IEC TS 63291-2

Edition 1.0 2023-09

TECHNICAL SPECIFICATION

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High voltage direct current (HVDC) grid systems and connected converter stations – Guideline and parameter lists for functional specifications – Part 2: Parameter lists

IEC TS 63291-2:2023-09(en)

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.200; 29.240.01

ISBN 978-2-8322-7572-6

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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

Part 2: Parameter lists

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IEC TS 63291-2 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
115/320/DTS	115/329/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 63291-1:2023.

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/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- withdrawn,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.

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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 as well as the 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 2: Parameter lists

1 Scope

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

IEC TS 63291-1:2023, *High voltage direct current (HVDC) grid systems and connected converter stations – Guideline and parameter lists for functional specifications – Part 1: Guideline*

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 portection 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 – The definition was neutralised with respect to technology (not only VSC converters) and uses the term PoC as defined 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 – The definition was 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.]

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

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

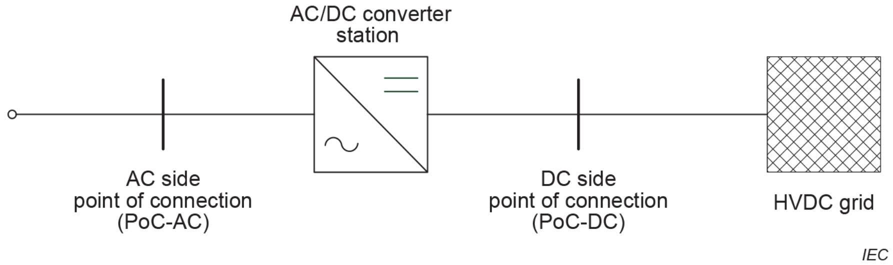


Figure 1 – Definition of the point of connection-AC and the point of connection-DC at an AC/DC converter station

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 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, DC switching 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 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]]

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

3.1.15
metallic return conductor
insulated conductor between the DC neutral busbars of HVDC stations

3.1.16
neutral bus earthing switch
NBES
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 [3], modified – The terms "neutral bus grounding switch" and "NBGS" have been omitted and the note added.]

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.

3.1.17
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.

3.1.18
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.]

3.1.19
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.

3.1.20
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 characteristic of the voltage value shall be further described, e.g.:

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

3.1.21
rigid bipole
rigid DC current bipolar system
bipolar HVDC system without neutral connection between both converter stations Figure 2

Note 1 to entry: Since only two (pole) conductors exist, no unbalance current between both poles is possible. In the event 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.

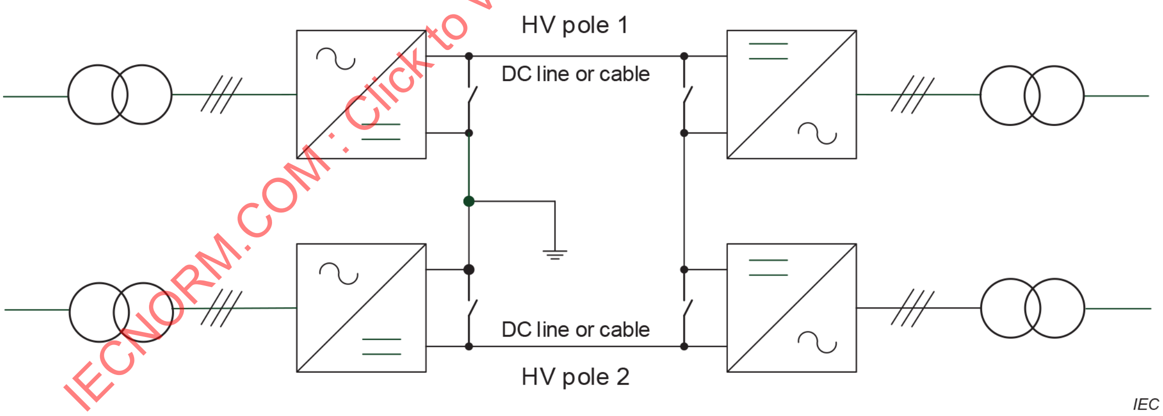


Figure 2 – Rigid bipolar HVDC system

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

3.1.22
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 [2], modified – The domain <in an electric power system> has been omitted.]

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.

3.1.23
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 may 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.

3.1.24
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, [5], modified – "HVDC transmission" added to the term.]

3.1.25
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, [5], modified – "transmission" added to the term, brackets added to the definition and note added.]

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	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

No parameters identified.

4.2 HVDC grid structure

No parameters identified.

4.3 Purpose of the HVDC grid and power network diagram

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 on 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),
- HVDC grid topology and converter station topology for each AC/DC converter station, DC switching station as well as each DC/DC converter station according to the nomenclature given in Table 1,
- DC earthing impedances at each AC/DC converter station and DC/DC converter station,
- FSDs,
- energy storages,
- energy absorbers, e.g. dynamic braking devices typically used for absorbing energy from wind farms or HV pole re-balancing after pole-to-earth DC faults.

Table 1 – Nomenclature of HVDC circuit topologies

Characteristics of the HVDC grid			-	Characteristics of a converter 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

4.4 AC/DC power flow optimisation

To provide a basis for the AC/DC power flow optimization, the purposes, basic functions and the operational concept of the combined AC/DC system shall be described. The optimization problem is expressed by objective function(s) and relevant boundary conditions.

The interface points between the HVDC grid and AC systems are the points of connection (PoC-AC).

The parameters needed to perform a power flow calculation for AC and DC systems both in normal or in abnormal operating state are listed in Table 2 and Table 3. Table 2 and Table 3 shall be specified for each AC/DC converter station or HVDC transmission line, respectively.

The active vs reactive power capabilities of an AC/DC converter station in Table 2 can alternatively be specified using PQ-diagrams and corresponding OP tables. All active and reactive power characteristics shall be stated with respect to a given AC system voltage operating range.

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 a 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.

Table 2 – Active and reactive power characteristics for a given AC system voltage operating range of an AC/DC converter station

Symbol	Parameter	Characteristic	Value	Unit
U_{ACmax_ss}		maximum steady-state voltage at the station defined at the PoC-AC		kV RMS
U_{ACmin_ss}		minimum steady-state voltage at the station defined at the PoC-AC		kV RMS
P_{ACmax_ss}	maximum active power	maximum steady-state active power exchange between AC and DC network defined at the PoC-AC [a]		MW
P_{ACmin_ss}	minimum active power	minimum steady-state active power exchange between AC and DC network defined at the PoC-AC [b]		MW
P_{ACmax_temp}	maximum active power	maximum temporary active power exchange between AC and DC network defined at the PoC-AC [c]		MW
P_{ACmin_temp}	minimum active power	minimum temporary active power exchange between AC and DC network defined at the PoC-AC [d]		MW

Symbol	Parameter	Characteristic	Value	Unit
$t_{P\_AC\_temp}$	time	time, for which limits of temporary maximum and minimum active power apply		s
P_{loss_rat}	power losses	power losses function of the station [e]		MW
$Q_{max\_ss}(.)$	maximum reactive power	maximum steady-state reactive power exchange capability chart (inductive and capacitive) depending on active power and voltage (P_{AC},U_{AC}) at the PoC-AC		Mvar
$Q_{min\_ss}(.)$	minimum reactive power	minimum steady-state reactive power exchange capability chart (inductive and capacitive) depending on active power and voltage (P_{AC},U_{AC}) at the PoC-AC		Mvar
$Q_{max\_temp}(.)$	maximum reactive power	maximum temporary reactive power exchange capability chart (inductive and capacitive) depending on active power and voltage (P_{AC},U_{AC}) at the PoC-AC		Mvar
$Q_{min\_temp}(.)$	minimum reactive power	minimum temporary reactive power exchange capability chart (inductive and capacitive) depending on active power and voltage (P_{AC},U_{AC}) at the PoC-AC		Mvar
$t_{Q\_AC\_temp}$	time	time, for which limits of temporary maximum and minimum reactive power apply		s
dP/dt_{max}		maximum rate of change of active power flow		MW/s
dP/dt_{min}		minimum required rate of change of active power flow		MW/s
dQ/dt_{max}		maximum rate of change of reactive power flow		Mvar/s
dQ/dt_{min}		minimum required rate of change of reactive power flow		Mvar/s
T_{AMB_min}	minimum ambient temperature	minimum ambient temperature at the station over which the real and reactive power capability shall be met		°C
T_{AMB_max}	maximum ambient temperature	maximum ambient temperature at the station over which the real and reactive power capability shall be met		°C

[a] Instead of P_{ACmax_ss}, the rated active power P_{DCmax_ss} can be defined at the PoC-DC.

[b] Instead of P_{ACmin_ss}, the rated active power P_{DCmin_ss} can be defined at the PoC-DC.

[c] Instead of P_{ACmax_temp}, the rated active power P_{DCmax_temp} can be defined at the PoC-DC.

[d] Instead of P_{ACmin_temp}, the rated active power P_{DCmin_temp} can be defined at the PoC-DC.

[e] Instead of P_{loss_rat}, power losses P_{loss_OP} at various operating points (OP) can be given.

Table 3 – Parameters of an HVDC transmission line

Symbol	Parameter	Characteristic	Value	Unit
I_{DC_Lrat}	rated current	rated current of the DC line		kA DC
	control mode	refer to Clause 6		N/A
	control mode parameters	refer to Clause 6		various
G_{DC}	DC conductance matrix[a] including the dedicated metallic return conductors, electrode lines and earthing impedances, if any	refer to: Table 26 – Component data – Earthing branch Table 27 – Component data – Standalone DC capacitors and DC filters of an HVDC station Table 28 – Component data – DC line reactors of an HVDC station Table 29 – Component data – DC lines (OHL, cable including electrode lines)[a]		$[G_{i,j}]$ = S
U_{DC}	DC voltage band vector			$[U_i]$ = kV DC
Z_{AC}	AC impedance matrix[a]			$[Z_{i,j}]$ = Ω
B_{AC}	AC conductance matrix[a]			$[B_{i,j}]$ = S
Y_{AC}	AC admittance matrix[a]			$[Y_{i,j}]$ = S
I_{AC_Lrat}	AC line rated current vector			$[I_i]$ = A RMS

[a] A matrix can also be provided as network diagram including parameters.

4.5 Converter operational functions

4.5.1 Basic operation functions – Converter normal operation state

4.5.1.1 General

No parameters identified.

4.5.1.2 AC system frequency following a frequency / power droop

The parameters listed in Table 4 shall be specified for each AC/DC converter station that shall be operated according to an "AC system frequency following a frequency / power droop".

Table 4 – Parameter list for AC system frequency following a frequency / power droop operation of an AC/DC converter station

Symbol	Parameter	Characteristic	Value	Unit
P_{ACrat}	rated active power	rated active power exchange between AC and DC network defined at the POC-AC [a]		MW
s_{PF}	AC frequency / active power droop	defines the droop constant for the converter control regarding the change of the active power reference with respect to the AC system frequency		N/A

[a] Instead of P_{ACrat}, the nominal active power P_{DCrat} can be defined at the PoC-DC.

4.5.1.3 DC voltage / DC power droop

The parameters listed in Table 5 shall be specified for each AC/DC converter station that shall be operated according to a DC voltage / DC power droop.

Table 5 – Parameter list for DC voltage / DC power droop operation of an AC/DC converter station

Symbol	Parameter	Characteristic	Value	Unit
U_{DCrat}	DC voltage	rated DC voltage, defined at the PoC-DC		kV DC
$s_{\mathrm{P\_UDC}}$	DC voltage / DC power droop	defines the change of active power reference in response to a deviation of the DC voltage from its reference value		N/A
$s_{\mathrm{IDC\_UDC}}$	DC voltage / DC current droop	defines the change of DC current reference in response to a deviation of the DC voltage from its reference value.		N/A

4.5.2 Basic operation functions – Converter abnormal operation state

4.5.2.1 General

No parameters identified.

