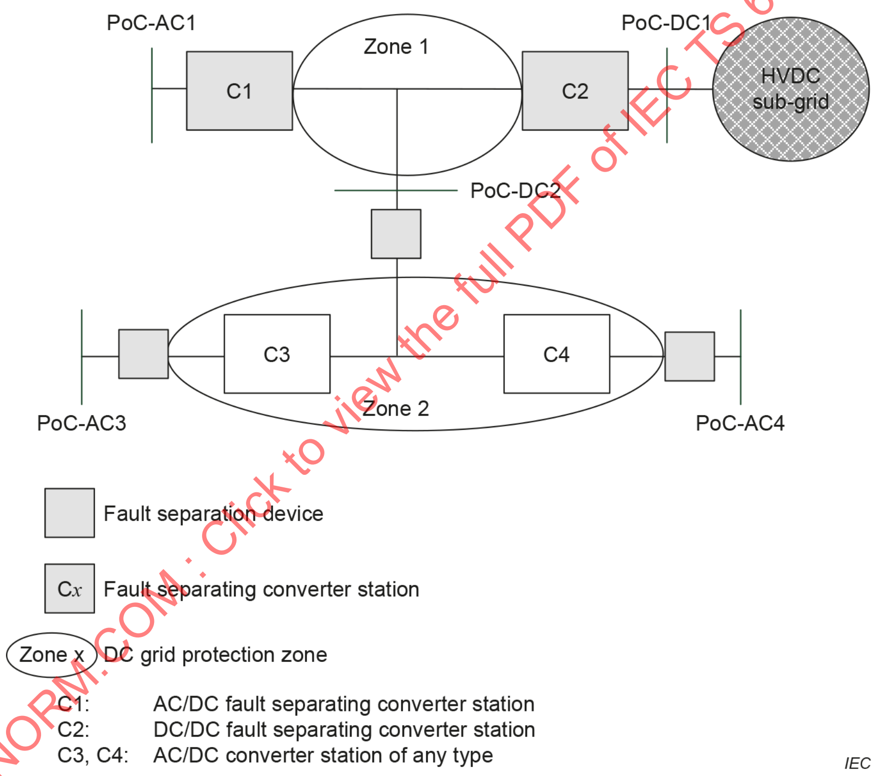


Figure 20 – Example illustrating the concept of HVDC grid protection zones in HVDC grids

The example shows primary protection only.

A similar diagram can be defined for backup protection.

In a real project, additional HVDC grid protection zones, which will normally be overlapping, can be applied.

7.4.2 Permanent stop P

7.4.2.1 Possible applications

The protection concept of permanent stop of active power (permanent stop P, PS-P) at a PoC is used when the system entering into alert, emergency or blackout state due to permanent or temporary DC faults is permissible.

Permanent stop P would typically be used at the PoC, where the benefit of fast fault separation is limited and/or the likelihood for a DC insulation fault is considered low, but a reactive power support is beneficial for the connected AC network in case of PoC-AC.

7.4.2.2 Basic characteristics

The behaviour at a PoC assigned to permanent stop P with respect to an insulation fault in a specific HVDC grid protection zone is characterized by:

- Active power is interrupted due to the fault.
- In the case of a PoC-AC, reactive power remains controllable at all times during the fault and fault separation process.
- The transmission system enters into an alert, emergency or blackout state due to the fault.
- The stop is considered permanent from the protection point of view. An automatic or manual restart procedure can be initiated by the control system once the fault is eliminated.

7.4.2.3 Requirements on protection

The DC side insulation fault defined for permanent stop P will be detected by all HVDC stations and FSDs at the boundaries to adjacent HVDC grid protection zones.

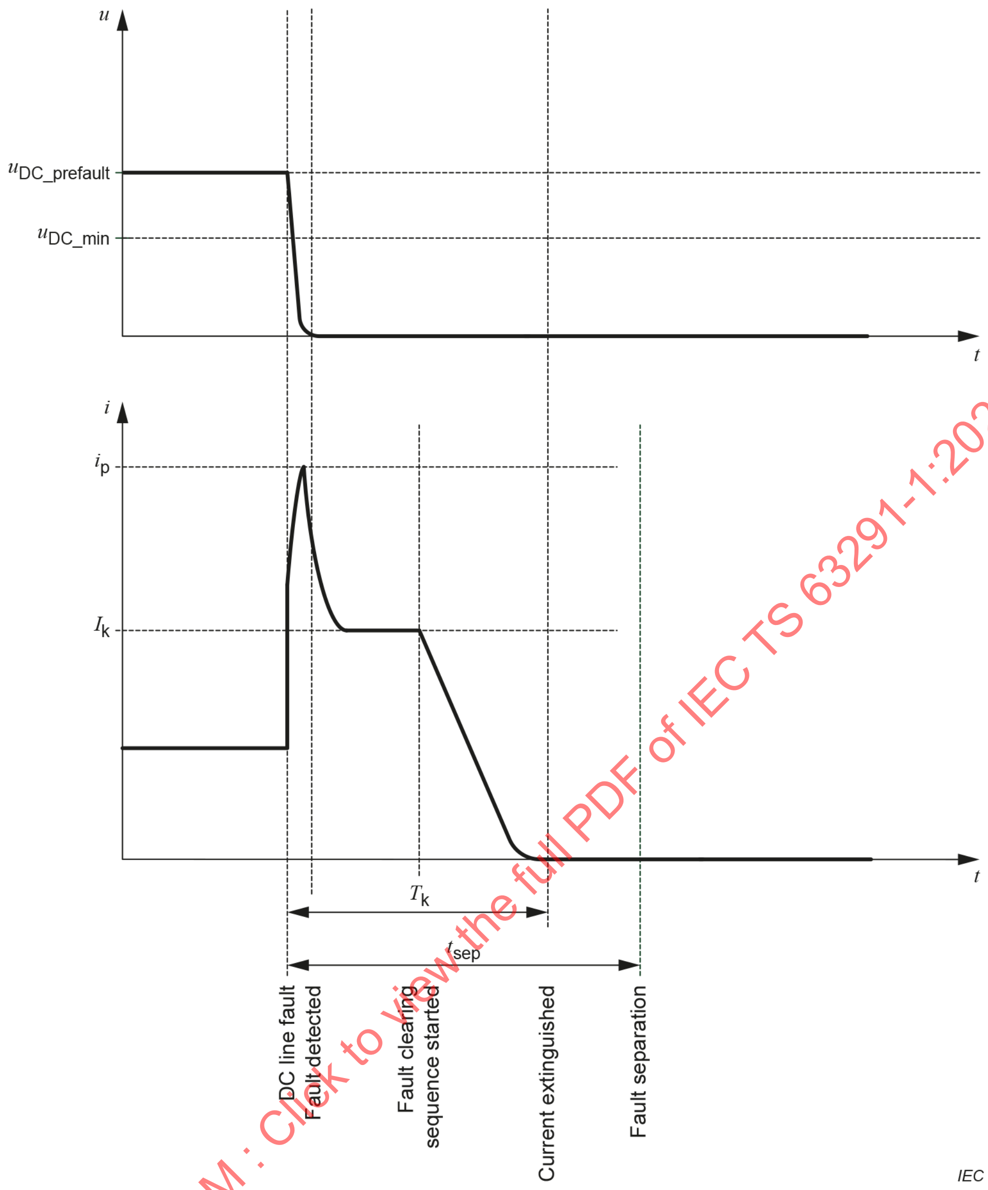
For fault detection between the fault and the PoC-AC assigned to permanent stop, no dedicated HVDC grid protection functions are required. For example, in the case of AC/DC converter stations the station protection functions, as in the case of a two terminal HVDC transmission system, are sufficient.

For PoC-DC dedicated protection functions are to be provided according to the FSDs applied.

Fault localization is not required for protection purposes.

7.4.2.4 Example voltage and current traces as well as timings

The decisive parameters of the fault current are found in 5.6.2. The example timing of the fault separation process can be found in Figure 21.



I_k steady-state short-circuit current

i_p peak short-circuit current

T_k short-circuit duration

$u_{DC\_prefault}$ pre-fault DC system voltage

u_{DC_min} minimum DC voltage

t_{sep} separation time

Figure 21 – Example of voltage and current traces in the event of "permanent stop"

7.4.2.5 Fault current breaking device

The fault current is extinguished by HVDC stations and this process shall be activated in all HVDC stations feeding the DC fault current in the respective HVDC grid protection zone.

The fault current breaking device for DC side insulation faults within this kind of HVDC grid protection zone are the type 2, 4 or 5 converter stations (see 8.2).

7.4.2.6 Fault separation device

Fault separation can be provided by converters, HVDC breakers or switches.

If switches are used, the fault current breaking devices have to be coordinated with the switches to perform the fault separation taking into account possible residual currents when opening the switches.

7.4.2.7 Recovery scenario

If required, a manual or automatic control sequence can be initiated from the control scheme to restart the healthy part of HVDC grid. The restoration time will be in the range of seconds and is not further described in this Clause 7.

For a timely restart, an automatic fault identification system can be used to identify the failed section of the HVDC grid protection zone or the possible fault location, respectively, to ensure selectivity of separation.

7.4.2.8 Backup scenario

In the event of a failure of the fault current breaking device, e.g. the AC station CB, a backup scenario similar to the application of a two terminal HVDC transmission system is required. This failure has to be treated locally in the respective AC/DC converter station by tripping higher level breakers.

7.4.3 Permanent stop PQ

7.4.3.1 Possible applications

The protection concept of permanent stop of active and reactive power (permanent stop PQ, PS-PQ) at a PoC-AC is used when the system entering into alert, emergency or blackout state due to permanent or temporary DC faults is permissible.

Permanent stop would typically be used at the PoC-AC of smaller HVDC grids or parts of an extended HVDC grid, where the benefit of fast fault separation is limited and/or the likelihood of a DC insulation fault is considered low and there are no requirements on reactive power support.

7.4.3.2 Basic characteristics

The behaviour at a PoC assigned to permanent stop PQ with respect to an insulation fault in a specific HVDC grid protection zone is characterized by:

- Active power is interrupted due to the fault. In case of a PoC-AC, reactive power is also interrupted due to the fault.
- The transmission system enters into an alert, emergency or blackout state due to the fault.
- The stop is considered permanent from the protection point of view. An automatic or manual restart procedure can be initiated by the control system once the fault is eliminated.

7.4.3.3 Requirements on protection

The DC side insulation fault defined for permanent stop PQ will be detected by all HVDC stations and FSDs at the boundaries to adjacent HVDC grid protection zones.

For fault detection between the fault and the PoC-AC assigned to permanent stop PQ, no dedicated HVDC grid protection functions are required. For example, in the case of AC/DC converter stations the station protection functions, as in the case of a two terminal HVDC transmission system, are sufficient.

For a PoC-DC, dedicated protection functions are to be provided according to the FSDs applied.

Fault localization is not required for protection purposes.

7.4.3.4 Principle voltage and current traces as well as timings

The decisive parameters of the fault current are found in 5.6.2. The principle timing of the fault separation process can be found in Figure 21.

7.4.3.5 Fault current breaking device

HVDC protections and FSDs used in a two terminal HVDC transmission system can be applied to a PoC-AC.

To break the fault current at an AC/DC converter station, the AC station CBs of the respective AC/DC converter stations can break the fault current and separate the fault from the respective AC system.

For a PoC-DC assigned to permanent stop, a dedicated FSD is needed.

7.4.3.6 Fault separation device

Converters and HVDC grid sections are normally connected via disconnect switches. These switches can disconnect the faulty section after fault clearing in order to prepare the healthy part of the HVDC grid for a possible restart.

7.4.3.7 Recovery scenario

If required, a manual or automatic control sequence can be initiated from the control scheme to restart the healthy part of HVDC grid. The restoration time will be in the range of seconds and is not further described in this Clause 7.

For a timely restart, an automatic fault identification system can be used to identify the failed section of the HVDC grid protection zone or the possible fault location, respectively, to ensure selectivity of separation.

7.4.3.8 Backup scenario

In the event of a failure of the fault current breaking device, e.g. the AC station CB, a backup scenario similar to the application of a two terminal HVDC transmission system is required. This failure has to be treated locally in the respective AC/DC converter station by tripping higher level breakers.

7.4.4 Temporary stop P

7.4.4.1 Possible applications

The protection concept of temporary stop of active power (temporary stop P, TS-P) at a PoC avoids the transmission system entering into alert, emergency or blackout state due to DC insulation faults in a specific HVDC grid protection zone.

It is typically used for systems prone to temporary DC faults, e.g. OHL.

7.4.4.2 Basic characteristics

The behaviour at a PoC assigned to temporary stop P with respect to an insulation fault in a specific HVDC grid protection zone is characterized by the following.

- Active power is interrupted due to the fault.