4.5.2.2 Network conditions and power flow requirements

The parameters listed in Table 6 and Table 7 shall be specified at each AC/DC converter station.

Table 6 – Parameters describing the operation conditions of the AC network at an AC/DC converter station prior to and after a fault

Symbol	Parameter	Characteristic	Value	Unit
$P_{\mathrm{outage\_max}}$	power	maximum loss of power at the station due to system outages [a]		MW
$I_{\mathrm{SCmin\_pre}}$	minimum short-circuit current	minimum steady-state short-circuit current level at the PoC-AC prior to a fault		kA RMS
$I_{\mathrm{SCmin\_post}}$	minimum short-circuit current	minimum steady-state short-circuit current level at the PoC-AC after a fault		kA RMS
I_{SCmax}	maximum short-circuit current	maximum steady-state short-circuit current level at the PoC-AC		kA RMS
$(X/R)_{\mathrm{min}}$	minimum value of the X/R ratio			N/A
$(X/R)_{\mathrm{max}}$	maximum value of the X/R ratio			N/A
I_{SCmin}''	minimum short-circuit current	minimum subtransient short-circuit current level at the PoC-AC		kA RMS
I_{SCmax}''	maximum short-circuit current	maximum subtransient short-circuit current level at the PoC-AC		kA RMS

[a] Different values for the maximum loss of power can be specified depending on the expected frequency of events.

Table 7 – Time requirements for power restoration in the event of temporary faults

Symbol	Parameter	Characteristic	Value	Unit
t_{PoffAC}	maximum time of active power interruption	interruption time due to AC system faults, counted from fault inception until restoration of active power to 90 % of its target value		ms
t_{QoffAC}	maximum time of reactive power interruption	interruption time due to AC system faults, counted from fault inception until restoration of reactive power to 90 % of its target value		ms
t_{PoffDC}	maximum time of active power interruption	interruption time due to DC system faults, counted from fault inception until restoration of active power to 90 % of its target value		ms

4.5.2.3 Abnormal AC voltage conditions

The AC undervoltage ride through requirements shall be specified for each AC/DC converter station by a diagram as shown in Figure 3 using the parameters listed in Table 8 (piecewise linear definition of the voltage versus time curve). Different values can be specified for symmetrical and asymmetrical faults.

Table 8 – AC undervoltage ride through requirements for an AC/DC converter station

Symbol	Parameter	Characteristic	Value	Unit
$U_{AC\_UV\iota}$	voltage level	voltage level defining the retained AC undervoltage during a fault at the PoC-AC at the time defined by $t_{AC\_UV\iota}$		kV RMS
$t_{AC\_UV\iota}$	time	time defining the maximum duration of the voltage level $U_{AC\_UV\iota}$		ms
$n_{AC\_UV\iota}$	number	number of consecutive undervoltage events		N/A

The following additional information is relevant:

- Table 2; U_{ACmin_ss}

The AC overvoltage ride through requirements shall be specified for each AC/DC converter station by a diagram as shown in Figure 3 using the parameters listed Table 9 (piecewise definition of the voltage versus time curve). Different values can be specified for symmetrical and asymmetrical faults.

Table 9 – AC overvoltage ride through requirements for an AC/DC converter station

Symbol	Parameter	Characteristic	Value	Unit
$U_{\text{AC\_OV}i}$	voltage level	voltage level defining one supporting point of the AC overvoltage at the PoC-AC at the time defined by $t_{\text{AC\_OV}i}$		kV RMS
$t_{\text{AC\_OV}i}$	time	time defining the maximum duration of the voltage level $U_{\text{AC\_OV}i}$		ms
$n_{\text{AC\_OV}i}$	number	number of consecutive overvoltage events		N/A

The following additional information is relevant:

- Table 2; $U_{\text{ACmax\_ss}}$

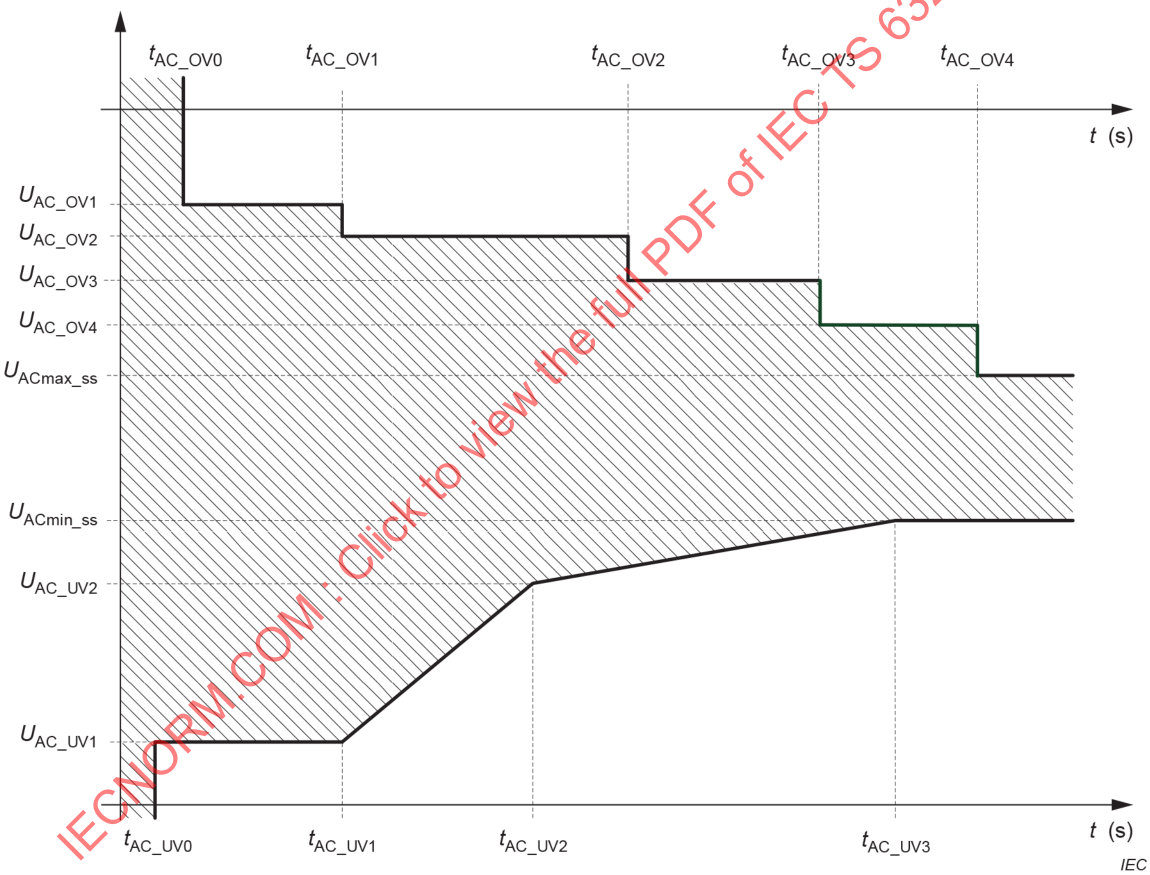


Figure 3 – Generic AC over- and undervoltage ride through profile of an AC/DC converter station: Different values can be specified for symmetrical and asymmetrical faults

4.5.3 Ancillary services

4.5.3.1 General

No parameters identified.

4.5.3.2 Frequency control related services

4.5.3.2.1 Synthetic inertia (differential frequency control)

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

$$\begin{bmatrix} \Delta P_{\mathrm{SZ},1} \\ \vdots \\ \Delta P_{\mathrm{SZ},i} \\ \vdots \\ \Delta P_{\mathrm{SZ},n_\mathrm{S}} \end{bmatrix} = \begin{bmatrix} K_{\mathrm{FCR},1,1} & \cdots & K_{\mathrm{FCR},1,j} & \cdots & K_{\mathrm{FCR},1,n_\mathrm{R}} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ K_{\mathrm{FCR},i,1} & \cdots & K_{\mathrm{FCR},i,j} & \cdots & K_{\mathrm{FCR},i,n_\mathrm{R}} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ K_{\mathrm{FCR},n_\mathrm{S},1} & \cdots & K_{\mathrm{FCR},n_\mathrm{S},j} & \cdots & K_{\mathrm{FCR},n_\mathrm{S},n_\mathrm{R}} \end{bmatrix} \begin{bmatrix} \Delta P_{\mathrm{RZ},1} \\ \vdots \\ \Delta P_{\mathrm{RZ},j} \\ \vdots \\ \Delta P_{\mathrm{RZ},n_\mathrm{R}} \end{bmatrix}$$

and

$$\sum_{k=1}^{n_\mathrm{S}} K_{\mathrm{FCR},k,j} = -1;\ K_{\mathrm{FCR},k,j} \leq 0$$

The parameters are listed in Table 10.

Table 10 – Coordination of power associated with primary frequency control

Symbol	Parameter	Characteristic	Value	Unit
t_{FCRact}	time	minimum step response time, to coordinate with inertia		s
t_{FCRprov}	time	maximum provision time, to coordinate with FRR		s
f_{DEADBAND}	frequency band	frequency dead band, to limit the activation to exceptional situations		Hz
$K_{\mathrm{FCR},i,j}$	coefficient	FCR-distribution coefficient indicating the amount of active power drawn from the sending zone i and fed into the receiving zone j		N/A
$\Delta P_{\mathrm{SZ},i}$	active power	active power drawn from the sending zone i		MW
$\Delta P_{\mathrm{RZ},j}$	active power	active power fed into receiving zone j		MW
n_R	number	number of asynchronous AC grid zones which are receiving zones		N/A
n_S	number	number of asynchronous AC grid zones which are sending zones		N/A

4.5.3.2.2 Frequency containment reserve (primary frequency control)

If providing FCR is a relevant function for an AC/DC converter station, the parameters listed in Table 11 shall be specified. Furthermore, the relevant AC grid code requirements shall be included. The ENTSO-E implementation guideline "Frequency Sensitive Mode" provides further details for grid code requirements applicable to the networks operated by the members of ENTSO-E in Europe [6].

Table 11 – FCR parameters for an AC/DC converter station, parameters for active power frequency response in FSM

Symbol	Parameter	Characteristic	Value	Unit
$P_{\Delta f\_max}$	active power	maximum active power limit for frequency controller		MW
$P_{\Delta f\_min}$	active power	minimum active power limit for frequency controller		MW
$\|\Delta P\|/P_{max}$	active power	active power range, change in $P_{SETPOINT}$ triggered by the step change in frequency		MW
Δf	frequency	frequency change in AC network measured continuously by the average of the rate of change of the AC network frequency (df/dt) for a defined time span		Hz
f_n	frequency	target frequency in the AC network		Hz
$f_{DEADBAND}$ $[f_{min}, f_{max}]$	frequency band	frequency response dead-band		Hz
s_1	droop factor	upward regulation droop		N/A
s_2	droop factor	downward regulation droop		N/A
$t_{initial}$	delay time	maximum initial delay of activation		s
t_{full}	delay time	maximum delay until full activation		s

The following additional information is relevant:

- Table 2; P_{ACmax_ss}

4.5.3.2.3 Frequency restoration reserve (secondary frequency control)

If providing FRR is relevant for an AC/DC converter station, the function shall be specified including:

- gains,
- time constants,
- limitations,
- dead bands,
- activation and de-activation criteria.

4.5.3.2.4 Replacement reserves (tertiary frequency control)

If providing replacement reserves are relevant for an AC/DC converter station, the function shall be specified including:

- gains,
- time constants,
- limitations,
- dead bands,
- activation and de-activation criteria.

4.5.3.3 AC voltage control related services

The function shall be specified of each AC/DC converter station according to Table 12 and Table 13.

Table 12 – Voltage range capability parameters for an AC/DC converter station

Symbol	Parameter	Characteristic	Value	Unit
U_{ACrat}	rated AC voltage	rated AC voltage at the PoC-AC		kV RMS
$U_{\text{ACcont}}[U_{\text{min}}, U_{\text{max}}]$	normal AC voltage operating range	normal voltage range for continuous operation at the PoC-AC		kV RMS
U_{ACtemp} $[U_{\text{min\_tmp}}, U_{\text{max\_tmp}}]$	temporary AC voltage operating range	extended voltage operating range at the PoC-AC for limited time		kV RMS
t_{Utmp}	time for extended voltage operating range	time for temporary operation defined for each range		s

Table 13 – Reactive power capability parameters for an AC/DC converter station

Symbol	Parameter	Characteristic	Value	Unit
$Q(U_{\text{AC}})$	function	reactive power depending on the AC voltage at the PoC-AC		Mvar
$\Delta Q/\Delta t$	ramp rate	ramp rate of reactive power		Mvar/s

4.5.3.4 Power oscillation damping services

4.5.3.4.1 General

No parameters identified.

4.5.3.4.2 Electromechanical oscillations

The parameters listed in Table 14 shall be specified for each AC/DC converter station.

Table 14 – Parameters describing electromechanical oscillations

Symbol	Parameter	Characteristic	Value	Unit
f_{POD} $[f_{\text{PODmin}}, f_{\text{PODmax}}]$	frequency range	frequency range of oscillations to damp	N/A	Hz
no symbol	control mode	control mode of this POD controller to specify if the response is in active or reactive power modulation	N/A	integer
no symbol	Operating conditions	Conditions of the network to reproduce the frequency range of oscillations (topology and load flow conditions, i.e., elements in service, generation and consumption levels, substation arrangement, etc.)	N/A	various
no symbol	Event	Type of event to reproduce the frequency range of oscillations	N/A	various

4.5.3.4.3 Sub-synchronous torsional interactions

No HVDC grid-specific parameters.

4.5.3.5 System restoration services

4.5.3.5.1 General

No parameters identified.

4.5.3.5.2 Restoration from blackout

The capabilities of the HVDC grid to restore connected AC systems or parts thereof after blackout shall be specified using a simplified representative test network.

For each relevant AC system, the following information shall be specified:

- Test network topology,
- Data of the network elements,
- Sequences to be demonstrated in the test network,
- Minimum DC short-circuit current to be provided by the relevant AC/DC converter station,
- Field tests.

In addition, the source and the MVA-rating for auxiliary power shall be specified.

4.5.3.5.3 Post-AC fault active power recovery

The parameters are listed in Table 15.

Table 15 – Parameters describing post-fault active power recovery at an AC/DC converter station

Symbol	Parameter	Characteristic	Value	Unit
$P_{\text{POST-FAULT}}$	Post fault active power recovery			MW
$t_{\text{POST-FAULT}}$	Time in which to recover P	specifies (together with $P_{\text{POST-FAULT}}$) a point of lower limits of active power recovery (measured from t_{FAULT} = 0)		s

5 HVDC grid characteristics

5.1 HVDC circuit topologies

5.1.1 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 characteristics of the HVDC grid shall be specified according to Table 16.

Table 16 – Characteristics of the HVDC grid

Characteristics of the HVDC grid		
Number of HV poles	DC	DC circuit earthing
	DC	

5.1.3 Attributes of HVDC grids or HVDC grid subsystems

5.1.3.1 Number of HV poles

No parameters identified.

5.1.3.2 DC circuit earthing

The parameter for DC circuit earthing is a global parameter for the entire HVDC grid and is listed in Table 17.

Table 17 – DC circuit earthing parameters

Symbol	Parameter	Characteristic	Value	Unit
u_{DCdisp}	effectively earthed / non-effectively earthed	low / HV displacement in the event of a single DC pole to earth fault, expressed by the voltage change of the unfaulty pole referenced to the rated DC voltage of that pole		%
Z_{earth}	effective earthing impedance	equivalent earthing impedance including all active earthing points in the HVDC grid, used to calculate short-circuit currents		Ω
no symbol	number of earthing points in operation	number of earthing points that are active for each operation mode of the entire HVDC grid		integer

5.1.4 Attributes of an HVDC station

5.1.4.1 Connection to HV poles

A station can be connected to HV pole 1, HV pole 2, or both. The connection to HV poles shall be specified for each AC/DC converter station individually according to 8.4.1.1.

5.1.4.2 Neutral return path

In an HVDC grid, a combination of the types of return paths may apply. A network diagram showing how the individual converter stations are connected, including elements such as lines, nodes and earth connections shall be provided.

The return path can be different for different parts of the HVDC Grid.

The parameters to be specified for each return path are listed in Table 18.

Table 18 – Parameters for each return path

Symbol	Parameter	Characteristic	Value	Unit
ER	earth return	"sea electrodes", "land electrodes" or "none"		N/A
MR	dedicated metallic return	"yes" or "none"		N/A
RB	rigid bipole	"yes" or "none"		N/A
I_{DCret_rat}	DC current	max. steady-state design DC current of the return path [a]		kA DC
t_{DCret_rat}	maximum duration at I_{DCret_rat}	maximum permissible duration of operation at rated DC earth return current [b] through the return path		hours

[a] Can be relevant for earth electrodes, earth return paths or station earthing system design.

[b] Can be relevant for earth electrodes, earth return paths or station earthing system design.

5.1.4.3 Station earthing

The earthing of an AC/DC converter station shall be specified for each station individually according to 8.4.1.1. The parameters of the earthing branch shall be specified according to Table 26.

5.2 Connection modes

The connection modes of the individual HVDC grid installations shall be specified according to 8.4.2.1 for AC/DC converter stations or 9.2.3.2.1 for DC switching stations. Their application shall be coordinated throughout the HVDC grid at all times when operating.

5.3 Grid operating states

5.3.1 General

No parameters identified.

5.3.2 Normal state

No parameters identified.

5.3.3 Alert state

Possible system contingencies shall be described.

5.3.4 Emergency state

No parameters identified.

5.3.5 Blackout state

No parameters identified.

5.3.6 Restoration

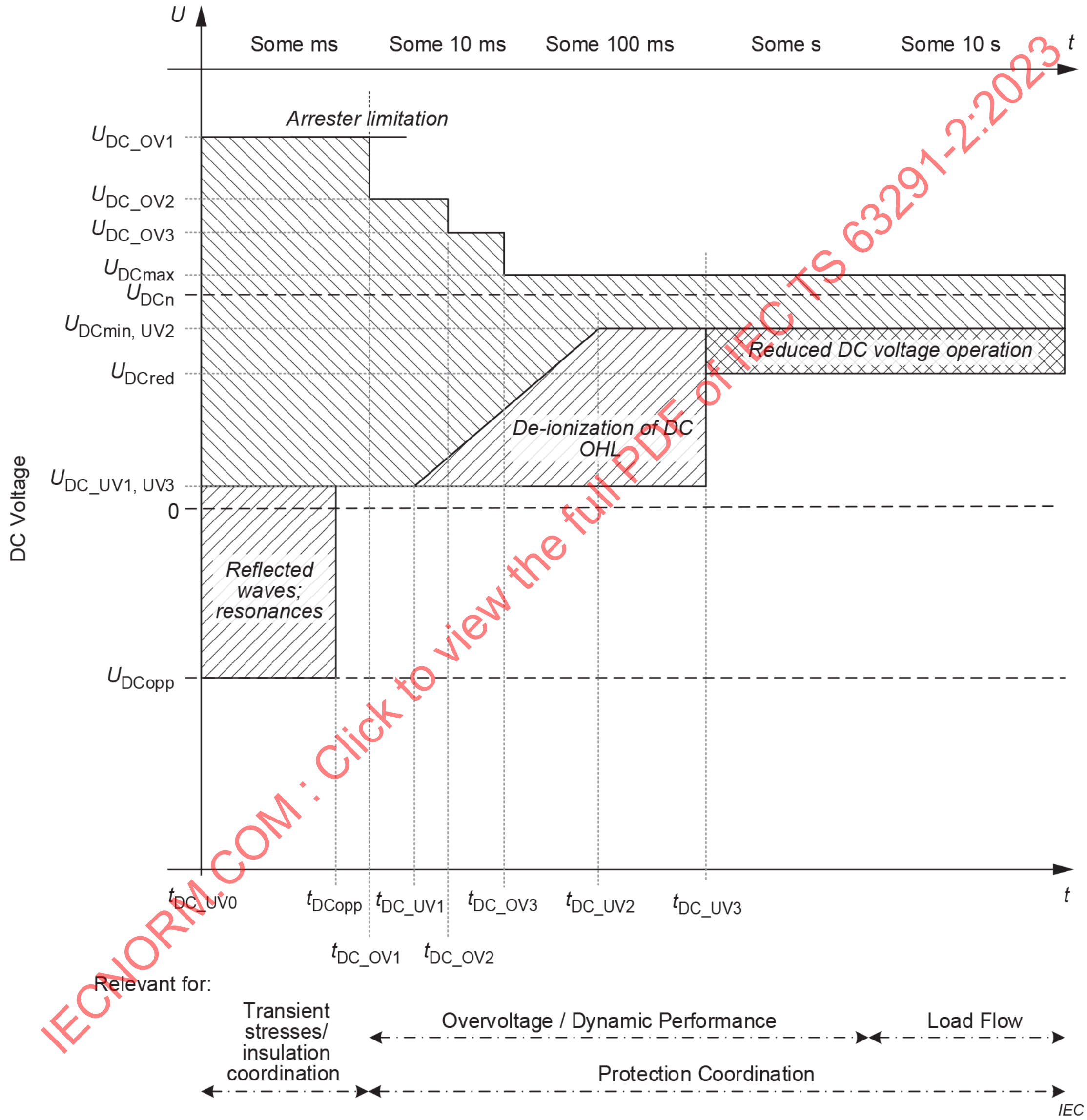
No parameters identified.

5.4 DC voltages

5.4.1 General

For each DC voltage level, including HVDC poles, lines and neutral points as well as return conductors, if any, within the HVDC grid the respective voltage levels shall be defined. These levels should be coordinated throughout the HVDC grid. The voltage values stated in this Subclause 5.4 shall be specified for each PoC-DC.

The levels describing the temporary DC pole to earth voltage profiles are illustrated in Figure 4.



[Source: Based on copyright Cigre Technical Brochure 657 [1] [7]]

Figure 4 – Temporary DC pole to earth voltage profiles at a PoC-DC

In cases where the positive and negative nominal pole voltages are different, provide a characteristic for each pole.

1 Reproduced from Cigre Technical Brochure 657, with the permission of CIGRE.

5.4.2 Nominal DC system voltage

The nominal DC system voltage shall be specified for each PoC-DC. The parameters are listed in Table 19.

The nominal voltage can be stated as the voltage with respect to earth (default) or with respect to neutral. If the nominal voltage is stated with respect to neutral, the entries in columns "Parameter" and "Characteristic" in Table 19 will have to be changed accordingly.

Table 19 – Nominal DC system voltage at a PoC-DC

Symbol	Parameter	Characteristic	Value	Unit
$U_{\text{DCpole\_n\_pos}}$	DC voltage to earth	nominal value of the positive DC pole voltage with respect to earth		kV DC
$U_{\text{DCpole\_n\_neg}}$	DC voltage to earth	nominal value of the negative DC pole voltage with respect to earth		kV DC

5.4.3 Steady-state DC pole voltage

The parameters listed in Table 20 shall be specified for each PoC-DC.

Table 20 – DC pole voltage range parameters at a PoC-DC of an HVDC station – Steady-state

Symbol	Parameter	Characteristic	Value	Unit
$U_{\text{DCpole\_max}}$	DC voltage to earth	maximum absolute value of the DC pole operating voltage range		kV DC
$U_{\text{DCpole\_min}}$	DC voltage to earth	minimum absolute value of the DC pole operating voltage range, including reduced DC voltage operating level, if any		kV DC

5.4.4 Temporary DC pole voltage

The parameters listed in Table 21 and Table 22 shall be specified for each HVDC station and each of its PoC-DC.