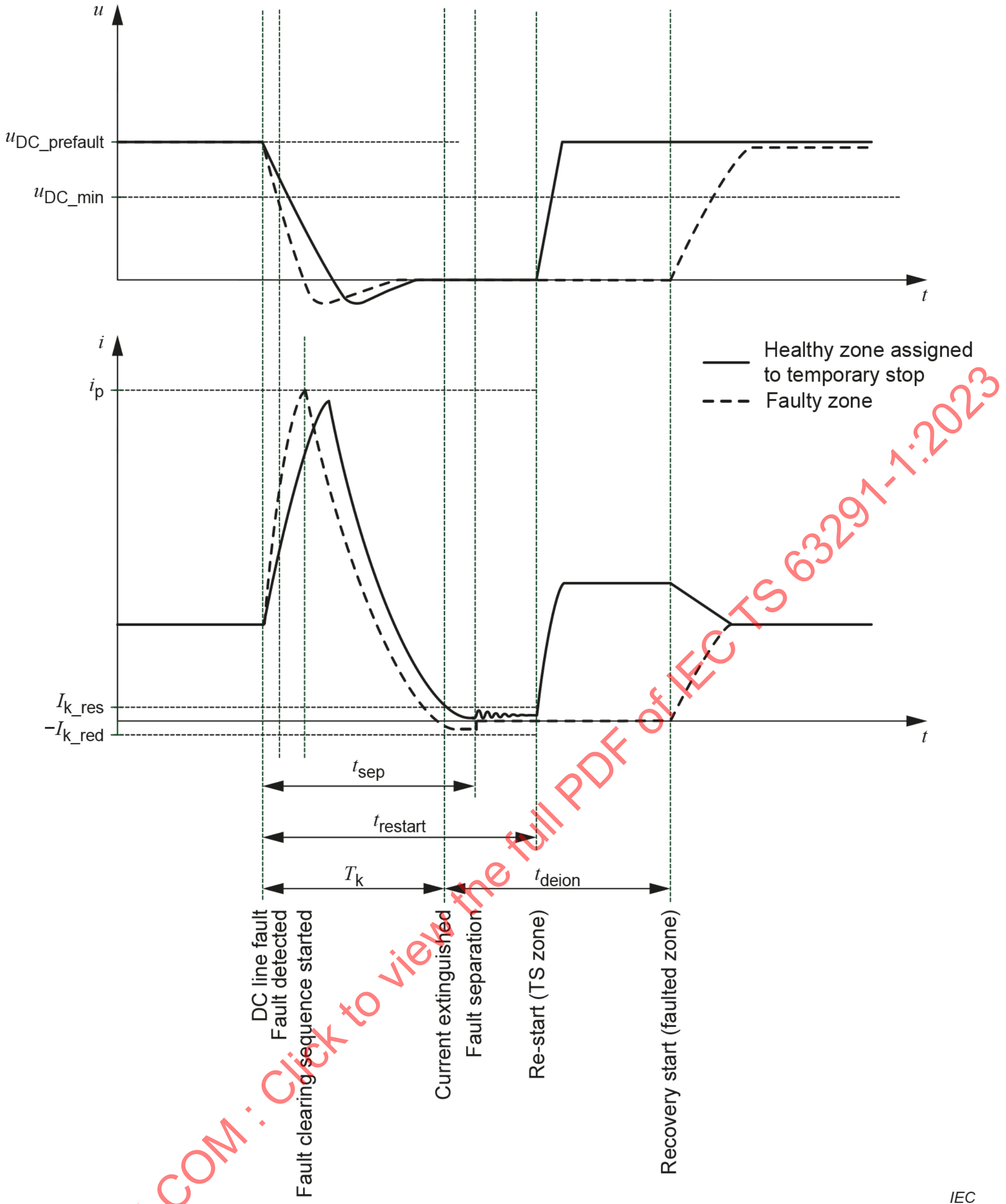
- In the case of a PoC-AC, reactive power remains controllable at all times during the fault and fault separation process.
- The active power is restored fast enough in order to prevent the transmission system from entering into an alert, emergency or blackout state due to the fault.

7.4.4.3 Requirements on protection

The protection system for this concept requires fault localization and current breaking. The faulty part has to be separated selectively from the rest of the transmission system.

7.4.4.4 Example voltage and current traces on the DC side as well as timings

An example timing of the fault separation process can be found in Figure 22.



I_{k_res}	steady-state residual short-circuit current (band)
i_p	peak short-circuit current
T_k	short-circuit duration
$u_{DC\_prefault}$	pre-fault DC system voltage
u_{DC_min}	minimum DC voltage
t_{sep}	separation time
$t_{restart}$	restart start time of healthy section
t_{deion}	deionisation time

Figure 22 – Example voltage and current traces in the event of "temporary stop P"

7.4.4.5 Fault current breaking device

The fault current is extinguished by HVDC stations or HVDC breakers and this process shall be activated in all HVDC stations feeding the DC fault current in the respective HVDC grid protection zone.

The fault current breaking device for DC side insulation faults within this kind of HVDC grid protection zone is provided by the type 2, 4 or 5 converter stations (see 8.2).

7.4.4.6 Fault separation device

Fault separation can be provided by converters, HVDC breakers or switches.

If switches are used, the fault current breaking devices have to be coordinated with the switches to perform the fault separation taking into account possible residual currents when opening the switches.

7.4.4.7 Recovery scenario

After the fault is separated by all relevant FSDs the converters can restart DC power transmission.

The restart is handled by the control system and shall be coordinated between the HVDC stations. As an example, a post-fault recovery current is shown in Figure 22.

The restart is handled by the control system and shall be coordinated between the HVDC stations.

For full performance of the temporary stop functionality, communication between the affected HVDC stations within the HVDC grid protection zone is required.

7.4.4.8 Backup scenario

The backup scenario has to be defined to cover two possible failure scenarios. A failure of the fault current breaking device, e.g. an AC/DC converter station, has to be treated locally in the respective AC/DC converter station and the backup scenario can be achieved by tripping the higher-level AC breaker.

A loss of communication between the HVDC stations within the HVDC grid protection zone can lead to a backup scenario as well.

The reaction in respect to a failure of the FSD has to be predefined for each individual device. The backup scenario has to be performed either by an adjacent switch or by a permanent stop of the converters.

7.4.5 Temporary stop PQ

7.4.5.1 Possible applications

The protection concept of temporary stop of active and reactive power (temporary stop PQ, TS-PQ) at a PoC-AC avoids the transmission system entering into alert, emergency or blackout state due to DC insulation faults in a specific HVDC grid protection zone.

It is typically used for systems prone to temporary DC faults, e.g. OHL.

7.4.5.2 Basic characteristics

The behaviour at a PoC assigned to temporary stop PQ with respect to an insulation fault in a specific HVDC grid protection zone is characterized by the following.

- Active power and reactive power are interrupted due to the fault.
- The active and reactive power is restored fast enough in order to prevent the transmission system from entering into an alert, emergency or blackout state due to the fault.

The requirements on protection, principle voltage and current traces on the DC side, timings, fault current breaking devices, FSDs and backup scenarios are the same as in the case of 7.4.4.

7.4.5.3 Recovery scenario

After the fault is separated by all relevant FSDs the converters can restart DC power transmission. The restart is handled by the control system and shall be coordinated between the HVDC stations.

For full performance of the temporary stop functionality, communication between the HVDC stations within the HVDC grid protection zone is required.

Depending on the technology used, reactive power can be resumed independently from active power during the fault clearing and fault separation process.

7.4.6 Continued operation

7.4.6.1 Possible applications

The protection concept of continued operation (CO) at a PoC decouples this PoC from the fault in the respective HVDC grid protection zones such that active and reactive power remain controllable at all times during the fault and the fault separation.

It is typically applied to extended HVDC grids or when the AC system is sensitive to loss of voltage and/or frequency control.

7.4.6.2 Basic characteristics

The behaviour at a PoC assigned to continuous operation with respect to an insulation fault in a specific HVDC grid protection zone is characterized by the following:

- The exchange of active and reactive power remains controllable at all times during the fault and the fault separation.

7.4.6.3 Requirements on protection

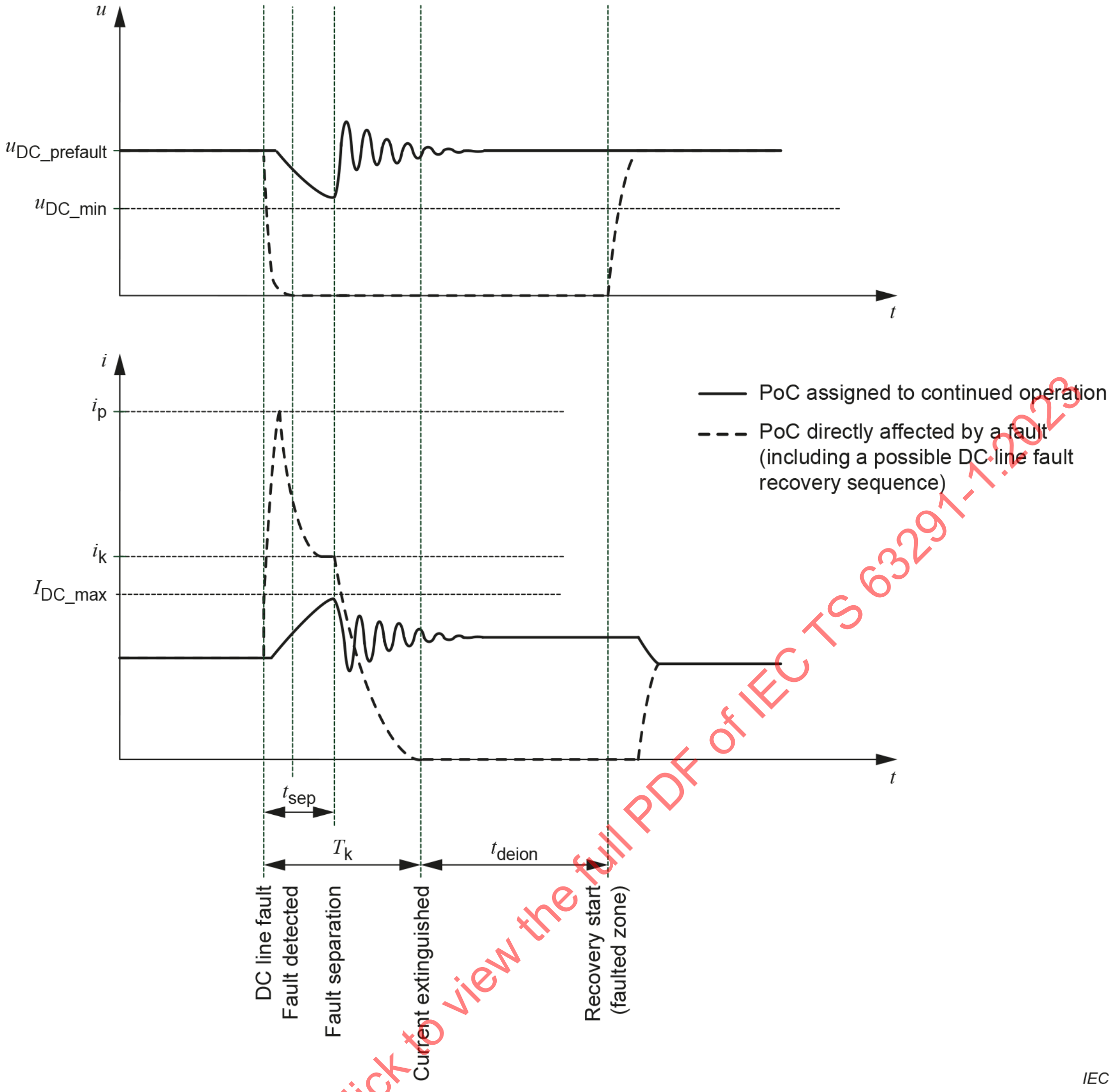
Special DC protection will be needed to provide selective and timely fault separation. For HVDC grids with several breaking devices it is important that the correct device responds. The requirement on protection outside the faulted HVDC grid protection zone for continued operation is that no specific actions related to the fault are needed and allowed.

The protection system assigned to a breaking device should be coordinated to be fast enough to break the fault current before the current capability of the device is exceeded and before the DC voltage drops in the remaining HVDC grid.

The protection concept should be based on local measurements. Typically, no communication is involved due to speed requirements.

7.4.6.4 Example voltage and current traces as well as timings

An example timing of the fault separation process can be found in Figure 23.



I_k	steady-state short-circuit current
i_p	peak short-circuit current
I_{DC_max}	maximum DC current in unfaulty system for DC fault ride through
T_k	short-circuit duration
$u_{DC\_prefault}$	pre-fault DC system voltage
u_{DC_min}	minimum DC voltage
t_{sep}	separation time
t_{deion}	deionisation time

Figure 23 – Example voltage and current traces in the event of "continued operation"

7.4.6.5 Fault current breaking device

The fault current is extinguished using HVDC breakers or DC/DC converters with corresponding functionality which will also separate the fault.

The breaking device can be placed separately from the converters as standalone equipment.

There is no or limited fault current contribution through the breaking device.

7.4.6.6 Fault separation device

Fault separation will be performed together with the fault current breaking by the HVDC breakers or DC/DC converters with the corresponding functionality.

7.4.6.7 Recovery scenario

The power flow at the respective PoC remains controllable at all times during the fault and the fault separation.

7.4.6.8 Backup scenario

The backup scenario has to be defined to cover two possible failure scenarios. A failure of the fault current breaking device, e.g. an HVDC breaker, has to be coordinated with other breaking devices or be treated as a temporary or permanent stop.

The reaction in respect to a failure of the FSD has to be predefined for each individual device.

7.4.7 Example of a protection zone matrix

As an example, an HVDC grid with four converters (C1 to C4) as shown in Figure 24 shall be considered with respect to the primary fault separation, i.e. not a backup fault separation. A typical backup fault separation concept can be permanent stop or a separate table can be specified.

It should be noted that the example illustrates the HVDC grid protection zone concept in HVDC grids. In a real project, additional HVDC grid protection zones, which are normally overlapping, can be applied.

A possible HVDC grid protection zone matrix is given in Table 5 as an example solution.

Table 5 – HVDC grid protection zone matrix

Faults in:	PoC-AC1	PoC-AC3	PoC-AC4	PoC-DC1	PoC-DC2
Zone 1	PS-P	CO	CO	PS-P	PS-P
Zone 2	TS-P	CO	CO	TS-P*	TS-P
Zone 3	TS-P	CO	CO	PS-P	TS-P
Zone 4	CO	PS-PQ	PS-PQ	CO	PS-P

PS-P Permanent stop P
PS-Q Permanent stop Q
TS-P Temporary stop P
TS-P* Temporary stop P used for DC line fault recovery; can change to PS-P for permanent faults
TS-PQ Temporary stop PQ
CO Continued operation

The requirements of Table 5 can be fulfilled by a system according to Figure 24. Station C1 is an AC/DC converter station of type 2, 4 or 5 (fault separating converter station), station C2 is a DC/DC converter station of type 2, 4 or 5 (fault separating converter station), stations C3 and C4 are AC/DC converter stations of any type.

The FSD connected to PoC-DC2 is an HVDC breaker. The FSDs connected to C2 and C3 are AC station CBs. A (fast) disconnect switch is installed between zone 1 and zone 2 without any PoC requirement at this location.

HVDC grid protection zones 1, 3 and 4 will be cable, zone 2 will be OHL.