Table 21 – DC pole voltage range parameters at a PoC-DC of an HVDC station – Temporary undervoltages

Symbol	Parameter	Characteristic	Value	Unit
$U_{\text{DC\_UV1}}$	DC voltage to earth	minimum retained DC voltage during a DC fault		kV DC
$t_{\text{DC\_UV0}}$	time	fault inception time		s
$t_{\text{DC\_UV1}}$	fault duration	measured from fault inception		s
$t_{\text{DC\_UV2}}$	time	specifies a point of lower limits of DC voltage recovery		s

Table 22 – DC pole voltage range parameters at a PoC-DC of an HVDC station – Temporary overvoltages

Symbol	Parameter	Characteristic	Value	Unit
U_{DC_OV1}	DC voltage to earth	overvoltage level 1		kV peak
U_{DC_OV2}	DC voltage to earth	overvoltage level 2		kV DC
U_{DC_OV3}	DC voltage to earth	overvoltage level 3		kV DC
U_{DC_OV4}	DC voltage to earth	overvoltage level 4		kV peak
…				
U_{DCopp}	DC voltage to earth	transient DC voltage in opposite polarity		kV peak
t_{DC_OV0}	time	time during which the overvoltage is solely limited by arresters		ms
t_{DC_OV1}	time	U_{DC_OV1} overvoltage during $t_{DC\_OV1} - t_{DC\_OV0}$		ms
t_{DC_OV2}	time	U_{DC_OV2} overvoltage during $t_{DC\_OV2} - t_{DC\_OV1}$		ms
t_{DC_OV3}	time	U_{DC_OV3} overvoltage during $t_{DC\_OV3} - t_{DC\_OV2}$		ms
t_{DC_OV4}	time	U_{DC_OV4} overvoltage during $t_{DC\_OV4} - t_{DC\_OV3}$		ms
t_{DCopp}	time	time of opposite DC voltage polarity		ms
…				
$t_{DC\_OV(n)}$	time	$U_{DC\_OV(n)}$ overvoltage during $t_{DC\_OV(n)} - t_{DC\_OV(n-1)}$		ms

5.4.5 DC neutral bus voltage

Typical levels describing the DC neutral bus, if any, to earth voltage profiles are illustrated in Figure 5 and listed in Table 23. The characteristics shall be specified for each PoC-DC.

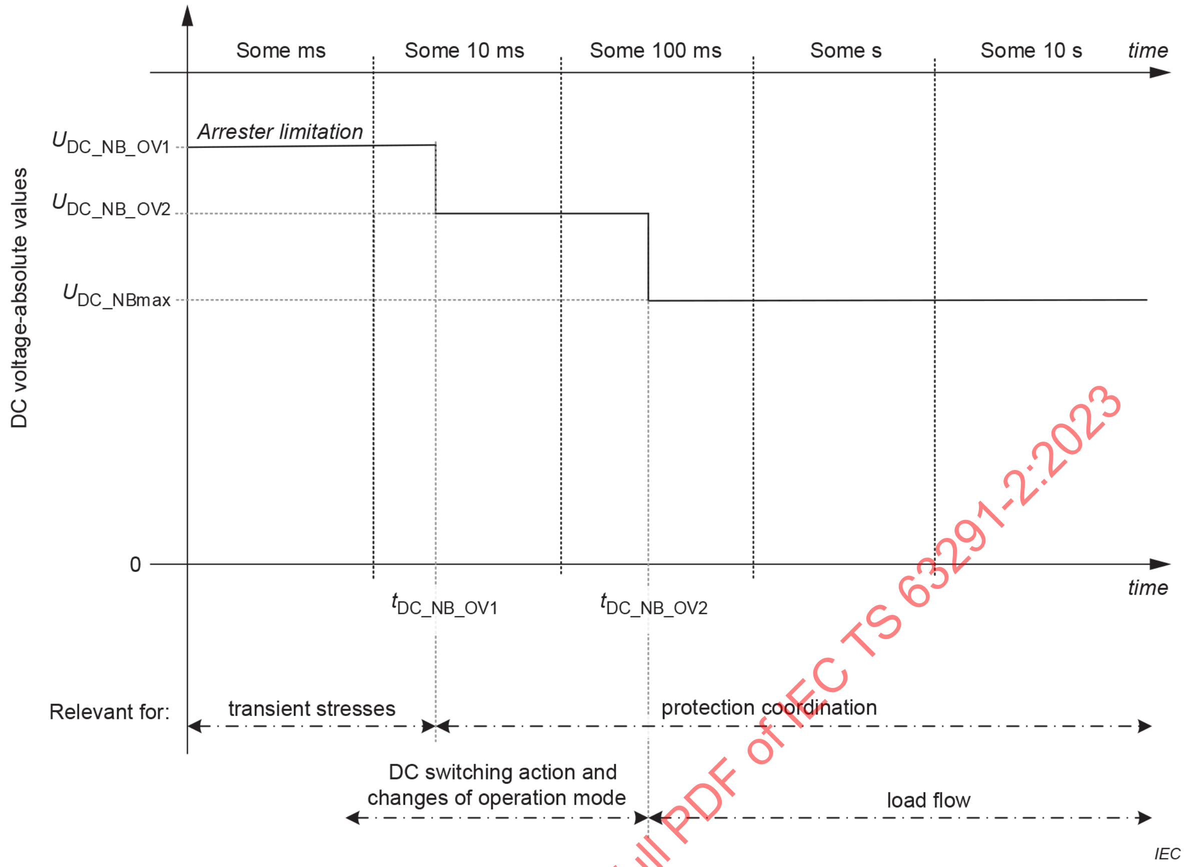


Figure 5 – Generic neutral bus voltage profile at a PoC-DC

The following information is relevant:

- Table 20
- Table 22

Table 23 – DC neutral bus voltage range parameters

Symbol	Parameter	Characteristic	Value	Unit
$U_{DC\_NB\_OV1}$	DC voltage to earth	overvoltage level 1, arrester protective voltage		kV peak
$U_{DC\_NB\_OV2}$	DC voltage to earth	overvoltage level 2		kV DC
$U_{DC\_NB\_max}$	DC voltage to earth	maximum value of the DC neutral bus voltage or at the return path		kV DC
$U_{DC\_NB\_rat}$	DC voltage to earth	rated voltage at DC neutral bus or the return path, if any		kV DC
…				
$t_{DC\_NB\_OV1}$	time	Time during which the overvoltage is solely limited by arresters		ms
$t_{DC\_NB\_OV2}$	time	U_{DC_OV2} overvoltage during $t_{DC\_OV2} - t_{DC\_OV1}$ due to DC switching actions and changes of operating mode		ms

5.5 Insulation coordination

For each PoC-DC, including HVDC poles, lines and neutral points as well as return conductors, if any, within the HVDC grid the insulation levels listed in Table 24 shall be defined. These levels should be coordinated throughout the HVDC grid.

The voltage profile along HVDC transmission lines during transient events or due to voltage and current distortions should be considered [8].

Table 24 – Insulation levels at a PoC-DC

Symbol	Parameter	Characteristic	Value	Unit
$U_{\text{DC\_SIWL}}$	insulation level	switching impulse withstand voltage		kV peak
$U_{\text{DC\_SIres\_}i1}$	residual voltage	residual voltage at current $i1$		kV peak
$U_{\text{DC\_SIres\_}i2}$	residual voltage	residual voltage at current $i2$		kV peak
$U_{\text{DC\_LIWL}}$	insulation level	lightning impulse withstand voltage		kV peak

5.6 Short-circuit characteristics

5.6.1 Calculation of short-circuit currents in HVDC grids

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

For the calculation of short-circuit currents based on converter and component data the values listed in Table 25, Table 27,

Table 28 and Table 29 shall be specified for each HVDC station. The values listed in Table 29 shall be specified for each HVDC transmission line or HVDC transmission line section, respectively.

- To specify the transient behaviour of the short-circuit current after fault initiation taking into account the C&P system of the converter stations as well as the data of the complete system (topology, line configuration, operational DC voltage, etc.), the data in Table 30 shall be specified at the PoC-DC.

Table 25 – Maximum converter current of an HVDC station into the HVDC grid

Symbol	Parameter	Characteristic	Value	Unit
$I_{\text{DC\_SCmax}}$	current	Maximum peak short-circuit current fed by the converters of the HVDC station		kA peak
$i_{\text{DC\_SCtherm}}$	current waveshape, diagram $i_{\text{DC\_SCtherm}}=\text{f}(t)$	Maximum short-circuit current vs. time characteristic as fed by the converters of the HVDC station relevant for the thermal rating of equipment		kA

Table 26 – Component data – Earthing branch

Symbol	Parameter	Characteristic	Value	Unit
C_E	capacitance			µF
L_E	inductance			mH
R_E	resistance			Ω

Table 27 – Component data – Standalone DC capacitors and DC filters of an HVDC station

Symbol	Parameter	Characteristic	Value	Unit
C_F	capacitance			µF
L_F	inductance			mH
R_F	resistance			Ω

Table 28 – Component data – DC line reactors of an HVDC station

Symbol	Parameter	Characteristic	Value	Unit
L_R	inductance			mH

Table 29 – Component data – DC lines (OHL, cable including electrode lines)[a]

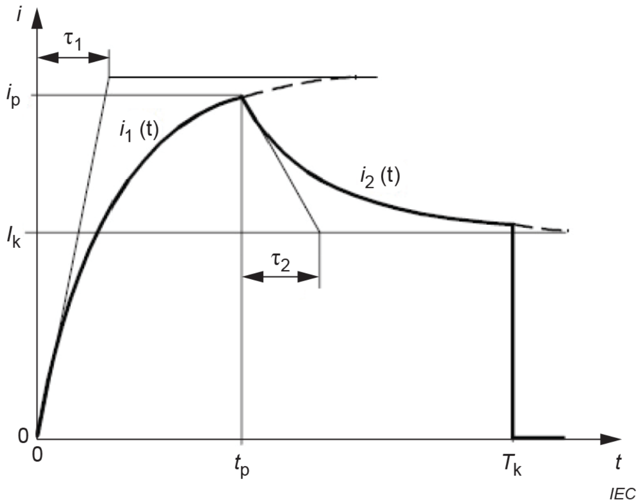
Symbol	Parameter	Characteristic	Value	Unit
L_{LE}	Line-earth inductance	monopolar/bipolar; loop: line-to-earth per length for each line		mH/km
Z_{LL}	Line-line impedance	bipolar; loop: line – line per length for each line		Ω/km
C_{LE}	capacitance	line-to-earth for each line		nF/km
C_{LL}	capacitance	line-to-line for each line		nF/km
ℓ	line lengths	for each line		km
ρ	electrical resistivity of the soil	for each line		Ω·m

[a] The tower or cable geometry together with the length and the DC resistance may be provided instead of the parameters in Table 29.

The following information is relevant:

- Table 3.

For each HVDC station, a short-circuit current characteristic as seen on the PoC-DC shall be specified. This characteristic shall include the contributions of capacitors, reactors and filters, if any, that are part of the HVDC station.



[SOURCE: IEC 61660-1:1997, Figure 2 [9]]

Figure 6 – Standard approximation function

The parameters are listed in Table 30.

Table 30 – Short-circuit current parameters at a PoC-DC

Symbol	Parameter	Characteristic	Value	Unit
i_p	instantaneous current	peak current in case of a short-circuit		kA peak
t_p	time to peak	related to the peak current		ms
I_k	steady-state current	after decaying of all oscillations		kA DC
T_k	duration	short-circuit duration		ms
τ_1	time constant	rise-time constant		s
τ_2	time constant	decay-time constant		s

The short-circuit current contributions of parts of an HVDC grid that are connected via a DC short-circuit current limiting device are to be specified according to the standard approximation function demonstrated by the wave shape of Figure 6.