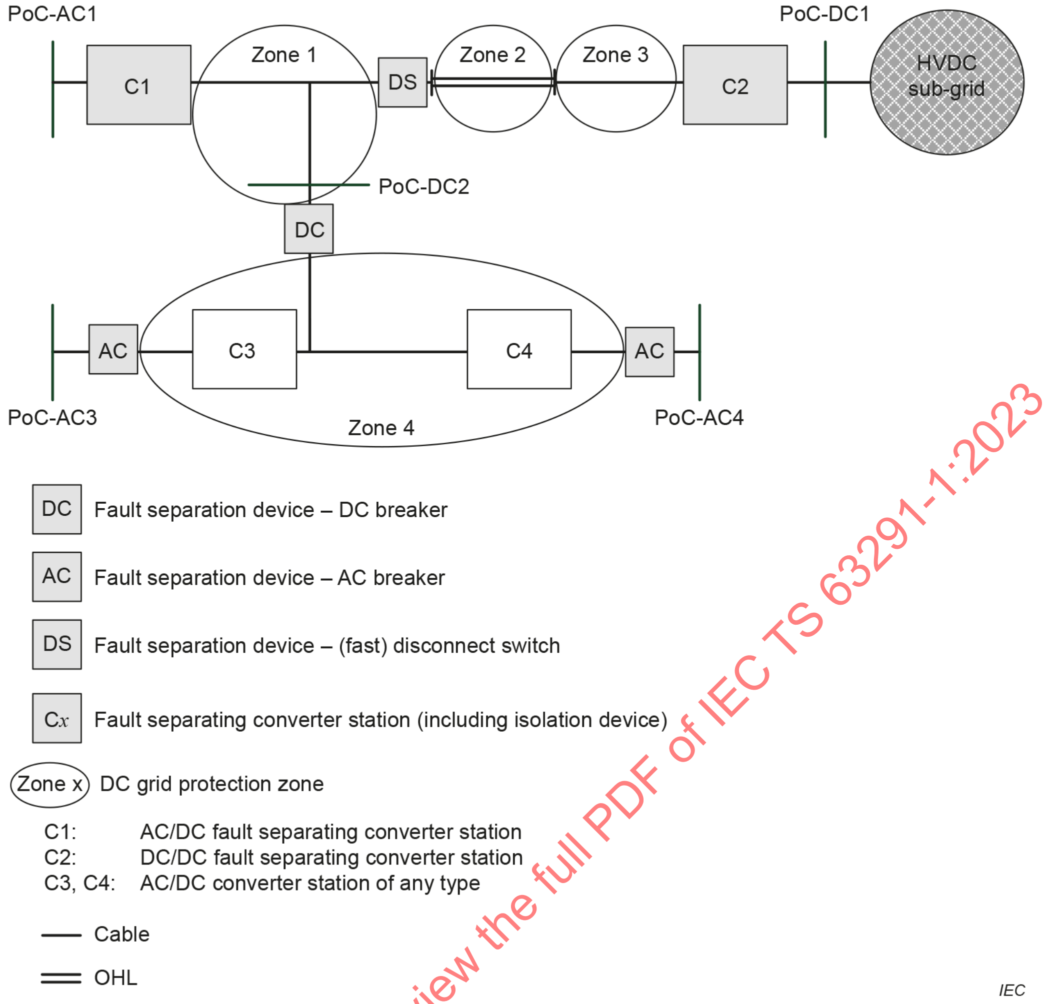


Figure 24 – Example of an HVDC grid protection zone layout

7.5 DC protection

7.5.1 General

The protection clearance and tripping of a fault has three important purposes:

a) to minimize hazard to personnel and environment;

b) to minimize disturbance to operation;

c) to minimizing the risk of any damage.

The safety aspect a) will always have the highest priority.

The higher the power transfer of the system, the higher the priority for b) to minimize the consequences to operation. The cost of outages could be significant, and this should be evaluated based on the likelihood of faults and the expected outage times. Consequently, the availability of spare parts in the HVDC station or close to it is important as this will impact the outage time.

In designing and specifying the protection system the following points have to be considered in detail:

- selection of typical HVDC grids (layout), including earthing and HVDC transmission system;
- behaviour of converters for earth faults and short-circuits;
- operating conditions of HVDC grids (voltage, current, power flow);

- definition of fault types (converter faults, AC faults or DC system faults);
- benefits of HVDC breakers for fault clearing;
- impact from communication:
  - delays in communication (physical signal propagation, buffering in sending/receiving blocks),
  - requirements on protocols to use,
  - consequences due to loss of communication (to other HVDC stations or protection devices).

7.5.2 DC converter protections

HVDC stations with symmetrical or asymmetrical DC voltage to earth will have basically the same set of protections. The DC unbalance, overvoltage and undervoltage shall be taken into consideration in the protection algorithms in the AC and DC voltage protections.

Bipolar schemes are normally designed to have the protection systems between the poles as independent as possible. They will be virtually the same as in case of two asymmetric monopoles. In some cases, common equipment to both poles such as an electrode line can require additional protection functions.

In general, it is expected that all faults within an HVDC station will be detected by two different protections; that is, all protections have a backup protection with a different operating principle and using different transducers as far as is practicable.

The converter protections are divided into three subgroups:

- those related to the HVDC grid; where settings primarily come from the HVDC grid requirements and are coordinated with other HVDC stations;
- those related to individual converters;
- those coordinated with the connected AC system.

7.5.3 HVDC grid protections

7.5.3.1 General

By "HVDC grid protection" the protection of the HVDC grid itself is meant. Thus, HVDC station faults are excluded from this Subclause 7.5.3 and only line faults are considered. In general, HVDC grid protection (as considered here) can be subdivided into protection schemes with and without communication.

In the following context, the term "communication" thereby refers to a bidirectional exchange of commands and status information between (at least) two HVDC stations or other protection devices.

Basic requirements for DC fault protection are the same as for the AC grid, namely:

- fast,
- selective,
- sensitive,
- economical,
- reliable.

7.5.3.2 Fault detection based on communication

Fault detection based on communication is usually selective by nature. However, since this relies on information being transmitted over a communication channel, the speed of the detection is limited by the delays associated with the telecommunication equipment and medium. Communication-based detection functions can improve the performance for high impedance, low current faults, as those faults are more difficult to detect. For low impedance, high current faults, fault detection without communication is recommended.

Synchronisation versus working frequency of the protection and transients shall be considered during the protection design in order to exclude unwanted trips. Also, a time related to the propagation speed of ~200 km/ms shall be taken into account if optical fibre communication support is considered, added to a processing time of the data.

All communication-based fault detection shall have a backup protection scheme not relying on communication.

7.5.3.3 Fault detection without communication

Fault detection without communication shall be based on local measurements. Selectivity is mainly achieved by the coordination of settings. The settings shall be determined by considering all relevant operation conditions and scenarios such as internal and external faults regarding protection zones to ensure selectivity. Furthermore, for the protection to operate reliably, a sufficient margin shall be ensured regarding both security and reliability.

This margin depends on the criterion used for the detection and can eventually be improved by adding HV installations to the HVDC grid such as current limiters / inductive elements. The higher the margin of the criterion between internal and external faults, the higher the probability of the detection algorithm to operate selectively. However, additional installations such as inductive elements can increase challenges for tripping the equipment. Thus, a trade-off between positive effects for detection and negative effects for fault clearing shall be made.

The following paragraphs only describe examples of typical protection algorithms. Best known AC protection functions not based on communication are overcurrent, undervoltage, and distance protections.

Distance protection algorithms as known from AC protection are not suitable for DC grids as reactances are not available ($\omega = 0$).

Overcurrent protection would require a threshold higher than the maximum current flowing under normal condition. With overcurrent protection the threshold and the current rate of change in the event of DC line faults leads to a certain minimum detection time. The current rate of change in the event of DC line faults will be influenced by converter design (e.g. phase arm inductors) or inductors in the DC line.

The undervoltage protection as such has to be considered unselective even with inductors in the DC line, since the DC resistance alone will generate a relatively small voltage drop only. Only a transient undervoltage protection in conjunction with inductors in the DC line could provide a certain level of selectivity.

Beside the protection functions known from AC protection, other algorithms can be required for selective fault detection.

Alternative algorithms can be based on comparing the measured DC voltages or currents during the fault with calculated or simulated dedicated characteristic waveforms/shapes or characteristic values in real time, either separately or in combination with each other. For example, this can be line current rate of change, a specific line current characteristic, etc.

A further detection algorithm could be a parallel modelling of the responses of DC voltages or currents for different fault distances in real-time and matching these responses to the measured DC voltages or currents.

7.5.4 HVDC grid protection communication

Communication is not expected to play an important role for fault detection, fault current limitation (either by HVDC breakers, fault current limiting HVDC stations or AC breakers) and fault separation. The protection operating time requirement can be faster than what can be achieved with communication. Therefore, protection that uses communication imposes special requirements on the protection system to handle selectivity on the HVDC grid as described in 7.5.3.2. It is expected that normal fast control requirements will be sufficient also for protections.

Communication can be used in order to improve or enable identification of faulty line sections. This is especially important for transmission systems with a combination of OHL and cable sections.

After fault separation and as a support function for the recovery process in 6.4.3, communication can be essential, i.e., for the identification of the faulted HVDC grid protection zone, synchronisation of switches and the release for restoration of the system. For coordination of these functionalities, typically a central approach (i.e., HVDC grid control level) will be required.

8 AC/DC converter stations

8.1 Purpose

An AC/DC converter station connects an HVDC grid to an AC system. It can provide various operational functions as described in 4.5.

Table 9, Table 10 and Table 11 provide an overview on functions changing operating states, functions of grid operation and protective functions.

The DC side of the AC/DC converter station can be connected directly to an HVDC transmission line or to a switching station.

A complete specification of each AC/DC converter station in the HVDC grid shall be provided.

8.2 AC/DC converter station types

8.2.1 General

For the purpose of this document, five types of AC/DC converter stations are defined differentiating an AC/DC converter station's operating range with respect to DC voltage and DC current. The AC/DC converter station types are visualized in Figure 25.

NOTE 1 The rectangular shapes of the different types are indicative only. Techno-economic aspects can lead to different shapes.

NOTE 2 The functions of an individual converter can be combined with other equipment, such as switchgear, to extend its operational capabilities.

8.2.2 AC/DC converter station type 1 (AC/DC type 1)

AC/DC converter station that can only operate in a part of quadrant 1 of the U/I characteristic, e.g. like a diode bridge.

8.2.3 AC/DC converter station type 2 (AC/DC type 2)

AC/DC converter station that can operate with both positive and negative voltage but only one current direction, i.e., operating in quadrants 1 and 4 of the U/I characteristic, e.g. like a Thyristor bridge without DC current reversal switches.

8.2.4 AC/DC converter station type 3 (AC/DC type 3)

AC/DC converter station that can operate in either current direction but is restricted in the range of DC voltage, i.e., operating in quadrants 1 and 2 of the *U*/*I* characteristic but limited to a minimum DC voltage level, e.g. like a MMC based on half bridge modules without DC voltage polarity reversal switches.

8.2.5 AC/DC converter station type 4 (AC/DC type 4)

AC/DC converter station that can operate continuously in quadrants 1 and 2 at any DC voltage level. This type of converter station can extinguish DC fault currents by operating transiently in quadrants 3 and 4, expressed by the dash-dotted line.

8.2.6 AC/DC converter station type 5 (AC/DC type 5)

AC/DC converter station that can operate with either DC current direction or DC voltage polarity i.e. in all four quadrants of the *U*/*I* characteristic, e.g. like an MMC based on full bridge modules.

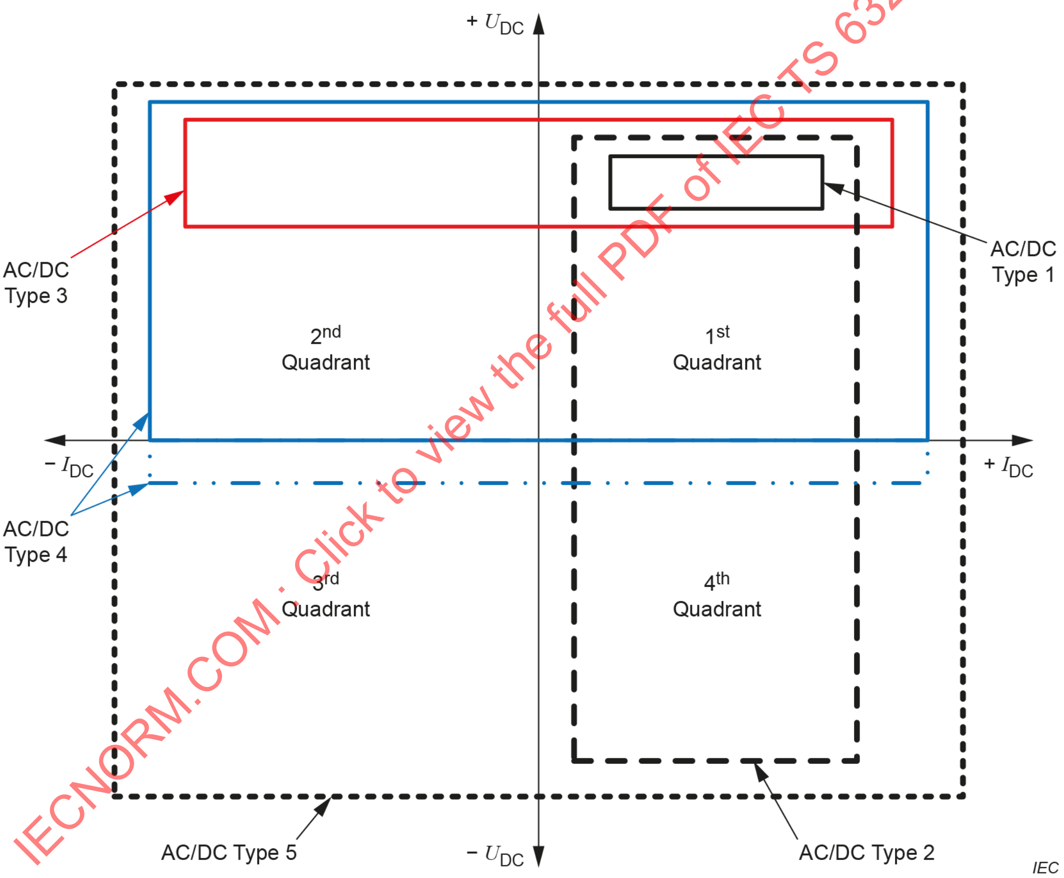


Figure 25 – AC/DC converter station types in the *U*/*I* diagram

8.3 Overall requirements

8.3.1 Robustness of AC/DC converter stations

The AC/DC converter station shall be capable of keeping or reaching a stable OP after all changes in the HVDC grid or the connected AC systems that are within the specified grid characteristics. The planned or unplanned changes of grid conditions for which the AC/DC converter station shall be capable of maintaining stable operation can include the following requirements:

- loss of communication

  - to the coordinated HVDC grid control layer (see Figure 15), relevant for the exchange of converter schedules and station information (see Figure 17)
  - to other HVDC stations, relevant for exchange of protection commands and status messages (see 7.5.3);
- predefined reconfigurations of the HVDC grid including response to system faults or converter faults (in particular in the case of so-called rigid bipole topology);
- reconfigurations of the AC systems;
- changes of the load flow conditions;
- changes of control modes (e.g. AC voltage, reactive power and power factor control mode).