5.6.2 Short-circuit current design requirements

Parameters defining the design of the HVDC grid with respect to all short-circuit current contributions are to be specified according to the standard approximation function demonstrated by the wave shape of Figure 6.

5.7 Steady-state voltage and current distortions

5.7.1 Emissions and impacts

The parameters listed in Table 31 are necessary to calculate voltage and current distortions at a 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.

Table 31 – Equivalent impedances for calculating voltage and current distortions at a PoC-DC

Symbol	Parameter	Characteristic	Value	Unit
$Z_{\text{Grid}}(f)$	grid impedance	equivalent impedance as seen from the PoC-DC into the grid at frequency f (self-impedance) [a, b]		Ω
$Z_{\text{Station}}(f)$	HVDC station impedance	equivalent impedance as seen from the PoC-DC into the station at frequency f [c]		Ω

[a] The equivalent network impedances will be different for pole mode and ground mode distortions. More details are described in Cigre Technical Brochure 811 [10].

[b] 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.

[c] 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.

Table 32 lists the pre-existing voltage and current distortions.

Table 32 – Pre-existing DC voltage and current distortions at a PoC-DC

Symbol	Parameter	Characteristic	Value	Unit
$U_{\text{Grid}}(f)$	grid voltage distortion	pre-existing voltage distortion at frequency f		V RMS
$I_{\text{Grid}}(f)$	grid current distortion	distortion current flowing at frequency f		A RMS

Table 33 lists the planning levels and permissible DC voltage and current distortion limits that shall be specified for a PoC-DC.

Table 33 – Planning levels and permissible DC voltage and current distortions at a PoC-DC

Symbol	Parameter	Characteristic	Value	Unit
$U_{\text{plan}}(f)$	planning voltage level	planning levels for voltage distortion emission		V RMS
$I_{\text{plan}}(f)$	planning current level	planning levels for current distortion emission		A RMS
$U_{\text{Station}}(f)$	distortion voltage limit	limits for distorting voltage emission for the station; $U_{\text{lim}}(f) < U_{\text{plan}}(f)$		V RMS
$I_{\text{Station}}(f)$	distortion current limit	limits for distorting current emission for the station; $I_{\text{lim}}(f) < I_{\text{plan}}(f)$		A RMS

Table 34 lists parameters necessary to calculate voltage distortions at a remote bus in the HVDC grid caused by voltage and current distortions of the converter station connected to the PoC-DC.

Table 34 – Coupling factors for calculating voltage distortions at a remote bus caused by emissions at a PoC-DC

Symbol	Parameter	Characteristic	Value	Unit
$Z_{Coup\_b}(f)$	grid impedance	equivalent impedance between the PoC-DC and a remote bus b at frequency f (coupling impedance)		Ω
$H_{Coup\_b}(f)$	factor	ratio of the coupling impedance between bus b and the PoC-DC and the self-impedance as seen from the PoC-DC (coupling factor) $\left\lvert H_{Coupb}(f) = \left\lvert \frac{Z_{Coupb}(f)}{Z_{Grid}(f)} \right\rvert \right\rvert$		%

5.7.2 Rights and obligations of a connectee

No parameters identified.

5.7.3 Similarities between HVDC grids and AC networks

The parameters are included in 5.7.1.

5.7.4 Voltage and current distortion limits

The parameters are included in 5.7.1.

5.7.5 Allocation of limits to individual connectees

The parameters are included in 5.7.1.

5.7.6 Frequency-dependent DC system impedance

The parameters are listed in Table 35.

Table 35 – Specification of DC system impedance

Symbol	Parameter	Characteristic	Value	Unit
f_{max}	maximum frequency	maximum frequency to be evaluated		Hz
f_{min}	minimum frequency	minimum frequency to be evaluated		Hz
Δf	frequency step	frequency step between two consecutive frequencies evaluated		Hz

NOTE 1 IEC 61000-4-7 requires Δf = 5 Hz [11]

NOTE 2 Alternatively, for small HVDC grids the harmonic impedances of the individual elements of the HVDC grid together with the topology and potential operational configurations of the grid can be specified.

5.8 DC system restoration

5.8.1 General

No parameters identified.

5.8.2 Post-DC fault recovery

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

5.8.3 Restoration from blackout

The HVDC stations to be foreseen to provide SRAS-DC shall be specified. The specific requirements applicable to this function are specified in 8.4.2.7.

6 HVDC grid control

6.1 Closed-loop control functions

6.1.1 General

No parameters identified.

6.1.2 Core control functions

No parameters identified.

6.1.3 Coordinating control functions

No parameters identified.

6.2 Controller hierarchy

6.2.1 General

No parameters identified.

6.2.2 Internal converter control

No HVDC grid-specific parameters identified.

6.2.3 DC node voltage control

Settings for control modes and related parameters (if any), such as P_{DCref} and U_{DCref} for a certain OP are incorporated in the converter schedules (see Table 43).

In the case of droop control modes, Table 36 lists the relevant parameters.

Table 36 – DC node voltage control parameters

Symbol	Parameter	Characteristic	Value	Unit
N	number of sections	number of sections with (different) droop characteristics; all sections are defined within the range between U_{DCmin} and U_{DCmax}		integer
$k_{Section\_x}$	droop	linear power-voltage characteristic at section x		MW/kV
P_{max}	power	power set point for DC voltages lower than U_{DCmin}		MW
P_{min}	power	power set point for DC voltages higher than U_{DCmax}		MW
U_{DCmax}	voltage	maximum DC voltage set point		kV
U_{DCmin}	voltage	minimum DC voltage set point		kV
t_S	settling time	time required for DC node voltages to settle to a new reference value after sudden changes, typically defined for a precision within x % absolute distance to new reference value		ms

A section can be defined in different ways. Figure 7 shows an example of piecewise linear droop characteristics. If other characteristics are used for one or more sections, respective shape parameters similar to the linear slope coefficient $k_{Section\_x}$ in Table 36 shall be given.

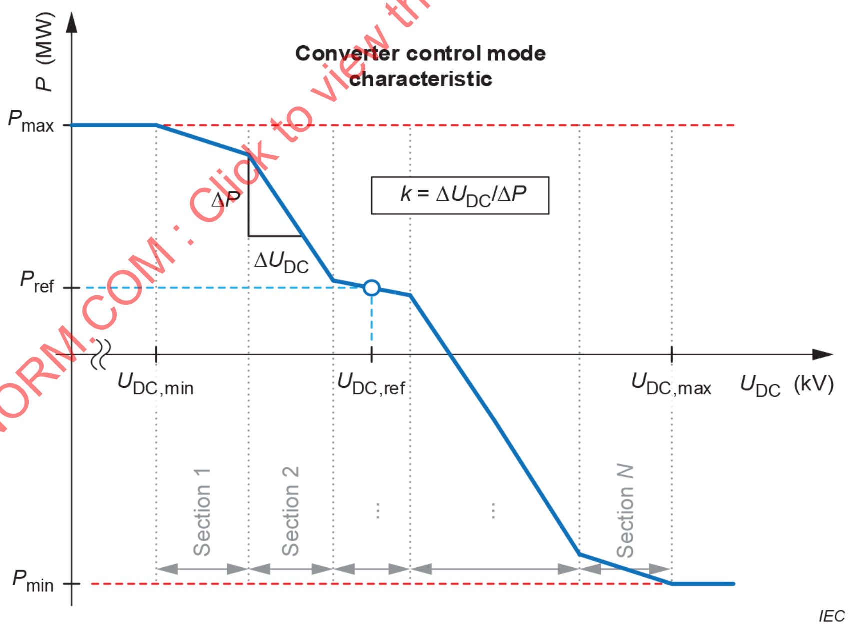


Figure 7 – Typical DC node voltage control modes (illustration in DC voltage/power plane)

6.2.4 Coordinated HVDC grid control

6.2.4.1 General

For proper communication within the entire HVDC grid the communication protocols used, as well as interface conventions, such as signal format including units and scaling shall be specified.

In Table 37, measured system state variables and essential equipment status signals are summarized that have to be communicated continuously within the HVDC grid for proper coordination.

Table 37 – System state variables and equipment status signals (interface list)

Symbol	Parameter	Characteristic	Value	Unit
no symbol	switches status	status messages (opened/closed) of switches related to all nodes connected to the HVDC grid		boolean
I_{DCmeas}	DC line currents	measured DC current through all HVDC transmission lines		kA
U_{DCmeas}	DC node voltage	measured DC voltage at all electrical nodes		kV

In addition, the provisions of Table 45 are also required for proper coordination in this control layer.

6.2.4.2 Autonomous adaptation control

The autonomous adaptation control layer is realized by a set of rules. Each rule is defined by one or more observations that activate at least one corresponding countermeasure.

The set of all rules shall be known to all converter stations of the HVDC grid. These rules have to be taken into account for the converter design and in the implementation of C&P functions.

Table 38 defines a general interface (signal list) for any rules implemented in the autonomous adaptation control layer of a converter station.

Table 38 – General interface (signal list) for autonomous adaption control rules

Interface parameter	Characteristic	Format
rule ID	unique identifier of a rule	integer
rule status_X	operational status of the rule (i.e., if the rule is "activated" in the autonomous adaptation controls of converter station X)	boolean
rule priority	priority of a rule, i.e., the active rule with highest priority is the only one being effective	integer
observation ID	unique identifier of the observation (single variable/threshold comparison or set of observation criteria) which corresponds to the rule	integer
holding time	minimum duration for which the threshold(s) in the associated observation have to be violated (before countermeasures are activated)	real
countermeasure ID(s)	one or more identifiers for all countermeasures that shall be triggered according to this rule	integer
comment	labelling and description of the purpose and context of the rule	string

A rule shall be triggered based on threshold violation of a single observation variable (detection of an abnormal condition) or a set of observations constituting a whole "event pattern" (identification of known contingency situations in the HVDC grid).

At least one countermeasure shall be associated with each rule.

Table 39 defines the general interface (signal list) required for defining observations for detection of abnormal conditions.

Table 39 – General interface (signal list) for defining an observation

Interface parameter	Characteristic	Format
observation ID	unique identifier of the corresponding observation	integer
observation variable(s)	one or more physical quantity (e.g., measurement signals) to be compared against the threshold parameters	string
threshold(s)	one or two threshold levels (e.g., upper/lower tolerance values) for each variable to be observed	real
comparison mode	mode of comparing the observation variable with the defined threshold(s) (e.g., "larger / less than" or "within / outside the band" in the case of two thresholds)	string

Once the observation threshold is violated, a counter shall be triggered that will activate the countermeasure(s) of the associated rule when the "holding time" is exceeded (see Table 38).

Table 40 defines the general interface (signal list) for characterizing the corresponding countermeasure action(s) of a rule. Every defined countermeasure shall be associated with at least one rule.

Table 40 – General interface (signal list) for defining countermeasures of rules

Interface Parameter	Characteristic	Format
countermeasure ID	unique identifier of the corresponding countermeasure action	integer
converter ID	ID of the HVDC station where this rule is to be implemented	integer
parameter	DC node voltage control parameter that will be modified by this rule (i.e., set point value, droop parameter, etc.)	string
modification mode	type of modification that is performed on the respective parameter (e.g., "discard old and replace by new", "add delta value", multiply by factor, etc.)	string
modification value	value of the implemented modification (effect depends on the type of modification)	real

6.2.4.3 HVDC grid control

The general propagation of information in the HVDC grid is given by the "converter schedules" as defined in Table 43. These represent the flow of orders and parameters from the AC/DC grid control at the top layer to the DC node voltage control at the bottom layer (see Figure 8).

In addition to this, the interface parameters from Table 41 are required from the HVDC grid control layer to control and coordinate the connections of all HVDC stations to the HVDC grid. As for the converter schedules, these interface parameters always refer to a specific HVDC station.