8.3.2 Availability and reliability

Reliability as well as availability calculation methods are described in IEC/TR 62672:2018 [20].

In the case of station topology BOZ the station topology has to be further specified regarding the arrangement of CUs:

- one CU connecting both HV poles (so-called symmetric monopole);
- separate CUs for each HV pole (so-called rigid bipole).

8.3.3 Active power reversal

An AC/DC converter station can be required to reverse power direction. If so, it shall be specified if the power reversal has to be realized by DC voltage reversal or DC current reversal. Depending on the converter type (see Figure 25) additional equipment can be needed.

The sequence and time for the power reversal shall be specified.

NOTE Typically, power reversal by current reversal is used because DC voltage reversals affect the operation throughout entire HVDC grid while DC current changes can be coordinated between individual HVDC stations.

8.4 Main circuit design

8.4.1 General characteristics

8.4.1.1 Topology

The topology of the AC/DC converter station shall be specified with respect to:

- connection to HV poles of the DC grid (according to 5.1.4.1);
- the connection to the neutral return path (according to 5.1.4.2);
- station earthing (according to 5.1.4.3).

8.4.1.2 Active and reactive power characteristics

The active power quantities shall be coordinated with the HVDC grid as well as with the AC system whereas reactive power quantities shall be coordinated with the local AC system.

The active and reactive power characteristics shall be specified using an active vs reactive power chart as described in 4.4, Figure 4.

As a minimum set of requirements, the following additional information shall be specified:

- minimum power, if applicable,
- minimum required and maximum allowed P and Q ramp rates,
- power demand overrides (power run-back and power run-up levels in MW).

If covered by its design and depending on its actual operating conditions, an AC/DC converter station can operate in overload. The overload capability is determined by the thermal time constants and the maximum operating temperature of all relevant components. Overload operation is understood to start from defined pre-load conditions.

Overload capability, if any, can be evaluated for existing systems, subsystems or components and depends primarily on:

- ambient temperature,
- availability of redundant ancillary systems,
- actual operating temperature of equipment.

AC/DC converter stations can be designed to provide a certain overload capability. The specification shall address the voltage and frequency operating conditions as well as ambient conditions applicable to this operation and shall include:

- percentage of nominal active and reactive power according to 4.4, Figure 4,
- duration:
  - permanent overload,
  - temporary (minutes up to hours),
  - dynamic (few cycles up to seconds),
  - transient (milliseconds up to a few cycles).

8.4.1.3 Energisation

The energisation of the AC/DC converter station including the HV system has an impact on the design. The requirement regarding the energy source can be:

- energisation from AC side,
- energisation from DC side,
- energisation from a local power source.

Further requirements for energisation are:

- repetition (number of events),
- minimum time between consecutive events.

8.4.1.4 Energy dissipation/absorption capability

An AC/DC converter station can be required to balance a certain amount of energy to fulfil the relevant AC and DC grid code requirements with respect to fault ride through, AC frequency support and DC voltage support. The following shall be specified as a minimum requirement:

- power vs time characteristic P = f(t) (MW);
- repetition (number of events);
- minimum time between consecutive events (min).

This function can require specific design measures and/or extra equipment in the AC/DC converter station.

8.4.2 DC side

8.4.2.1 DC connection

8.4.2.1.1 HV poles

The topology of the AC/DC converter station shall be specified according to 5.1 and Table 1, Table 2 or Table 3, respectively. A given HVDC grid and station topology allows for different DC connection modes. The DC connection modes describe the designated connections between the individual terminals of the converter and the terminals of the PoC-DC.

The terminals of the converter are described by the following nomenclature:

CUx converter unit x

Ty terminal y

CUxTy terminal y of converter unit x

Px pole x; x being 1 or 2

The terminals at the PoC-DC are described by the following nomenclature:

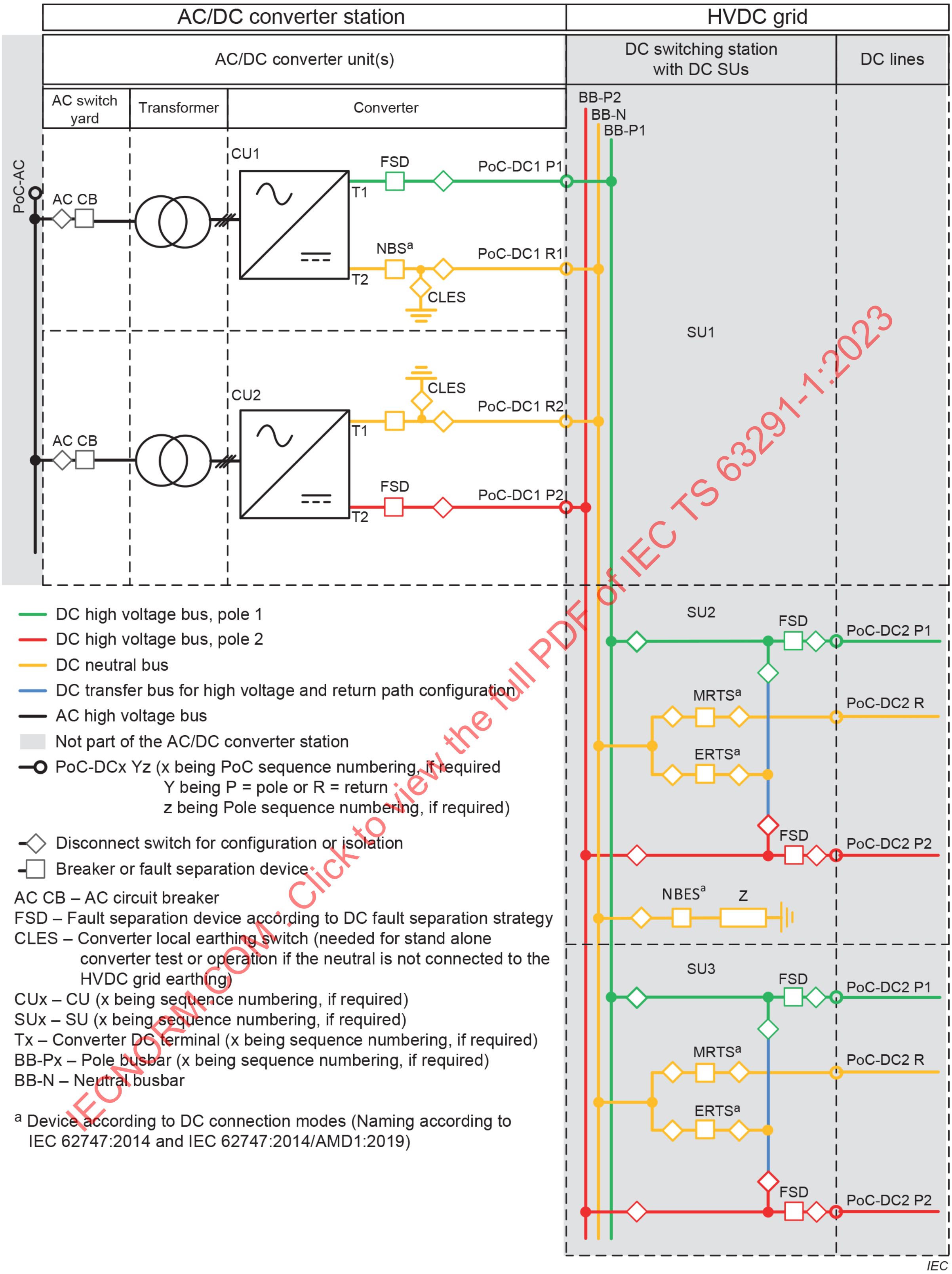
PoC-DCx Py station DC PoC x, x being the number of the PoC-DC with HV pole Py, y being 1 or 2

PoC-DCx Ry station DC PoC x, x being the number of the PoC-DC with station return path connection point R; if there are more than one return path connection points, the connection points are numbered (Ry, y being 1 or 2)

Figure 26 shows an example for a bipolar AC/DC converter station (type BRO) which is connected to two HVDC transmission lines via a dedicated DC switching station (type BRZ). The AC/DC converter station is connected between the PoC-AC and PoC-DC1 and consists of:

- AC switch yard
- transformers
- converter units CU1 and CU2.

NOTE AC switch yard and transformers are not described in further detail in this document.



NOTE In AC/DC converter stations being connected to just one DC transmission circuit, the adjacent DC switching station can become part of the AC/DC converter station. The assembly of the DC switches is typically referred to as the DC switchyard. In this case, the design of protection zones can be similar to those of an AC/DC converter station being part of a point-to-point link.

Figure 26 – Example of a BRO AC/DC converter station with connected BRZ DC switching station. The AC/DC converter station is of bipolar topology. Its adjacent DC switching station connects two bipolar transmission circuits with DMR in this example

In Figure 26 the PoC-DC1 comprises the HV poles P1 and P2 as well as the return path connections R1 and R2. Since the DC switching station provides earth reference as well as the realisation of the different DC connection modes, like bipole or monopole, the CU DC terminals CU1 T1, CU1 T2 as well as CU2 T1, CU2 T2 are connected to the respective PoC-DC1 terminals P1, P2, R1 and R2 without any possible interconnections in between.

In the example given in Figure 26, each CU is equipped with an FSD in the HV path, an NBS in the neutral path as well as necessary disconnectors. A dedicated earthing switch is foreseen at each CU to provide earthing if the AC/DC converter station is disconnected from the HVDC grid earthing.

To specify the DC connection modes, a scheme like in Table 6 shall be used. Table 6 shows an example of DC connection modes as applicable to the AC/DC converter station shown in Figure 26.

In connection mode 1, both CUs are connected to the HVDC grid. The HVDC grid provides earth reference and the connection to the neutral return path.

In connection modes 2 and 3, only one CU is connected to the HVDC grid, while the other one is disconnected. Under disconnected conditions, the corresponding CU can be switched off or exchange reactive power with the AC system. In the latter case, an earth reference is normally needed. In the present case this would be done by closing the earthing switch CLES.

In connection mode 4, both CUs are disconnected from the HVDC grid. They can be switched off or exchanging reactive power with the AC system as described for connection modes 2 and 3 above.

The required DC connection modes can also be specified in form of single line diagrams showing the connections between the converter terminals and the PoC-DC terminals including the necessary switchgear.

The reconfiguration requirements between the individual DC connection modes including the maximum transition times from no-load operation in the former mode to no-load operation in the new mode shall be specified using Table 7.

Table 6 – DC Connection modes of an AC/DC converter station

Connection mode		CU1T1	CU1T2	CU2T1	CU2T2
Mode 1	"coupled"	PoC-DC1 P1	PoC-DC1 R1	PoC-DC1 R2	PoC-DC1 P2
Mode 2	CU2 "DC decoupled"	PoC-DC1 P1	PoC-DC1 R1		
Mode 3	CU1 "DC decoupled"			PoC-DC1 R2	PoC-DC1 P2
Mode 4	CU1, CU2 "DC decoupled"				

Table 7 – DC circuit re-configuration requirements

Previous connection mode S_x	Next connection mode S_y			
	Mode 1	**Mode 2**	**Mode 3**	**Mode 4**
Mode 1		t_{max12}	t_{max13}	t_{max14}
Mode 2	t_{max21}		*)	t_{max24}
Mode 3	t_{max31}	*)		t_{max34}
Mode 4	t_{max41}	t_{max42}	t_{max43}	
*) no direct transition t_{maxxy}: time for transition between previous connection mode S_x and next connection mode S_y				

8.4.2.1.2 Neutral point earthing

The DC neutral terminal of the AC/DC converter station, if any, can be connected to earth. This connection can be provided by the adjacent DC switching station or via return conductor somewhere within the HVDC grid.

The location of the earthing point shall be selected considering conductive structures in the earth and above, like cable sheaths, pipelines, OHLs, transformers in AC systems or others with respect to magnitude and time. This can require the earthing point being located outside the physical boundaries of an HVDC station and being connected by a dedicated HVDC transmission line.

The earth connection of the AC/DC converter station, if any, as well as the switching conditions, if any, shall be specified. The branch can be switched or permanent and consist of resistors, reactors, capacitors, arresters or any combination thereof.

The electrical characteristics of the earthing branch shall be specified.

The conditions for switching the earthing branches on or off shall be specified.

In the special case of a so-called symmetric monopole, no DC neutral terminal exists.

8.4.2.2 DC voltages

The requirements with respect to DC voltage for the HV poles as well as the neutral bus are described in 5.4.

8.4.2.3 DC insulation levels

Withstand or protective levels shall be specified only at the PoC-AC or PoC-DC including the neutral terminal, if any. The protective levels shall be coordinated within the HVDC grid, especially with HVDC stations in close vicinity.

Effective measures shall be taken in the AC/DC converter station limiting any self-generated DC overvoltages at the PoC DC to protective levels defined for the HVDC grid.

8.4.2.4 DC fault ride through behaviour

The DC fault ride through behaviour is driven by the fault separation concept to be supported by the AC/DC converter station. To describe the fault separation capabilities, the behaviour at the PoC-AC in response to an insulation fault appearing at the PoC-DC of the AC/DC converter station shall be specified according to one of the following fault separation concepts (see Table 4):

- permanent stop PQ
- permanent stop P
- temporary stop PQ
- temporary stop P
- continued operation.

If continued operation is specified, the AC/DC converter station could be equipped with appropriate energy storage or a dynamic braking device, respectively. In this case, the fault duration and the required power shall be specified.

For temporary separation concepts, the corresponding timings shall be specified.

Independent of the fault separation concept, the maximum number of subsequent fault events including a specified number of recovery attempts within a certain time span shall be stated together with the tolerable time to restore full capabilities for DC fault ride through.

8.4.2.5 Capability of switching and breaking DC currents

8.4.2.5.1 Energisation and de-energisation, connection and disconnection of DC circuits

8.4.2.5.1.1 General

AC/DC converter stations can be required to provide certain DC current turn-on and turn-off capabilities under normal operation. Such turn-on and turn-off capabilities can apply to the entire station, its individual poles or its individual converters and can include:

- energisation of a DC circuit,
- connecting the AC/DC converter station to an energised HVDC grid,
- disconnecting the AC/DC converter station from an energised HVDC grid,
- de-energisation of a DC circuit.

Decisive factors determining the required switching capabilities include:

- HVDC grid topology, especially the coordination with other relevant installations, like DC switching stations or DC/DC converter stations;
- concepts of HVDC grid operation including DC circuit energisation or system reconfigurations.

8.4.2.5.1.2 Energisation of a DC circuit

When the HVDC grid or parts thereof are to be energised from the AC/DC converter station, the following shall be specified as a minimum set of requirements:

- equivalent circuit of the system to be energised including, if any, OHLs, cables and other HVDC stations;
- equivalent impedances of all relevant components, especially its capacitances;
- any residual DC voltages prior to energisation, if any;
- target DC voltage band for energisation;
- maximum transient DC overvoltage due to energisation;
- maximum transient DC undervoltage due to energisation;
- minimum and maximum time to reach the target DC voltage band;
- maximum charging current (peak value);
- maximum charging energy;

- maximum number and repetition rate of DC circuit energisation.

All components involved with the energisation process, such as converters or switches shall be capable of withstanding the associated charging currents. Methods limiting or controlling the charging currents include:

- additional impedances temporarily switched into the charging current path, i.e. reactors, resistors or arresters which shall be designed to withstand the corresponding voltage, current and energy duties, respectively;
- AC/DC converters having full DC voltage control capability (converters type 2 or 5);
- HVDC breakers.

With respect to any pre-existing insulation faults inside the DC circuit to be energised, the element providing the energisation shall have a short-circuit making capability according to the design short-circuit current as specified for the feeding AC system considering all relevant current limiting measures of the AC/DC converter station, such as the converter DC voltage control capabilities, transformers or pre-insertion impedances, if any.

8.4.2.5.1.3 Connecting the AC/DC converter station to an energised HVDC grid

When connecting the AC/DC converter station to an energised HVDC grid, tolerances in adapting the DC voltages between converter and HVDC grid shall be considered. Depending on the equivalent impedances of the circuit, such tolerances will result in transient currents when closing the respective switches. To limit such transient currents, additional impedances temporarily switched into the charging current path, i.e. reactors, resistors or arresters can be considered.

8.4.2.5.1.4 Disconnecting the AC/DC converter station from the HVDC grid

Before disconnecting the AC/DC converter station from the HVDC grid, the AC/DC converter station shall be de-loaded, i.e. the DC current through the disconnecting switch shall be controlled to zero. However, due to measuring tolerances and the dynamic behaviour of the HVDC grid the disconnecting switch shall be designed to interrupt specified residual currents.

8.4.2.5.1.5 De-energisation of a DC circuit

When the HVDC grid or parts thereof are to be de-energised through the AC/DC converter station, the following shall be specified as a minimum set of requirements:

- equivalent circuit of the system to be de-energised including, if any, OHLs, cables and other HVDC stations;
- equivalent impedances of all relevant components, especially its capacitances;
- maximum DC voltage reversal, if any, due to discharging the DC circuit;
- minimum and maximum time to reach the target DC voltage;
- maximum discharging current (peak value);
- maximum discharging energy;
- maximum number and frequency of DC circuit de-energisation events per period of time.

All components involved with the de-energisation process, such as converters or resistors and switches shall be capable of withstanding the associated discharging currents. Methods limiting or controlling the discharging currents include:

- additional impedances temporarily switched into the discharging current path, i.e. resistors, reactors or arresters which shall be designed to withstand the corresponding voltage, current and energy duties, respectively;
- AC/DC converters having full DC voltage control capability (converters type 2, 4 or 5).

8.4.2.5.2 Breaking DC fault currents

The requirements for the AC/DC converter station to break DC fault currents resulting from faults in the HVDC grid shall take into account their AC system short-circuit current level, fault separation concepts applied for main and backup protection of the HVDC grid as well as the AC/DC converter station itself. Inside the station the relevant FSDs can be:

- AC station CB at the AC side of the converter(s),
- AC/DC converter in combination with mechanical disconnectors,
- HVDC breaker(s) at the DC side of the converter(s),
- DC residual current breakers, typically neutral bus switches.

The requirements for DC fault current breaking depend on the following factors to be considered and specified:

- type of DC line, i.e. OHL or cable. The type of DC line is relevant with respect to the possibility of repetitive fault events as well as the recovery voltages after fault current breaking;
- possible AC/DC intersystem faults, especially on parallel AC and DC line corridors, together with the relevant AC system data, such as AC system short-circuit current or nominal AC system voltage;
- equivalent circuit of the DC system;
- equivalent impedances of all relevant components;
- number of consecutive faults;
- number of recovery attempts;
- minimum time between recovery attempts.

The DC fault current breaking capabilities shall be specified according to 5.6.

8.4.2.6 Fault current levels

8.4.2.6.1 Contribution to short-circuit currents

The existing equipment in an HVDC grid is designed for a certain level of peak current and for the thermal effect of short-circuit currents (current magnitude and current-time characteristic). A new AC/DC converter station will add additional short-circuit contribution. Therefore, the maximum allowed contribution of a new AC/DC converter station to the short-circuit currents at the PoC-DC it will connect to, shall be specified in terms of current and time (e.g. peak current, time to peak etc., as shown in Figure 11).

If more than one converter shall connect to the same point of the HVDC grid or shall connect in close proximity, then the definition of individual headroom for short-circuit contribution will be required.

The calculation of short-circuit currents at the nodes of an HVDC grid shall be carried out according to 5.6.1.

The following fault types have to be taken into consideration for the calculation of the maximum or minimum short-circuit currents:

- pole-to-earth fault,
- pole-to-neutral fault,
- pole-to-pole fault with and without earth connection,
- AC/DC or DC/DC intersystem faults, if any.

If required for fault localisation, a minimum fault current contribution should be specified. This specification shall include the timings to provide the required DC fault current level.

8.4.2.6.2 Short-circuit current withstand capability

The new AC/DC converter station shall be designed for a certain short-circuit current contribution from the HVDC grid in case of a fault inside the AC/DC converter station. That is why:

- the pre-existing short-circuit current level (peak current and its characteristic as a function of time as in Figure 11; or
- the planned maximum total short-circuit current level for the PoC-DC (peak current and its characteristic as a function of time) including the new AC/DC converter station

shall be specified. Alternatively,

- all relevant parameters of each individual grid component of the whole HVDC grid

shall be specified for the calculation of this fault case.

The same applies to existing AC/DC converter stations (besides other components in the DC grid) in case of DC grid extensions.

8.4.2.7 DC side system restoration

An AC/DC converter station can be required to provide services for the restoration of the HVDC grid or parts thereof from blackout state, also referred to as SRAS-DC. SRAS-DC means the AC/DC converter station shall be able to maintain the DC voltage at its PoC-DC within defined limits for defined network configurations. The limits of the DC voltage at the PoC-DC shall be defined based on the DC voltage profile given in 5.4.

NOTE The start-up of an AC/DC converter station from a connected AC system, DC system or an internal power source like a diesel generator is considered an energisation process and not a system restoration service.

During SRAS-DC, the AC/DC converter station shall provide:

- earth reference for the DC circuit,
- active power demand of connected loads,
- charging the relevant DC circuit including inrush or charging currents of equipment to be energised,
- short-circuit currents according to the DC network protection concepts.

For design purposes a generic DC network model shall be specified considering the following aspects:

- philosophy and procedures including sequences for restoring the real network including all relevant scenarios until reaching the normal operating state (see 5.3);
- relevant network configurations, e.g. switching states;
- earthing concept for the HVDC grid;
- all relevant network elements or equivalents;
- transient and dynamic characteristics of all relevant network elements;
- control characteristics and relevant data of other HVDC stations to be connected to the network during the restoration process.

The representative test network shall be sufficient to demonstrate the AC/DC converter station's capabilities.

Representative test sequences demonstrating the capabilities of the AC/DC converter station can typically include:

- switching the longest relevant HVDC transmission line,
- energisation of the relevant HVDC stations.

8.4.2.8 Steady-state DC voltage and current distortions

The requirements with respect to steady-state DC voltage and current distortion are described in 5.7.

8.4.3 AC side

8.4.3.1 AC voltages

The AC/DC converter station shall meet the requirements of the corresponding grid code valid for the AC grid regarding normal steady-state AC operating voltage range as well as temporary and transient voltages.

Simulations shall be performed to calculate the maximum slow front and fast front over voltages (e.g. switching operations, lightning strikes). If necessary, the maximum transient voltages at the connection point (PoC-AC) have to be reduced by appropriate devices (surge arresters or other measures).

8.4.3.2 AC fault ride through behaviour

The AC over and undervoltage fault ride through profiles are typically defined by the AC grid codes. The profiles shall be specified by an AC voltage versus time characteristic as described in 4.5.3.3.

In the case of faults in the AC system, the AC/DC converter station shall be capable of staying connected to the AC system and remain in stable operation. Fault ride through shall be specified for symmetrical as well as asymmetrical AC faults. The behaviour shall be described for faults followed by AC over- and undervoltages (overvoltage ride through and undervoltage ride through). Depending on pre-fault conditions, multiple fault ride through characteristics can be given. The AC/DC converter station shall be capable of staying connected in a specified series of faults.

AC fault ride through can be required from an AC/DC converter station at its PoC-DC independently from its PoC-AC. In order to provide such functionality, additional equipment can be needed to temporarily provide additional power exchange with the HVDC grid. Such additional equipment can be, e.g. dynamic braking devices and/or energy storages. If this functionality is needed, the corresponding requirements shall be specified as described in 9.2.3.2.4.

As AC fault ride through is a functionality relevant for the HVDC grid, it is recommended to consider appropriate control coordination within the HVDC grid as described in 6.2.4. Alternatively, corresponding equipment can be installed in other AC/DC converter stations or in any HVDC grid installation.

8.4.3.3 AC frequency

The AC grid codes indicate the range of operating frequencies at which the AC/DC converter station shall remain connected to the AC grid.

The AC/DC converter station shall have functions for:

- frequency sensitive mode (FSM);
- limited frequency sensitive mode – underfrequency (LFSM-U);

- limited frequency sensitive mode – overfrequency (LFSM-O),

as described in 4.3 and 4.5.4.2.

8.4.3.4 AC side fault current contribution

The short-circuit current calculation at the AC terminals shall be performed according to the IEC 60909 series with an appropriate representation of the short-circuit current contribution of the particular converter station. The initial, peak and breaking short-circuit currents are necessary to get the correct rating of the installed components.

The typical contribution depends on the requirements of the system operator with respect to the AC voltage drop at the HVDC terminals during short-circuit condition. Depending on their technology, AC/DC converter stations can contribute to the peak, breaking, and steady-state short-circuit current of the AC grid.

The discharge of the AC filters only impacts the initial fault currents due to the different time to peak compared to the operational frequency and the different AC voltage condition during fault current initiation.

8.4.3.5 Capability of switching and breaking AC currents

The following IEC International Standards shall be applied for the design of the switching devices (circuit-breakers, disconnectors and earthing switches):

- Circuit-breakers: IEC 62271-100,
- Disconnectors and earthing switches: IEC 62271-102.

8.5 HVDC grid control and protection interface

The control and protection equipment of the AC/DC converter station shall be provided with the necessary interfaces to the HVDC grid and AC/DC grid control layers according to 6.3.

The control and protection equipment of the AC/DC converter station shall be provided with the necessary interfaces to subsystems like:

- control equipment,
- operator controls,
- switching devices,
- measuring system,
- fault recorder.

If required by the DC fault separation concept, communication interfaces to HVDC grid equipment shall be used to contribute to the DC fault separation process. For further information, refer to 8.7.5.

8.6 Controls

8.6.1 General

This addresses the functions described by the 6.2.3 layer as shown in Figure 15.

8.6.2 Automated vs manual operation

During normal operation, the core control functions are governed by the converter schedule as propagated through the higher-order control layers (see Figure 17). The AC/DC converter station receives its set values and related parameters (e.g., control mode, ramp rates, etc.) and will effectuate these orders by its internal converter controls (see 6.2.2).

The data required by the higher-order control layers regarding the status of the AC/DC converter station is collected in the "station information" (see 6.3).

Further to this automated operation, a manual operation shall be possible for the AC/DC converter station, e.g., in the event of sustained loss of communication with HVDC grid control (see Figure 17).

8.6.3 Control modes and support of coordination

The control modes of the AC/DC converter station shall be specified according to 6.2.3. In addition, different target options can be available for the control of reactive power.

The chosen control mode can be changed over time by either manual or automatic means in coordination with the whole HVDC grid.

Within its design limits the AC/DC converter stations shall be able to support the coordination of distributed control functions in the HVDC grid.

Autonomous adaptation control functions as specified in 6.2.4.2 shall be specified.

8.6.4 Limitation strategies

In the event of set values for active and reactive power contributions exceeding the actual capability of the AC/DC converter station, the following strategies can be applied, depending on the AC/DC converter station type, see 8.2:

- limiting the last set value change,
- limiting active power while fulfilling the requirements for reactive power (Q priority),
- limiting reactive power while fulfilling the requirements for active power (P priority),
- limiting active as well as reactive power proportionally or unproportionally.

Criteria for setting and leaving a specific strategy shall be specified.

8.6.5 Operating sequences for AC/DC converter stations

For all AC/DC converter stations, operating states according to Figure 27 can be differentiated.