Table 41 – Interface parameters required from the HVDC grid control layer

Interface Parameter	Characteristic	Format
DC connection mode (HV poles)	request for the respective HVDC station to change its DC connection to this new mode (see 8.4.2.1, 9.2.3.2.1 and Table 55 for definition of possible transitions)	integer
earthing (neutral point)	request to switch-on the earthing or remove it from the neutral point of the HVDC station	boolean
switching time	desired time for putting the requested changes on DC connection mode or earthing into effect; this shall be a reasonable point of time in the future	real / time
rule management	(temporary) activation or deactivation of rules in the autonomous adaptation layer (see Table 38); this can be required in the case of active rules preventing a superordinate coordination by the HVDC grid control	boolean

6.2.5 AC/DC grid control

According to the current market conditions, all relevant TSOs will add their active and reactive power orders as defined by the list in Table 42, indicating a general interface (signal list).

The corresponding parameters have to be given for each HVDC station.

Table 42 – General interface (signal list) for orders from TSOs

Interface parameter	Characteristic	Format / Unit
P_{ACorder}	desired active power for a given HVDC station / PoC-AC for the next dispatch or control cycle	MW
Δp_{ramp}	desired ramp rate for implementing the desired active power reference value at the given HVDC station	MW/s
Q_{order}	desired reactive power for a given HVDC station / PoC-AC for the next dispatch or control cycle	Mvar
Δq_{ramp}	desired ramp rate for implementing the desired reactive power reference value at the given HVDC station	Mvar/s

The following information is relevant:

- Subclause 5.4.

6.3 Propagation of information

For convenience, the principal signal exchange is again illustrated in Figure 8. This shows the top-down propagation of the dispatched converter schedule (black arrows) as well as the bottom-up back propagation of modifications and station information (blue arrows).

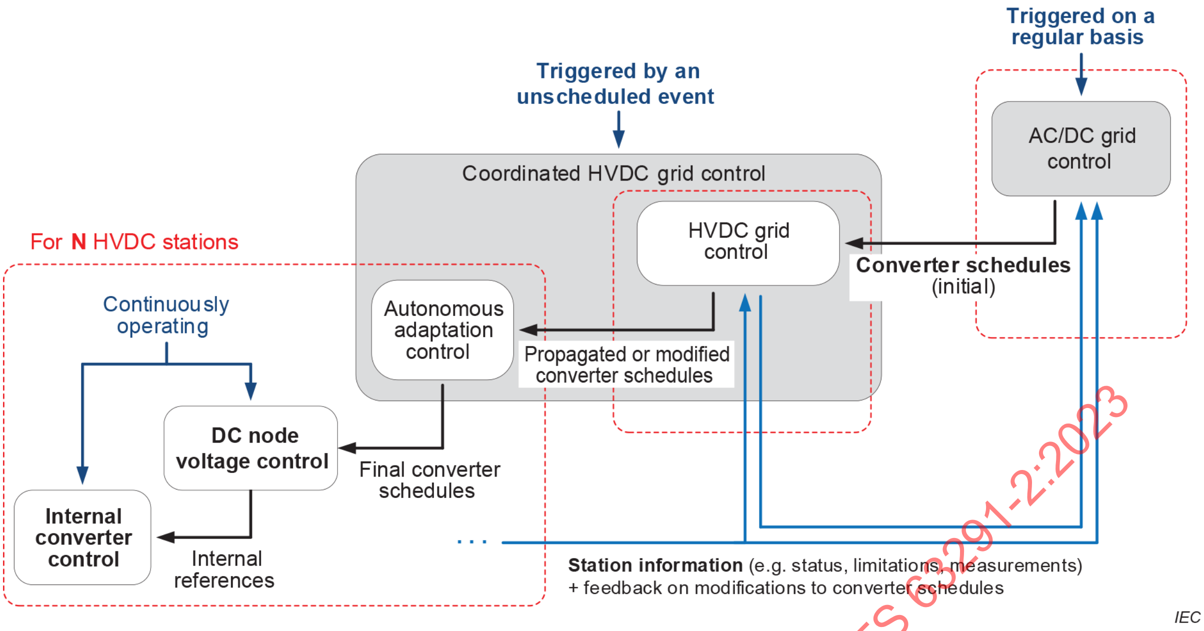


Figure 8 – Generation of final converter schedules including converter control modes and its parameters

The definition of the "converter schedules" is given in Table 43 in the form of a general interface (signal list).

Note that this constitutes the minimum set of information that is required for control functions in the individual control layers.

The interface and the flow of information in Figure 8 only applies to HVDC stations that can actively control the power exchange with the HVDC grid.

Table 43 – General interface (signal list) defining a "converter schedule"

Interface parameter	Characteristic	Format / Unit
active power reference	desired steady-state active power at the point of control	MW
DC voltage reference	desired steady-state DC voltage at the point of control	kV
reactive power reference	desired steady-state reactive power at the point of control	Mvar
AC voltage reference	desired steady-state AC voltage at the point of control	kV
control mode	control mode for DC quantities; each mode shall be specified by a unique integer number that shall be consistent throughout the HVDC grid	integer
parameters for control mode	additional parameters for the chosen control mode (e.g. droop characteristics), see Table 36	real
active power ramp rate	speed of implementing the desired active power reference value at the given HVDC station	MW/s
reactive power ramp rate	speed of implementing the desired reactive power reference value at the given HVDC station	Mvar/s
DC voltage ramp rate	speed of implementing the desired DC voltage reference value at the given HVDC station	kV/s
AC voltage ramp rate	speed of implementing the desired AC voltage reference value at the given HVDC station	kV/s

The schedules are initially dispatched by the highest-level controls (AC/DC grid control) and propagated through all lower-level control layers.

Each HVDC station receives its own converter schedule, comprising values for both active and reactive power control, if any. During normal operation, this converter schedule has to be respected by the AC/DC converter station until the next dispatch cycle.

If modifications to one or more dispatched values in the converter schedule are performed by lower-level controls (if e.g., required due to short-term contingencies) as illustrated in Figure 6, these changes shall be reported back to the higher-level control layers. This information is to be incorporated into the station information (blue arrows in Figure 8).

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 9.

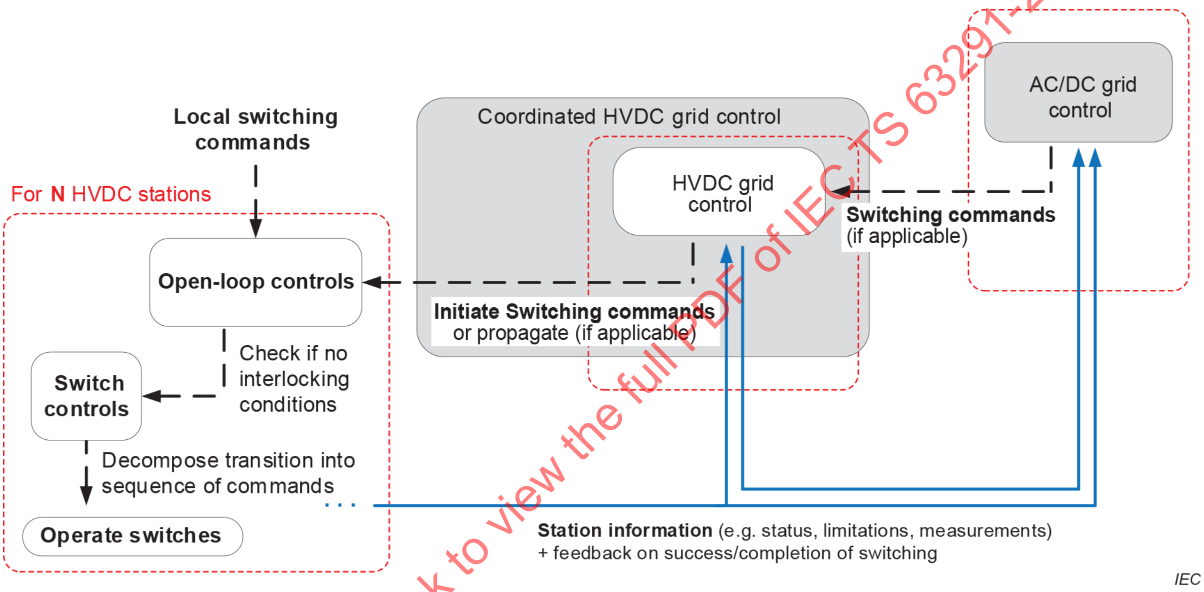


Figure 9 – Propagation of switching commands to individual HVDC stations

As for the converter schedules, the minimum set of information for the switching commands is summarised in the interface list of Table 44. The definition of the connection modes is given in 8.4.2.1 for converter stations and in 9.2.3.2.1 for switching stations.

Table 44 – General interface (signal list) defining "switching commands"

Interface parameter	Characteristic	Format / Unit
DC connection mode	Desired (next) connection mode to which the PoC-DC should be switched.	
Earthing mode	Desired (next) earthing mode to which the HVDC station should be switched.	

According to the distinction between the converter schedule and the switching commands, the "station information" for reporting the conditions of the HVDC stations back to the higher-level controls is also split in two parts:

- information on the physical quantities of the HVDC station is given in Table 45,
- information regarding the control states of the HVDC station is given in Table 46.

This constitutes the minimum set of information that is required as feedback for control functions in the higher-level control layers.

Table 45 – General signal interface (physical quantities) of the "station information"

Symbol	Interface parameter	Characteristic	Value	Format/ Unit
P_{meas}	measured active power	measured active power at this HVDC station. Since this is propagated to the higher levels of the HVDC grid controls, this will typically refer to DC power.		MW
U_{DCmeas}	measured DC voltage	actual measured DC voltage at each of the PoC-DC at the HVDC station.		kV
Q_{meas}	measured reactive power	actual measured reactive power at this HVDC station.		Mvar
U_{ACmeas}	measured AC voltage	actual measured AC voltage at the PoC -AC of the HVDC station.		kV
P_{max}, P_{min}	power limitations	limitations for the active power capability of this HVDC station. These may be different from the actual rating due to external influences and internal design parameters (e.g. state of cooling system, power electronics, etc.) refer to Table 2.		MW
Q_{max}, Q_{min}	Reactive power limits	limits for the reactive power capability of the converter station		Mvar
U_{DCmax}, U_{DCmin}	DC voltage profile(s)	tolerable maximum and minimum values for the DC voltage and allowed durations, may be different for each PoC-DC depending on type of connected HVDC line (e.g. submarine cable), has to account for manufacturer's transient over-voltage specifications (refer to Table 21 for the definition of voltage profiles)		list of tuples: kV, s

Table 46 – General signal interface (control parameters) of the "station information"

Interface parameter	Characteristic	Format/ Unit
active control mode	active control mode of this HVDC station	integer
parameters for active CM	all required parameters for the currently active control mode of HVDC station	various, real-valued
DC connection mode	current DC connection mode (HV poles) for the given HVDC station	integer / string
DC connection options	options for possible transitions of the DC connection mode (see 8.4.2.1, 9.2.3.2.1 and Table 55); only required if transitions are to be coordinated globally by the HVDC grid control	integer / string
earthing mode	current earthing mode of the HVDC station (e.g. none, solid or via arrester)	integer / string
earthing mode options	options for changing the earthing of the HVDC station during operation (if any)	integer / string
limitation strategy	priority of power limitation strategy, i.e., if active or reactive power will be limited first (see Table 64)	integer
state of limitation	indication of whether limitation is currently active in the HVDC station. If active, the result of the limitation can be observed by comparing the reference values (Table 43) to the max/min values (signalled by this Table 45)	boolean
operating state	state in which the HVDC station is currently operating (see Figure 10)	integer
autonomous adaptation controls status	indication of whether autonomous adaptation controls are generally enabled for the respective HVDC station (if applicable).	Boolean
active autonomous adaptation control rule	ID of the currently active rule (if any) of the autonomous adaptation controls of the HVDC station. The set of rule IDs shall be consistent throughout the HVDC grid.	Integer

6.4 Open-loop controls

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

The reconfiguration timings as specified in Table 55 (AC/DC converter stations) or Table 71 (DC switching stations), respectively are relevant.