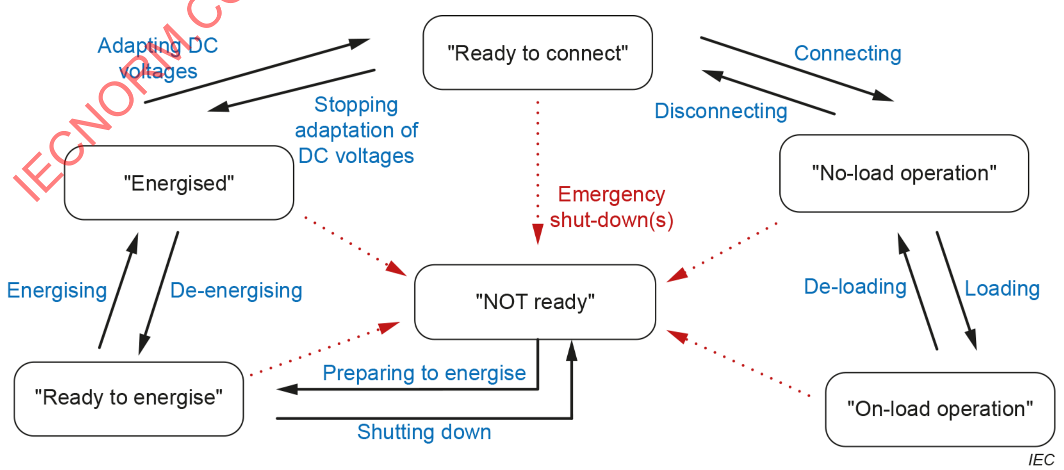


Figure 27 – Operating states and transitions for AC/DC converter stations

These states are governed by the switching configuration of the AC/DC converter station as well as both primary and secondary equipment conditions (i.e. electrical parts and control units). They are defined as follows:

- "Not ready":
  - not operational;
  - converter is disconnected from all energy sources.
- "Ready to energise":
  - all systems and subsystems necessary to energise are ready;
  - internal converter communication is active, no interlocking is present.
- "Energised":
  - depending on mode of energisation:
    - energised from AC: Connection to (one) AC side has been made and desired AC voltage of the AC busbars within the AC/DC converter station is established;
    - energised from DC: Connection to (one) DC side has been made and desired DC voltage of the DC transmission path is established;
    - energised from auxiliary power: Desired DC voltage established and controlled from the auxiliary power source.
- "Ready to connect":
  - depending on intended side of connection:
    - connect to AC (following energisation from DC or auxiliary power): Converter AC voltages (magnitude and phase) are synchronised with AC voltage at PoC-AC in order to prevent transient currents when closing the AC station CB;
    - connect to DC (following energisation from AC or auxiliary power): DC voltages at converter's DC terminals are adapted (magnitude) with DC voltage at PoC-DC in order to prevent transient currents when closing the DC disconnector / breaker.
- "No-load operation":
  - converter is able to provide active or reactive power; however:
    - if controllable by the AC/DC converter station, initial set points remain at 0 MW and 0 Mvar at PoC-AC and 0 MW at PoC-DC, otherwise, the external network controls power to a minimum value;
    - depending on intended type of operation:
      - ready for on-load operation (reactive power): converter has been connected to the AC grid;
      - ready for on-load operation (active power): converter has been connected to both AC and DC grid;
- "On-load operation":
  - all local converter controls have been initialised for on-load operation
    - if controllable by the AC/DC converter station, active and reactive power set points (and ramp rates) can be received and will be effectuated, otherwise, the external network determines the actual power exchange.
    - depending on type of operation:
      - on-load operation (reactive power): converter is at least connected to the AC grid
      - on-load operation (active power): converter is connected to both AC and DC grid.

For the transition between these states, the following sequences (i.e. series of required actions) are defined. These refer to the arrows indicated in Figure 27.

- "Preparing to energise":
  - initialisation of all internal converter communication;

- enabling the control system and its interfaces to receive commands for next state transitions.

- "Energising":
  - establishing connection to one energy source;
  - charging of related converter and connected equipment by this source.
- "Adapting DC voltages":
  - further control of converter voltage with respect to AC or DC terminal voltage;
  - keeping a permanent alignment of the voltage magnitude and phase (AC side) or voltage level (DC) for an upcoming connection request.
- "Connecting":
  - closing of all switching equipment required to create the desired connection between the AC/DC converter station and the related AC and/or DC grid;
  - if controllable by the AC/DC converter station, initialisation of set values for active and reactive power to 0 MW and 0 Mvar, respectively.
- "Loading":
  - establishing connection to the HVDC grid control (or manual operator entries);
  - if controllable by the AC/DC converter station, reception of set values and ramp rates;
  - if controllable by the AC/DC converter station, routing of set values to local controllers and ramping towards OPs with given rate, otherwise, the external network determines the actual power exchange.
- "De-loading":
  - if controllable by the AC/DC converter station, ramping of converter power down to 0 MW and 0 Mvar, otherwise, the external network controls the power exchange to a minimum value;
  - disconnecting from the HVDC grid control (or manual operators).
- "Disconnecting":
  - opening of respective switching equipment between AC/DC converter station and the related AC and/or DC grid.
- "Stopping adaptation of DC voltages":
  - adaptation of DC voltages is no longer performed actively (i.e. voltage alignment will be lost over time).
- "De-energising":
  - disconnecting of AC/DC converter station from energy source;
  - internal converter equipment will be discharged.
- "Stopping":
  - deactivating converter control systems and communication interfaces.

8.6.6 Dynamic behaviour

8.6.6.1 Step responses

The AC/DC converter stations shall fulfil certain requirements on sudden changes in reference values in order to demonstrate stability and smoothness of the underlying controls.

Relating to 8.3.3, reversing the active power flow through an AC/DC converter station shall be understood as an extreme case of a sudden change up to two times the maximum power. Such considerable changes with respect to the dispatched active power set values can arise in the event of severe system disturbances.

To this end, the definition of step responses shall be specified according to the definition in IEV 351-45-27.

Different step response parameters can apply for different physical quantities (e.g. DC voltage, AC active power contribution, etc.) of the same AC/DC converter station.

8.6.6.2 Stability criteria

In order to confirm HVDC grid stability, an assessment by network simulations is necessary, see 10.2.

In this context, stability of HVDC grids has to be considered as a minimum influence of one DC node to another. That is, the outage or sudden drop in capability of one AC/DC converter station (defined by a certain extent) shall only affect the related physical quantities of any other AC/DC converter station by a specified amount that is not to be exceeded. These aspects shall be covered by the respective models and studies according to 10.2.

Together with these models, a reasonable set of HVDC grid scenarios to be simulated shall be agreed so as to demonstrate stability. These scenarios are defined by power flow conditions at all DC nodes in the HVDC grid and defined events (e.g. contingencies, inappropriate commands etc.). The system stability requirements shall be verified in accordance with 11.2.2.3.

8.7 Protection

8.7.1 General

The requirements on AC/DC converter stations protections are summarized in 7.3.1.

8.7.2 Configuration requirements

For the protection system of the AC/DC converter station, the following protection zones are defined: (see Figure 26)

- AC switch yard protection zone,
- converter transformer protection zone,
- CU protection zone,
- DC switching station protection zone (optional, if required by fault separation concept or due to station layout),
- DC line protection zone (optional, if required by fault separation concept or due to station layout).

The definition of the protection zones depends on the station topology. Figure 26 shows all possibilities for the given example. Depending on a specific situation, individual protection zones can be omitted. For example, for AC/DC converter stations with just one CU, a DC switchyard protection zone is not necessary. In this case the CU protection zone typically includes the equipment up to the connection to the DC lines, respectively the HVDC grid.

For AC/DC converter stations with more than one CU, the CU protection zone is typically provided for each individual converter or pole, respectively.

The DC switch yard protection zone is the interface to the DC lines or the HVDC grid, respectively, and includes equipment assigned to both poles.

The DC line and the return line can be considered as part of the HVDC grid. Nevertheless, a DC line protection zone in the DC protection of the AC/DC converter stations can be required (depending on the fault separation concept) in order to identify faults at the DC line(s) and contribute to the fault separation process.

AC system protection zone and transformer protection zone include standard protections normally used together with HVDC converters or in AC substations. Therefore, they are not described any further in this document.

8.7.3 Function requirements

8.7.3.1 Converter unit protection zone

The following faults within the converter protection zone shall be detected:

- internal valve or submodule faults;
- phase-to-phase or phase-to-earth short-circuit at the AC connection of the converter transformer valve side;
- faults to earth at the DC circuit;
- abnormal AC system conditions (i.e., abnormal AC voltages or frequencies beyond specified limits);
- inadvertent opening of CBs feeding the AC/DC CU;
- DC side abnormal voltages.

The following faults affecting the neutral bus and the DC switches, if any, shall be detected:

- DC switch failure, if any;
- open circuit fault of the neutral, if any;
- current at the station earth, if any.

The following protection functions are typically provided:

- differential protections;
- overcurrent protections (can include equipment from other protection zones);
- DC side abnormal voltages protection;
- AC side abnormal voltages protection;
- special equipment protection, if any;
- neutral DC bus overvoltage protection;
- DC switch protection.

The following failures shall be detected by the overall protection system, control or specific protections associated to that equipment:

- elements inside the converter;
- converter control circuits including the identification of failed devices;
- auxiliary systems.

8.7.3.2 DC line protection zone

The need for and the requirements on protection functions for this protection zone depend on the requirements of the DC fault separation concepts for the AC/DC converter station. The DC fault separation concepts shall comprise a concept for main protection as well for backup protection. The backup protection concept can require a dedicated DC line protection if a different fault separation concept compared to the main protection is applied.

The selectivity between faults within the AC/DC converter station and faults at the HVDC grid is a basis for fault separation concepts where the AC/DC converter station provides fault separation or where AC/DC converter station (including services for the AC side only) shall resume operation after fault separation.

Examples where no DC line fault protection zone is necessary, are:

- cases with exclusive use of the fault separation concept of "Permanent Stop PQ";
- cases, where the DC line protection function is provided by the HVDC grid including DC switching station.

To identify faults in individual sections (i.e. transition between cable and OHL) of the same pole or neutral conductor of the HVDC grid, dedicated supervision functions, e.g. a section fault locating function, can be added. This would not be a protection function. The protection of the conductor will be located in the corresponding DC switching stations at both ends and shall not depend on the information from the supervision functions. The additional information from the supervision functions can influence the protection function but is not urgently required (e.g. in the event of loss of communication).

The individual DC fault separation concepts have different requirements on reaction and timing.

Further, depending on the different fault separation concepts connecting the PoC-DC, individual protection for each HVDC grid protection zone can be necessary.

For further information, refer to 8.7.5.

When the AC/DC converter station is required to separate faults according to continuous operation or temporary stop (see 7.4), a DC line protection zone is necessary. The DC line protection zone shall detect the following faults:

- faults to earth or neutral (pole-to-earth fault);
- faults between two poles (pole-to-pole fault with and without earth connection).

For the neutral line, if any, the DC line protection zone shall detect the following faults:

- open circuit fault of the neutral line;
- neutral line to earth fault.

8.7.4 Fault separation strategy for faults inside the AC/DC converter station

The AC/DC converter station protection shall be coordinated with the AC/DC converter station's control system to inhibit the development of faults or rapidly limit the consequences of a fault.

Considering the variety of HVDC protection principles, the following fault clearance actions are recommended to meet specific project requirements, some of which are realized by the control system according to the commands from the protection system:

- inhibit de-block;
  De-blocking of the converter will be inhibited by this order.
- trip AC station CB;
  Tripping the AC station CB disconnects the AC side of the converter transformers from the AC power source.
- converter block;
  Converter blocking stops the switching pulses to the converter. Depending on the converter type, this shut-down might not prevent the converter from further current feeding to potential fault locations within the converter or the DC circuit.
- converter/pole isolation;
  Isolating the converter from the DC yard.
- current limit;
  Reducing the DC current of the pole to a predefined value with a predefined ramp rate.
- close NBES;
  Closing the station's NBES as a protection action (e.g. at neutral overvoltage).

- re-close of the DC switch or HVDC breaker;
  Re-close the DC switch or HVDC breaker in order to protect the latter if not opened successfully (e.g. fault at current interruption).
- transfer trip to DC grid protection;
  Removing the DC voltage from the CU in the event of converter/pole isolation failure. This requires communication to the coordinated HVDC grid control or HVDC stations.

8.7.5 Coordination of the DC protection with the HVDC grid

The protections of the AC/DC converter station shall be coordinated with those of the HVDC grid. The DC fault separation concepts according to 7.4 presuppose a defined reaction and timing of the AC/DC converter stations protection in the event of faults within the HVDC grid protection zones. From the DC protections at the AC/DC converter station's point of view this will be covered by the DC switching station / DC line protection zone and/or corresponding signals from remote protection zones. The requirements are defined for the relevant PoC-AC or PoC-DC of the AC/DC converter station.

In the event of pole-to-pole or pole-to-earth faults at the HV conductors of the HVDC grid, the response by control and protections of the AC/DC converter station shall in principle be as follows:

- continued operation: fault ride through – no tripping from protection functions;
- all others: safe fault detection and defined reaction.

To achieve a proper coordination, the reach of the DC line protection of the AC/DC converter stations in respect to each individual HVDC grid protection zone shall be defined. For each individual zone (separated between main and backup) the following detection requirements are possible:

- local detection of the fault by AC/DC converter station's DC line protection;
- remote detection of the fault and transferred trip (to be processed and start actions in the AC/DC converter station);
- no detection (because the separation concept is completely remote).

For faults at the return conductor the following reactions can be required:

- pole current balancing for bipolar operation (adjust the DC currents of both poles to reduce the bipolar neutral bus and return conductor current);
- return conductor fault clearing sequence when pole current balancing is not possible (e.g. at monopolar operation).

8.7.6 Example for coordination of the DC protection with the HVDC grid

For an example for coordination of the DC Protection of AC/DC converter station 1 with the HVDC grid, refer to Table 8 and Figure 28. Table 8 shows the separation concept and the FSD for main and backup protection concept. Further, the detection reach requirements are stated.

Table 8 – Example protection coordination of AC/DC converter station 1 and HVDC grid (for main and backup concept including the separation concept and the FSD)

Faulted zone	PoC-AC1				PoC-DC1			
	Main		Backup		Main		Backup	
	Sep. concept (FSD)	Detection reach require-ment	Sep. concept (FSD)	Detection reach require-ment	Sep. concept (FSD)	Detection reach require-ment	Sep. concept (FSD)	Detection reach require-ment
Zone 1	PS-P (C1)	Local	PS-PQ (AC)	Local	PS-P (C1)	Local	PS-PQ (AC)	Local
Zone 2	TS-P (DS)	Remote	PS-P (C1)	Local	TS-P (DS)	Remote	PS-P (C1)	Local
Zone 3	CO (DC)	No	PS-P (C1)	Local	CO (DC)	No	PS-P (C1)	Local
Zone 4	CO (C2)	No	TS-P (DS)	Remote	CO (C2)	No	TS-P (DS)	Remote

PS-P permanent stop P
PS-PQ permanent stop PQ
TS-P temporary stop P
TS-PQ temporary stop PQ
CO continued operation
Local local detection of the fault by AC/DC converter station's DC line protection
Remote remote detection of the fault and transferred trip
No no detection
C1, C2, DS, DC, AC FSDs according to Figure 28

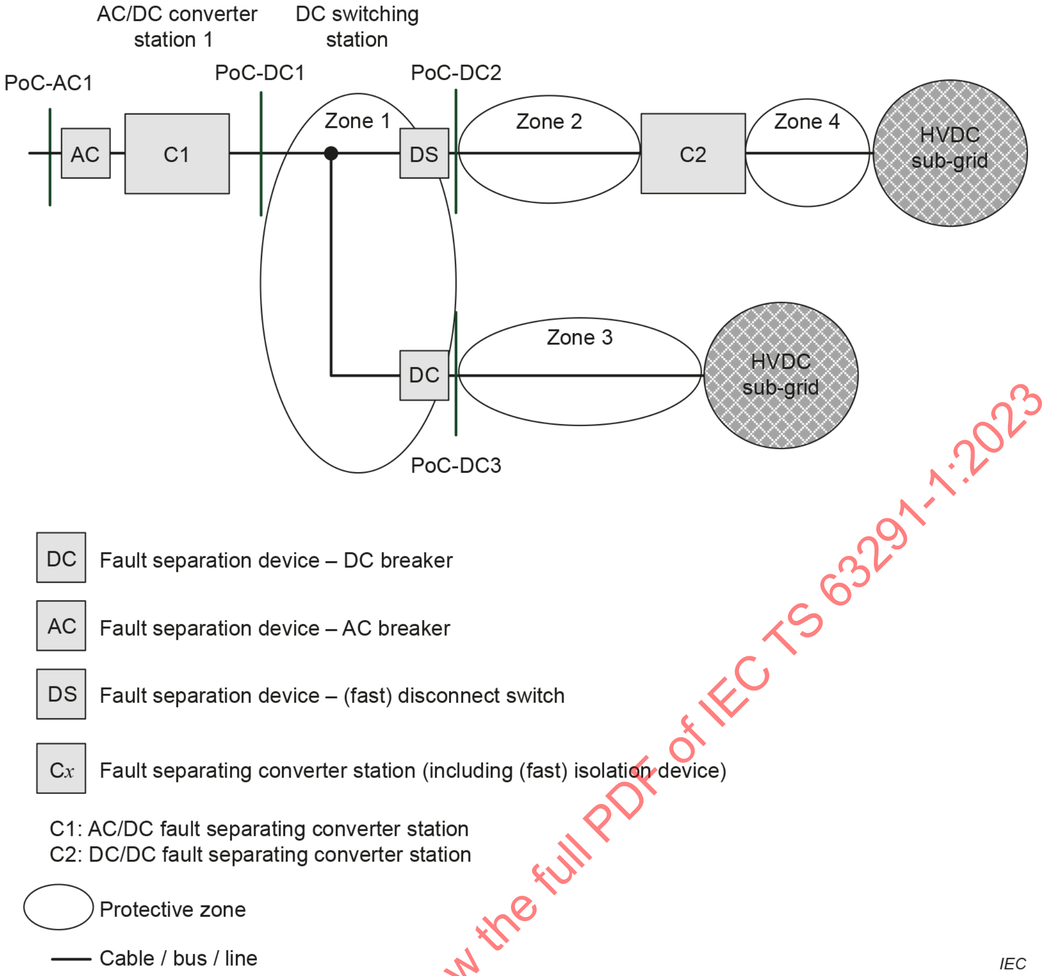


Figure 28 – Example illustrating the coordination of the DC protection of AC/DC converter station 1 with the HVDC grid

9 HVDC grid installations

9.1 General

HVDC grids can comprise one or more of the following installations depending on their network topology:

- DC switching station,
- HVDC transmission line (OHL, cable or combinations thereof),
- DC/DC converter station.

AC/DC converter stations are the binding element between AC system and HVDC grid and are addressed in Clause 8.

Each HVDC grid installation comprises a set of devices and/or apparatuses associated in a single location including all relevant auxiliaries and subsystems. Table 9, Table 10 and Table 11 provide an overview on the HVDC grid installations including a reference to AC/DC converter stations. Read in the vertical direction, the tables show what functionalities are relevant to an installation. Read in the horizontal direction, the tables show what installations can fulfil a function considered.

The functions are defined in 6.4.2 and 8.6.5. They are grouped according to the following categories:

- functions changing the operating states (Table 9);
- functions of HVDC grid operation (Table 10);
- protective functions (Table 11).

The capabilities of an installation to fulfil the corresponding functions are described as follows:

"yes": Characterizing a core function of the installation. This function shall be addressed in the specification.

"optional": Characterizing a function which can be specified as an optional requirement for the installation. Fulfilling the function can require additional dedicated design measures.

NOTE Such a function can be required depending on the system planning and design.

"N/A": Characterizing a function which is not applicable to the installation. It shall not be specified.

Each installation can comprise dedicated systems or subsystems for providing additional functions indicated as "optional" in Table 9, Table 10 and Table 11. Such systems or subsystems can include:

- dynamic braking devices,
- energy storage devices.

Only core functions of an installation are addressed in this Clause 9.

Table 9 – Functions changing operating states

Function	**AC/DC interface**	**HVDC grid installation**		
	AC/DC converter station	DC switching station	HVDC transmission line and transition stations	DC/DC converter station
Preparation for energisation / shut down	yes	yes	N/A	yes
Energisation / de-energisation	yes	optional	N/A	yes
Adaptation of DC voltages / stop adaptation of DC voltages	yes	optional	N/A	yes
Connection / disconnection	yes	yes	N/A	yes
Loading AC side / de-loading AC side	yes	N/A	N/A	N/A
Loading DC side / de-loading DC side	yes	optional	N/A	yes

Table 10 – Functions of grid operation

Function (relevant aspects)	AC/DC Interface AC/DC converter station	HVDC grid installation DC switching station	 HVDC transmission line and transition stations	 DC/DC converter station
Operation on-load (withstand voltage, current stresses)	yes	yes	yes	yes
Measuring (DC and AC voltages and currents, active and reactive power)	yes	yes	optional	yes
Energy balancing (Maintaining the average DC grid voltage)	optional	optional	N/A	optional
Reconfiguration (DC circuit, e.g. connection of lines, bipolar to monopolar, DMR to earth return)	optional	yes	N/A	yes
Discharge (DC circuit)	optional	optional	N/A	optional
Earthing (Providing earth reference, functional earthing)	yes	yes	N/A	yes
Interconnection (Connecting different DC voltage levels)	N/A	N/A	N/A	yes
Power flow control (through HVDC transmission lines)	N/A	optional	N/A	yes

Table 11 – Protective functions

Function	AC/DC Interface AC/DC converter station	HVDC grid installation DC switching station	 HVDC transmission line and transition stations	 DC/DC converter station
Limitation of transient DC over voltages	yes	yes	optional	yes
Limitation of temporary DC over and under voltages	optional	optional	N/A	optional
Limitation of DC fault current di/dt and/or magnitude	yes	optional	N/A	yes
Separation of DC faults (pre-condition for recharging the healthy part of the HVDC grid during a DC insulation fault)	optional	yes	N/A	optional
Limit DC inrush currents	optional	optional	N/A	optional
Limitation of emission of DC voltage and current distortions	yes	optional	N/A	yes
Damping of DC voltage and current distortions	optional	optional	N/A	optional

9.2 DC switching station

9.2.1 Purpose

A DC switching station shall establish electrical connections between HVDC grid installations including connections to earth at one location, such as:

- AC/DC converter stations,
- HVDC transmission lines,
- DC/DC converter stations.

In addition to the functions listed in Table 9, a DC switching station can be required to provide optional functions as listed in Table 10 and/or protective functions as listed in Table 11. This requires the DC switching station to be equipped with additional passive or active elements capable of exchanging power with the HVDC grid, such as:

- pre-insertion resistors,
- discharge resistors,
- HVDC breakers,
- dynamic braking devices,
- energy storages,

or between connected HVDC transmission lines:

- DC line power flow controllers.

Appropriate operational procedures shall ensure that each HVDC transmission line is either earthed or connected to another grid element in order to prevent unintentional self-charging of HVDC lines, especially HVDC cables. The required switching actions shall be performed by the HVDC switching stations.

9.2.2 Overall requirements

9.2.2.1 Coordination and communication

Except local protection functions, all switching and reconfiguration actions at the DC switching station shall be coordinated with the surrounding HVDC grid and therefore require communication to the coordinated HVDC grid controls (see Figure 15).

9.2.2.2 Availability and reliability

Reliability as well as availability calculation methods are described in IEC/TR 62672:2018 [20].

9.2.3 Main circuit design

9.2.3.1 General characteristics

9.2.3.1.1 Topology

The topology of the DC switching station shall be specified with respect to:

- connection to HV poles (according to 5.1.4.1),
- connection to the neutral return path (according to 5.1.4.2),
- station earthing (according to 5.1.4.3).

The requirements on switchgear are described in 9.2.3.2.1.3 and in 9.2.3.2.5.

9.2.3.1.2 Active power characteristics

A DC switching station can be equipped with additional components to temporarily exchange power with the HVDC grid, such as energy storages and/or dynamic braking devices.

For steady-state or dynamic power flow control in individual HVDC transmission lines connected to the DC switching station, DC line power flow controllers can be used to modulate the DC voltage at a PoC-DC. DC line power flow controllers, if any, would be integrated into the corresponding SU. The DC voltage modulation will be associated with a corresponding power exchange which can be balanced inside the HVDC grid by modulating the DC voltage at one or more other SU of the DC switching station accordingly. That functionality would require the power flow controllers of the individual SU to be connected for power exchange.

NOTE DC line power flow controllers are connected to the HVDC grid having the same nominal DC voltage on both terminals. Devices that are designed to connect parts of the HVDC grid having different nominal DC voltages are referred to as DC/DC converter stations.

If elements for temporary power exchange with the HVDC grid or power flow control are used, the functionality for active power control shall be specified.

9.2.3.1.3 Energisation of the DC switching station

The HV pole busbars and the neutral busbar of a DC switching station can be energised, if necessary, via a pre-insertion resistor including bypass switch:

- together with any part of the HVDC grid previously connected to the DC switching station,
- by connecting to a DC line already energised.

Adaptation of DC voltages before closing a switch will typically be provided by other installations, like AC/DC converters, DC/DC converter stations, if any, or energy storages, if any.

A DC switching station can also be equipped with additional components to temporarily exchange power with the HVDC grid. Such elements, if any, can be used to adapt DC voltages before closing a switch.

9.2.3.1.4 Energy dissipation and absorption capability

In principle, a DC switching station can in addition to its "natural" switching tasks be required to balance a certain amount of energy to fulfil the relevant grid code requirements of the adjacent AC and DC grids with respect to fault ride through, frequency of the respective AC systems and DC voltage support. However, dedicated additional, power electronic-based devices would be needed to absorb or store the required amount of energy, such as a dynamic braking device or energy storage.

The following shall be specified as a minimum requirement:

- power vs time characteristics $P = f(t)$ (MW),
- repetition (number of events),
- minimum time between consecutive events (min).

9.2.3.2 DC side

9.2.3.2.1 DC connection

9.2.3.2.1.1 HV poles

The topology of the DC switching station shall be specified according to 5.1, Table 1, Table 2 and Table 3. A given HVDC grid and station topology allows for different DC connection modes. The DC connection modes describe the designated connections between the individual terminals of the DC switching station per SU. They have to be coordinated with other HVDC stations (e.g. DC switching stations, DC/DC converter stations) connected directly or connected to the remote ends of the individual DC lines.

The busbars of the DC switching station are described by the following nomenclature:

BB-Py pole busbar y; y being 1 or 2

BB-N neutral busbar

The terminals at the PoC-DC are described by the following nomenclature:

PoC-DCx Py station DC PoC x, x being the number of the PoC-DC with HV pole Py, y being 1 or 2

PoC-DCx Ry station DC PoC x, x being the number of the PoC-DC with station return path connection point R; if there are more than one return path connection points, the connection points are numbered (Ry, y being 1 or 2).

Figure 29 shows an example for a dedicated DC switching station (type BRZ), consisting of three SUs connecting one bipolar AC/DC converter station (type BRO) to two HVDC transmission lines. There are numerous other configurations depending on the specific requirements (e.g. the type of converters, polarity reversal, series connected CUs, busbar arrangements). Moreover, there are numerous intermediate configurations in the transition from one connection mode to another one. Those are neither addressed in Figure 29 nor in Table 12 or Table 13.

Figure 29 shows switches relevant for operation only; i.e. other equipment is not shown.