6.4.2 Operating sequences for HVDC grid installations

Figure 10 illustrates the principal state transitions for equipment in HVDC grids.

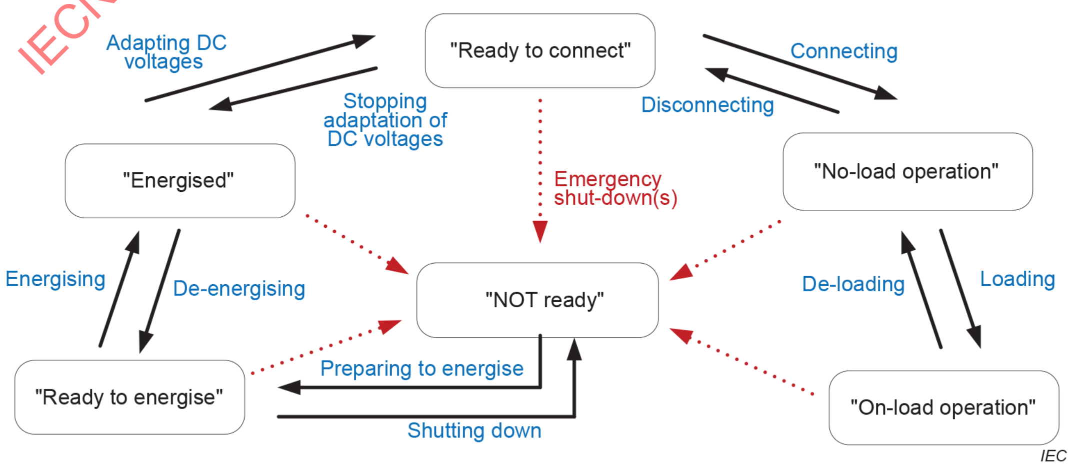


Figure 10 – Operating sequences as transitions between operating states

The parameters in Table 47 are required in order to provide a unified description for operating sequences.

Table 47 – Unified description of operating sequences

Symbol	Parameter	Characteristic	Value	Unit
$t_{\max X}$	Maximum time for step "X"	maximum tolerable duration after which sequence step "X" has to be completed. This may refer to commands or status messages in the control system as well as feedback messages from any associated primary components (e.g. switching components).		S
$t_{\text{max\_seq}}$	maximum time for sequence completion	maximum time allowed for completing an operating sequence. This has to be specified in order to guarantee a timely response of the HVDC station. If this time is exceeded, the requested operation is set to status "failed".		S
ΔU_{DCdiff}	DC voltage	maximum difference between measured DC voltage on the terminals of a switch before closing the switch		V
ΔI_{DCres}	DC current	maximum residual DC current before opening the switch.		A

6.4.3 Post-DC fault recovery

The parameters are listed in Table 48.

Table 48 – Parameters for recovery sequences after DC line faults

Symbol	Parameter	Characteristic	Value	Unit
t_{deion}	time chosen to account for de-ionization	duration after which the air surrounding the faulty element (e.g. arc) is expected to be deionised such that a certain withstand voltage can be achieved.		S
$t_{\text{U\_DC90}}$	time of DC voltage recovery	time after which the DC voltage has recovered to 90 % of its target value.		S
$t_{\text{P\_DC90}}$	time of active power restoration	time after which the active power flow has been restored to 90 % of its target value (at all affected converters).		S
$N_{\max}$	maximum number of recovery attempts	number of attempts to perform a recovery. If the number of unsuccessful trials in restoration of power transmission reaches this number, the recovery sequence will be stopped.		Intege r

7 HVDC grid protection

7.1 General

NOTE The parameters to define the protections in an HVDC grid depend on the basic concept of converter operation.

7.2 DC fault separation

The following information is relevant:

- Subclause 5.4,
- Subclause 5.5,
- Subclause 4.3.

7.3 Protection system related installations and equipment

7.3.1 AC/DC converter station

No parameters identified.

7.3.2 HVDC grid topology and equipment

A single line diagram shall be specified including relevant equipment.

7.4 HVDC grid protection zones

7.4.1 General

Split the HVDC grid into individual protection zones and provide the HVDC grid protection matrix by defining continuous operation (CO), temporary stop P (TS-P), temporary stop PQ (TS) or permanent stop (PS) for DC fault behaviour at each PoC-AC or PoC-DC with respect to every zone. An example of a protective matrix is given in Table 49. Table 50 lists additional parameters, which apply depending on the selected fault separation concept. Figure 11, Figure 12 and Figure 13 show example voltage and current traces for the three fault separation concepts.

Table 49 – Example of an HVDC grid protection zone matrix

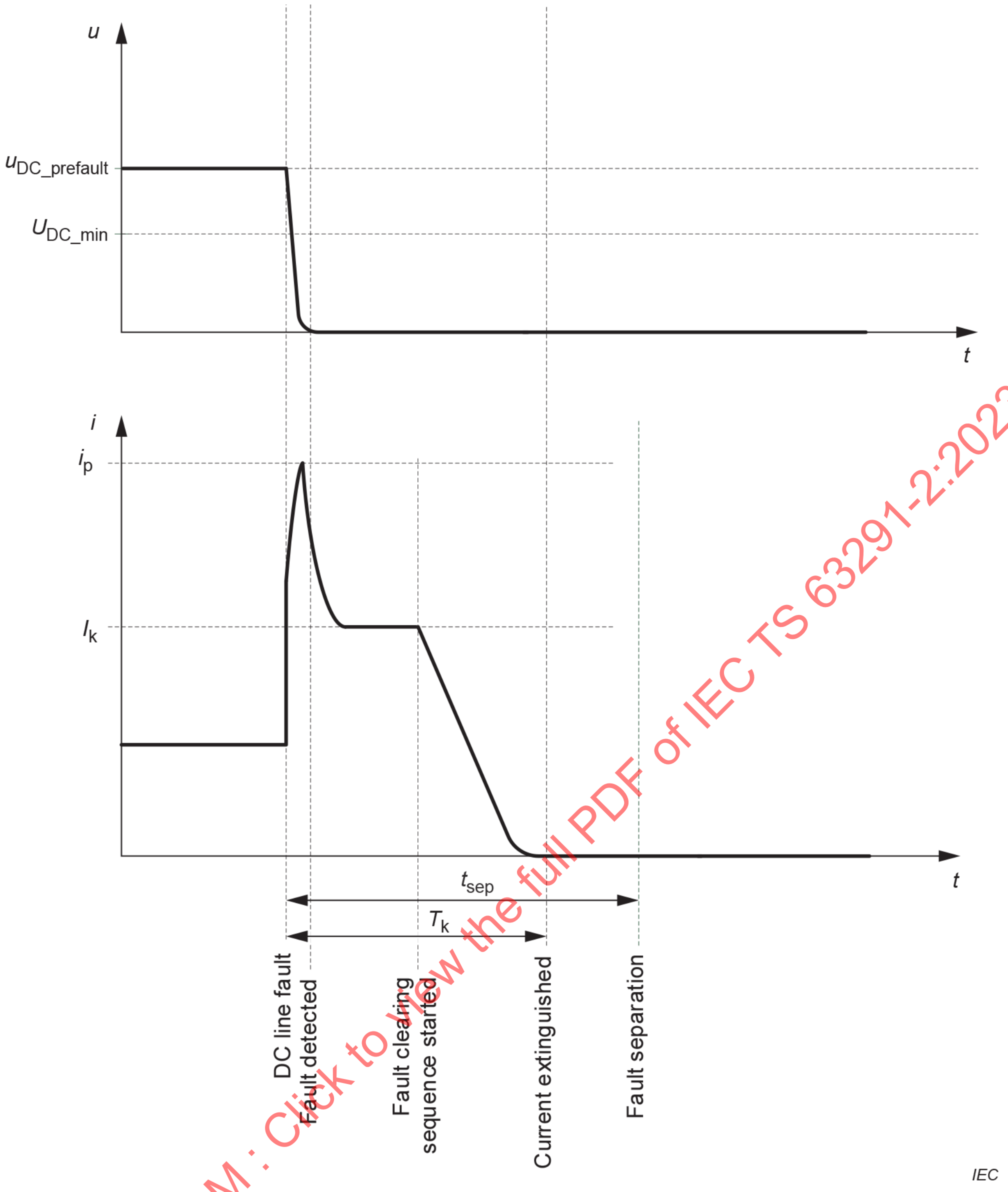
Faults in	PoC-AC1	PoC-AC2	PoC-DC1	PoC-DC2
Zone 1				
Zone 2				
Zone 3				
Zone 4				

Table 50 – DC protection parameter list

Symbol	Parameter	Characteristic	Value	Unit
$M_{\mathrm{l\_PZ}}$	protection zones	sparse matrix (number of PoC over number of protection zones) 1 indicates the existence of a line between two nodes and its belonging to a specific protection zone		matrix
t_{sep}	fault current separation time	maximum time, see Figure 10		ms
$I_{\mathrm{DC\_Comax}}$	DC current	maximum DC current in unfaulty system for DC fault ride through in the DC fault separation concept "continuous operation"		kA
$I_{\mathrm{k\_res}}$	DC current	steady-state residual short-circuit current (band)		kA

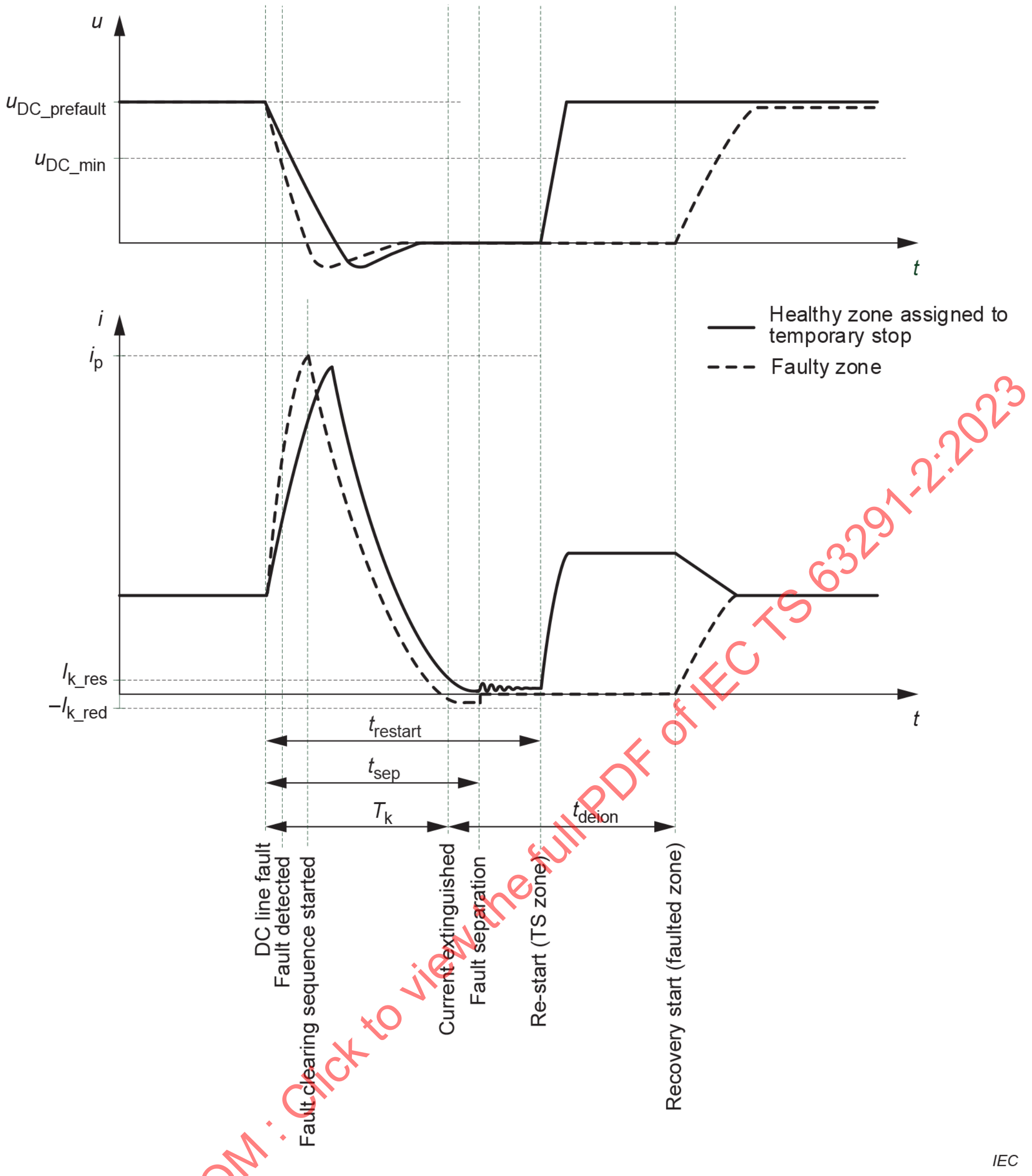
In addition, the following information is relevant:

- Table 30, i_p, I_{k}, T_{k};
- Table 48, t_{deion};
- Subclause 5.4: DC voltage level $U_{\mathrm{DCpole\_min}}$.