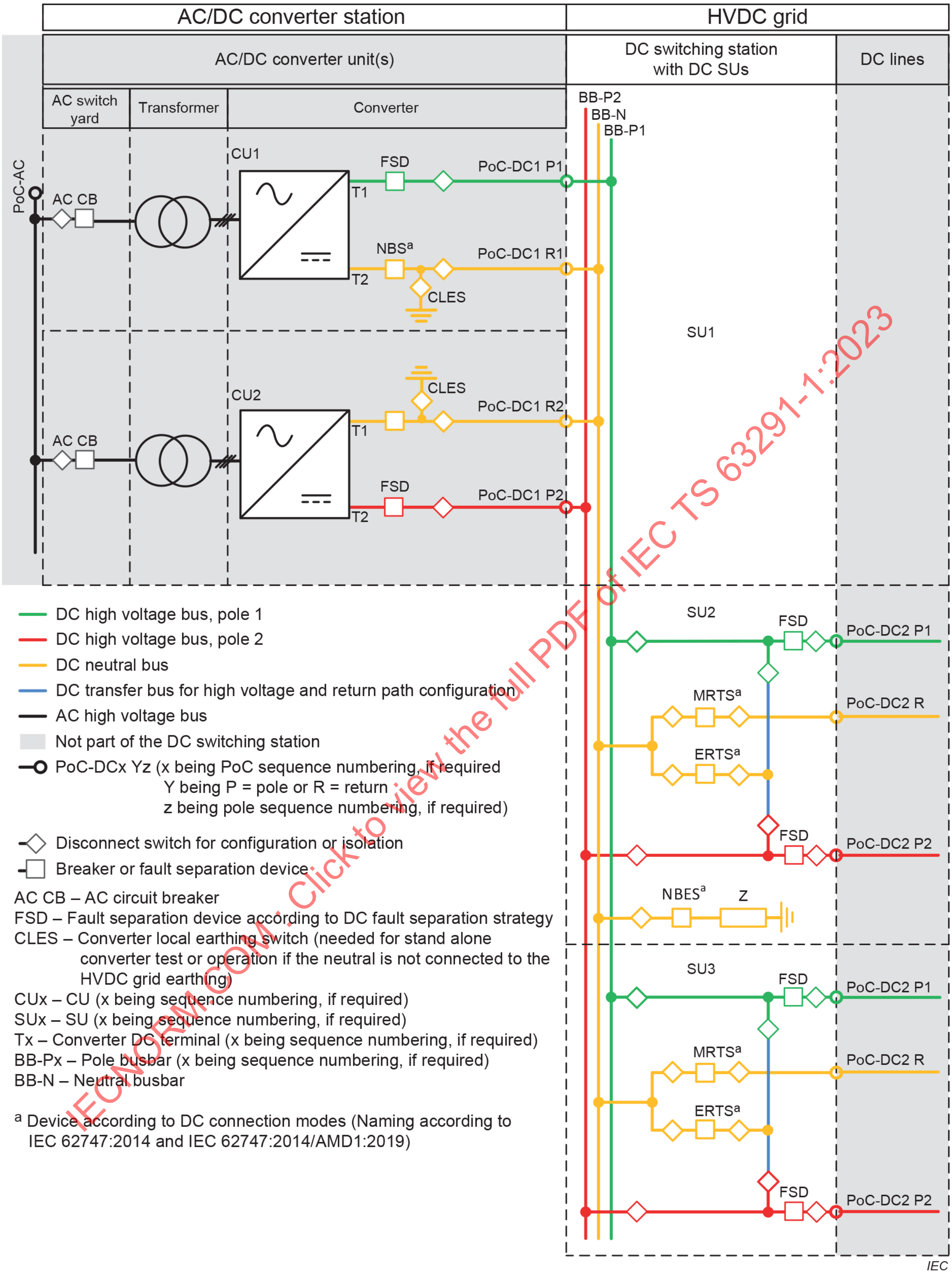


Figure 29 – Example of a BRZ DC switching station. The DC switching station connects two bipolar transmission circuits with DMR and an AC/DC converter station of bipolar topology

The first switching unit (SU1) covering PoC-DC1 as per the example in Figure 29 comprises the HV poles P1 and P2 as well as the return path connections R1 and R2 towards the AC/DC converter station. Since the DC switching station provides earth reference as well as the realisation of the different DC connection modes, like bipolar or monopolar, the CU DC terminals

U1T1, U1T2 as well as U2T1, U2T2 are connected to the respective PoC-DC1 terminals P1, P2, R1 and R2 without any possible interconnections in between.

In the given example, the DC switching station provides two SUs for the connection of the DC lines at PoC-DC2 and PoC-DC3 while the AC/DC converter station comprises its own SU and is therefore directly connected to the busbars of the DC switching station. Furthermore, the DC SUs serving the connection of DC lines contain the transfer switching elements MRTS and ERTS for the return path. The NBES for the earth reference is assigned to one DC SU, in the given example the DC SU for PoC-DC2 was chosen.

To specify the DC connection modes, a scheme like in Table 12 and Table 13 shall be used. Table 13 shows an example of DC connection modes for a PoC-DC connecting an AC/DC converter station as applicable to Figure 29, whereas Table 12 describes this for the connection to HVDC transmission lines.

In connection mode 1, both HV poles and the return path connection of the PoC-DC are connected to the corresponding busbars of the DC switching station. The HVDC grid or the DC switching station provides earth reference.

In connection mode 2, both HV poles of the PoC-DC are connected to the corresponding busbars of the DC switching station. The DC SU connecting to an HVDC transmission line has no connection to the return path. The HVDC grid or the DC switching station provides earth reference.

In connection modes 3 and 4, only one HV pole and the return path connection of the PoC-DC are connected to the corresponding busbars of the DC switching station, while the other HV pole is DC decoupled. The earth reference is given by the HVDC grid or the DC switching station.

Connection modes 5 and 6 correspond to mode 3 and 4 from AC/DC converter stations' perspective. In addition, the unused HV pole transmission line is connected to the neutral busbar of the DC switching station and thus in parallel to the return line.

Connection modes 7 and 8 correspond to mode 5 and 6 from AC/DC converter stations' perspective. The return HVDC transmission line is DC decoupled and the HV conductor of the other pole is used as return conductor instead by its connection to the neutral busbar of the DC switching station.

In connection mode 9, all pole lines and the return line of the AC/DC converter station are DC decoupled. The HVDC grid or the DC switching station provides earth reference. This connection mode is not relevant for the connection of the HVDC transmission lines and thus not listed in Table 12.

The required DC connection modes can also be specified in form of single line diagrams showing the connections between the individual PoC-DC terminals including the necessary switchgear.

The reconfiguration requirements between the individual DC connection modes of a DC SU (corresponding to PoC-DC) including the maximum transition times from no-load operation in the former mode to no-load operation in the new mode shall be specified using Table 14. Table 14 indicates the times for reconfigurations used normally as per example in Figure 29. In all reconfiguration actions, attention shall be paid to assure proper earth reference in the HVDC grid.

The reconfiguration from mode 1 to mode 2 differentiates regarding the type of the return path as follows:

- dedicated metallic return (-BRZ or -BRE SU),

- earth electrodes, typically connected via an electrode line (-BEE SU).

In the case of a bipole with return path (-BRZ, -BRE or -BEE unit), the reconfiguration from mode 1 to mode 2 will include opening the MRTS.

In the case of a bipolar SU with earth electrode (-BEE station) and a corresponding electrode line, the reconfiguration process from mode 1 to mode 2 can – before opening the MRTS – also include closing the NBES and thus using the station earth as the return path temporarily. This will typically be done as part of a protection sequence in the event of an interrupted electrode line or DMR. In this case the earthing branch shall not contain any additional impedance and the station earthing system has to be designed accordingly. Mode 2 will eventually be achieved by opening the NBES at least on one end of the link to prevent unwanted earth currents.

The reconfigurations and their timing requirements shall be specified individually according to the functional requirements of the HVDC grid and can include transitions other than those shown in Table 14. Some of the reconfigurations can be specified to be done only when de-energised, some reconfigurations can require several intermediate switching configurations.

The durations for reconfigurations are not only defined by the switching elements of the DC switching station (as in AC grids), but by the decay of voltage and current transients to achieve proper conditions for the next step in a sequence, furthermore by the coordination of HVDC grid controls and the performance of the connected active systems like AC/DC or DC/DC converter stations regarding control of load-flow and DC voltage. It is necessary to define the instance of start and end of the individual reconfiguration sequences clearly.

Table 12 – Connection modes of the bipolar DC SU of Figure 29 connecting a PoC-DC of an HVDC transmission line

Connection mode		**Busbar**		
		BB-P1	**BB-N**	**BB-P2**
Mode 1	Bipolar with return path	PoC-DC*x* P1	PoC-DC*x* R	PoC-DC*x* P2
Mode 2	Bipolar without return path ("rigid bipolar")	PoC-DC*x* P1		PoC-DC*x* P2
Mode 3	Monopolar pole 1	PoC-DC*x* P1	PoC-DC*x* R	
Mode 4	Monopolar pole 2		PoC-DC*x* R	PoC-DC*x* P2
Mode 5	Monopolar pole 1 with HV parallel return	PoC-DC*x* P1	PoC-DC*x* R PoC-DC*x* P2	
Mode 6	Monopolar pole 2 with HV parallel return		PoC-DC*x* R PoC-DC*x* P1	PoC-DC*x* P2
Mode 7	Monopolar pole 1 with HV return	PoC-DC*x* P1	PoC-DC*x* P2	
Mode 8	Monopolar pole 2 with HV return		PoC-DC*x* P1	PoC-DC*x* P2
Mode 9	DC decoupled pole 1 and pole 2			

Table 13 – Connection modes of the bipolar DC SU of Figure 29 connecting a PoC-DC of an AC/DC converter station (x = 1)

Connection mode		Busbar		
		BB-P1	BB-N	BB-P2
Mode 1, 2	Bipolar	PoC-DCx P1	PoC-DCx R1 PoC-DCx R2	PoC-DCx P2
Mode 3, 5, 7	Monopolar pole 1 (DC decoupled pole 2)	PoC-DCx P1	PoC-DCx R1	
Mode 4, 6, 8	Monopolar pole 2 (DC decoupled pole 1)		PoC-DCx R2	PoC-DCx P2
Mode 9	DC decoupled pole 1 and pole 2			

Table 14 – Normally used DC circuit reconfiguration time requirements for the DC SU example of Figure 29 (PoC-DC)

Previous connection mode S_x	Next connection mode S_y								
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8	Mode 9
Mode 1		t_{max12}	t_{max13}	t_{max14}	*)	*)	*)	*)	t_{max19}
Mode 2	t_{max21}		*)	*)	*)	*)	*)	*)	t_{max29}
Mode 3	t_{max31}	*)		*)	t_{max35}	*)	*)	*)	t_{max39}
Mode 4	t_{max41}	*)	*)		*)	t_{max46}	*)	*)	t_{max49}
Mode 5	*)	*)	t_{max53}	*)		*)	t_{max57}	*)	t_{max59}
Mode 6	*)	*)	*)	t_{max64}	*)		*)	t_{max68}	t_{max69}
Mode 7	*)	*)	*)	*)	t_{max75}	*)		*)	t_{max79}
Mode 8	*)	*)	*)	*)	*)	t_{max86}	*)		t_{max89}
Mode 9	t_{max91}	t_{max92}	t_{max93}	t_{max94}	t_{max95}	t_{max96}	t_{max97}	t_{max98}	

*) no direct transition

t_{maxxy}: time for transition between previous connection mode S_x and next connection mode S_y

9.2.3.2.1.2 Neutral point earthing

For providing earth reference potential the DC neutral conductor or terminal, respectively, of the HVDC grid can be connected to earth. This connection, if any, can be provided by the DC switching station or via return conductor somewhere else within the HVDC grid.

The location of the earthing point shall be selected considering conductive structures in the earth and above, like cable sheaths, pipelines, OHLs, transformers in AC systems or others with respect to magnitude and time. This can require the earthing point being located outside the physical boundaries of an HVDC station and being connected by a dedicated HVDC transmission line.

The earth reference shall be provided throughout the entire HVDC grid. Therefore, this shall be respected for reconfigurations considering the state of the entire HVDC grid.

The earth connection, if any, as well as the switching conditions, if any, shall be specified. The earthing branch can be switched by the NBES or be permanent and can include resistors, reactors, capacitors, arresters or any combination thereof.

The electrical characteristics of the earthing branch shall be specified.

The conditions for switching the earthing branches on or off shall be specified.

9.2.3.2.1.3 Neutral path and earthing point transfer switches

Technical requirements and specifications of neutral path and earthing point transfer breakers are described in Cigre Technical Brochure 683 [21] and IEC TS 63014-1.

The earthing point shall be coordinated throughout the HVDC grid or subsystem. Connecting or disconnecting parts of the grid can require moving the earthing point. Moving the earthing point is accomplished by coordinated switching of the relevant transfer breakers. The coordination and sequence shall be provided by the HVDC grid controls.

The HVDC grid has to provide the conditions needed for the transfer breakers to operate, such as:

- provide an alternative path for current commutation
- assure the appropriate sequences
- limit the currents according to the switching capabilities of the relevant switches.

9.2.3.2.2 DC voltages

The requirements with respect to DC voltage are described in 5.4. The values according to the parameter list apply.

9.2.3.2.3 DC insulation levels

The requirements with respect to DC insulation levels are described in 5.4.

Withstand or protective levels shall be specified at the PoC-DC including the neutral terminal, if any. The protective levels shall be coordinated within the HVDC grid, especially with HVDC stations in close vicinity.

Effective measures shall be taken in the DC switching station limiting any overvoltages at the PoC DC to protective levels defined for the HVDC grid.

9.2.3.2.4 DC fault ride through behaviour

DC fault ride through requirements for a PoC-DC in response to an insulation fault appearing at another PoC-DC of the DC switching station shall be specified according to one of the following concepts as described in 7.4:

- continued operation,
- temporary stop P,
- permanent stop P.

For temporary separation concepts, the corresponding timings shall be specified.

Independently of the fault separation concept, the maximum number of subsequent fault events including a specified number of recovery attempts within a certain time span shall be stated together with the tolerable time to restore full capabilities for DC fault ride through.

9.2.3.2.5 Capability of switching and breaking DC currents

9.2.3.2.5.1 Energisation and de-energisation, connection and disconnection of DC circuits

9.2.3.2.5.1.1 General

DC switching stations can be required to provide certain DC current turn-on and turn-off capabilities under normal operation. Such turn-on and turn-off capabilities can apply to its individual poles and the return path and can include:

- energisation of a DC circuit,
- connecting a DC circuit to an energised HVDC grid,
- disconnecting a DC circuit from an energised HVDC grid,
- de-energisation of a DC circuit.

Decisive factors determining the required switching capabilities include:

- HVDC grid topology, especially the coordination with other relevant installations, like AC/DC converter stations or DC/DC converter stations;
- concepts of HVDC grid operation including DC circuit energisation or system reconfigurations;
- type of HVDC transmission lines and type of converters including their operational states.

9.2.3.2.5.1.2 Energisation of a DC circuit

When the HVDC grid or parts thereof are to be energised via the DC switching station, the following shall be specified as a minimum set of requirements:

- equivalent circuit of the system to be energised including, if any, HV OHLs, cables and other HVDC stations;
- equivalent impedances of all relevant components, especially its capacitances;
- any residual voltages prior to energisation, if any;
- target DC voltage band for energisation;
- maximum transient DC overvoltage due to energisation;
- maximum transient DC undervoltage due to energisation;
- minimum and maximum time to reach the target DC voltage band;
- maximum charging current (peak value);
- maximum charging energy;
- maximum number and repetition rate of DC circuit energisation.

All components involved with the energisation process shall be capable of withstanding the associated charging currents. Methods limiting or controlling the charging currents include additional impedances temporarily switched into the charging current path, i.e. reactors, resistors or arresters which shall be designed to withstand the corresponding voltage, current and energy duties, respectively.

With respect to any pre-existing insulation faults inside the DC circuit to be energised, the element providing the energisation shall have a short-circuit making capability according to the design short-circuit current as specified as well as appropriate protection elements.

9.2.3.2.5.1.3 Connecting a DC circuit to an energised HVDC grid

When connecting a DC circuit to an energised HVDC grid, measures by the associated DC circuits shall be performed to gain limited voltages across the switching element. Tolerances in