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



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

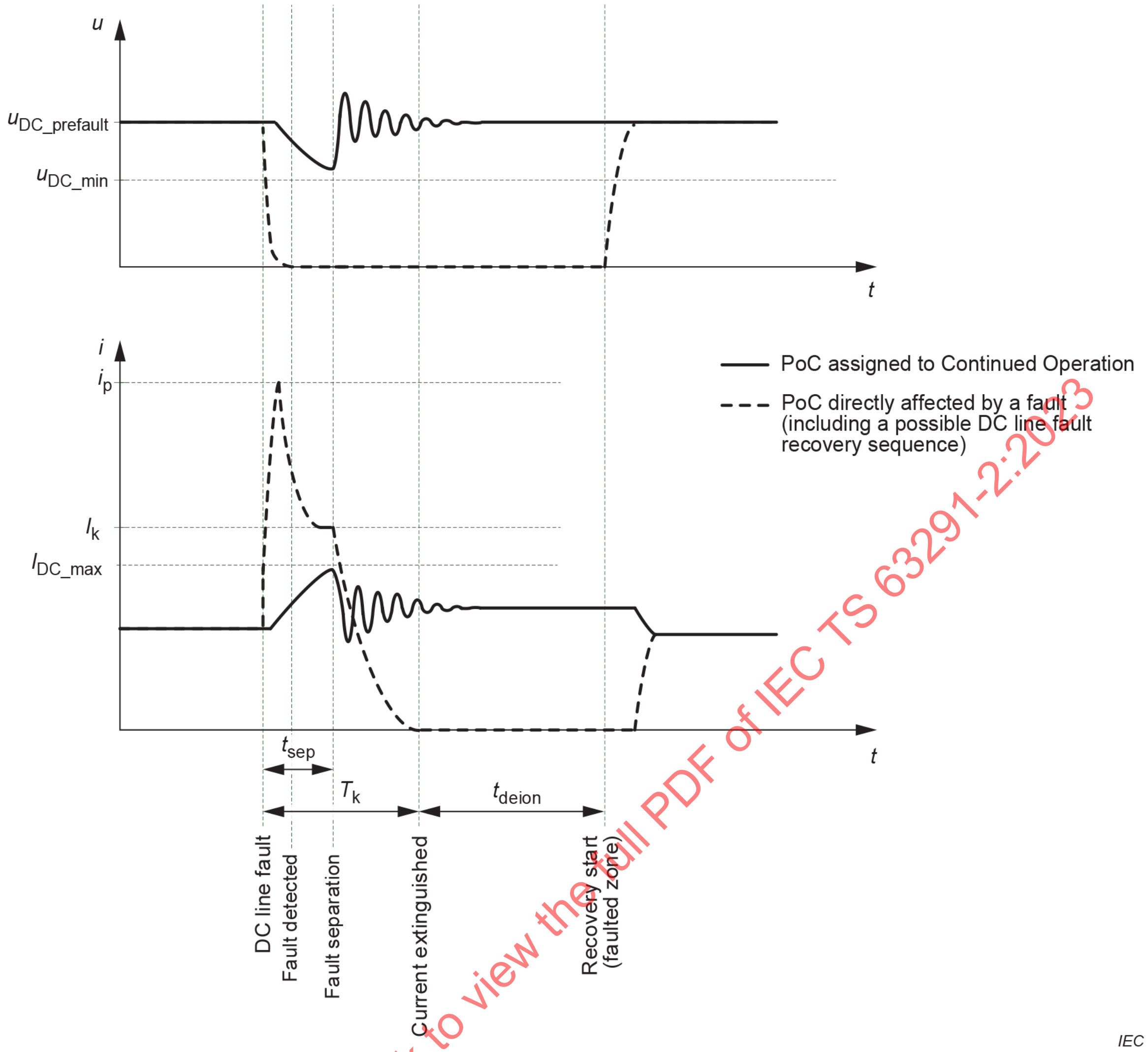
u_{DC_min} minimum DC voltage

t_{sep} separation time

$t_{restart}$ restart start time of healthy section

t_{deion} deionisation time

Figure 12 – Example voltage and current traces in the event of "temporary stop P"



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

7.4.2 Permanent stop P

The following functions shall be specified:

- Fault detection (differentiating faults from system transients that do not lead to protection actions);
- Fault identification including:
  - – classification (type of fault)
  - – fault location (location of the faulty HVDC grid or device).

Parameters to be specified shall be according to the protection concept chosen and HVDC grid capabilities.

7.4.3 Permanent stop PQ

The following functions shall be specified:

- Fault detection (differentiating faults from system transients that do not lead to protection actions);
- Fault identification including:
  - classification (type of fault)
  - fault location (location of the faulty HVDC grid or device).

Parameters to be specified shall be according to the protection concept chosen and HVDC grid capabilities.

7.4.4 Temporary stop P

The following functions shall be specified:

- Fault detection (differentiating faults from system transients that do not lead to protection actions);
- Fault identification including:
  - classification (type of fault)
  - fault location (location of the faulty HVDC grid or device).

Parameters to be specified shall be according to the protection concept chosen and HVDC grid capabilities.

The tolerable time for temporary stop is specified in Table 7.

7.4.5 Temporary stop PQ

The following functions shall be specified:

- Fault detection (differentiating faults from system transients that do not lead to protection actions);
- Fault identification including:
  - classification (type of fault)
  - fault location (location of the faulty HVDC grid or device).

Parameters to be specified shall be according to the protection concept chosen and HVDC grid capabilities.

The tolerable time for temporary stop is specified in Table 7.

7.4.6 Continued operation

No parameters identified.

7.4.7 Example of a protection zone matrix

No parameters identified.

7.5 DC protection

7.5.1 General

No parameters identified.

7.5.2 DC converter protections

One threshold and time is given as parameters in Table 51, but it could be required to give several thresholds or an inverse time characteristic.

Table 51 – DC converter protection parameter list

Symbol	Parameter	Characteristic	Value	Unit
$U_{DCunbal}$	threshold	DC voltage unbalance		kV DC
$t_{DCunbal}$	time	time of DC voltage unbalance		ms

In addition, the following information is relevant:

- Subclause 5.4; DC voltages (rated DC voltage, steady-state DC voltages, temporary DC voltages).

7.5.3 HVDC grid protections

7.5.3.1 General

No parameters identified.

7.5.3.2 Fault detection based on communication

No parameters identified.

7.5.3.3 Fault detection without communication

No parameters identified.

7.5.4 HVDC grid protection communication

No parameters identified.

8 AC/DC converter stations

8.1 Purpose

This Clause 8 summarizes the HVDC grid-specific requirements for AC/DC converter stations. A complete specification of each AC/DC converter station in the HVDC grid shall be provided.

8.2 AC/DC converter station types

The type of each converter of the AC/DC converter station shall be specified.

8.3 Overall requirements

8.3.1 Robustness of AC/DC converter stations

The required operating range of the AC/DC converter station specified shall cover all relevant AC grid and HVDC grid conditions.

8.3.2 Availability and reliability

The requirements for availability and reliability of an AC/DC converter station shall be specified according to overall transmission system planning aspects.

For the reliability as well as availability calculation method, reference is made to Cigre Technical Brochure 713 [12].

8.3.3 Active power reversal

The following shall be specified:

- Type of power reversal:
  a) By voltage reversal ☐
  b) By current reversal ☐
- Sequence and time for power reversal.

8.4 Main circuit design

8.4.1 General characteristics

8.4.1.1 Topology

The station topology shall be specified by the station code as shown in Table 52 according to the following criteria:

- 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).

Table 52 – Converter station topology

Criteria	Connection to pole	Neutral return path	Station earthing
options	"1" pole 1 "2" pole 2 "B" both	"O" none "R" return conductor "E" earth electrode	"O" none "Z" impedance "E" direct
station code			

8.4.1.2 Active and reactive power characteristics

The active and reactive power characteristics shall be specified according to Table 2. All active and reactive power characteristics shall be stated with respect to a given AC system voltage operating range.

The power flow shall be specified such that the power exchange of an AC/DC converter station operating in rectification mode (rectifier) shall be counted positive, i.e., power flowing from the PoC-AC into the converter and further on from the converter into the PoC-DC shall have positive sign.

8.4.1.3 Energisation

The requirement regarding the energy source for the energisation shall be specified:

- energisation from AC side,
- energisation from DC side,

- energisation with auxiliary power.

Further requirements for energisation are:

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

8.4.1.4 Energy dissipation/absorption capability

The information listed in Table 53 shall be specified as a minimum requirement for the PoC-AC and the PoC-DC.

Table 53 – Energy dissipation/absorption capability at a PoC

Symbol	Parameter	Characteristic	Value	Unit
$E_{D/A}$	power versus time P=f(t) integrated	worst case power versus time characteristic integrated to outline energy dissipation/absorption capability requirement		MWs
no symbol	number of events	number of energy dissipation/absorption events		integer
$t_{min\_D/A}$	minimum time	minimum time between consecutive energy dissipation/absorption events		min

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 Table 52. A given 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 and shall be specified using Table 54.

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

Ux converter unit x

Ty terminal y

UxTy 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 is more than one return path connection point, the connection points are numbered (Ry, y being 1 or 2)

Table 54 – DC connection modes of the AC/DC converter station

Connection mode		U1T1	U1T2	U2T1	U2T2
Mode 1	*name*				
Mode 2	*name*				
Mode 3	*name*				
Mode 4	*name*				

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

The maximum transition time requirements for reconfiguration 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 in accordance with Table 55.

Table 55 – DC circuit re-configuration time requirements

Previous connection mode S_x	Next connection mode S_y				
	Mode 1	**Mode 2**	**Mode 3**	**...**	**Mode *n***
Mode 1		$t_{\max 12}$	$t_{\max 13}$	…	$t_{\max 1n}$
Mode 2	$t_{\max 21}$		$t_{\max 23}$	…	$t_{\max 2n}$
Mode 3	$t_{\max 31}$	$t_{\max 32}$		…	$t_{\max 3n}$
…	…	…	…		…
Mode *n*	$t_{\max n1}$	$t_{\max n2}$	$t_{\max n3}$	…	
$t_{\max xy}$: time for transition between previous connection mode S_x and next connection mode S_y					

8.4.2.1.2 Neutral point earthing

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 parameters of the earthing branch shall be specified according to Table 26.

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

8.4.2.2 DC voltages

The values according to

- Table 19 (nominal DC system voltage),
- Table 20 (DC pole voltage range parameters at a PoC-DC of an HVDC station, steady-state),
- Table 21 (DC pole voltage range parameters at a PoC-DC of an HVDC station, temporary undervoltages); and
- Table 22 (DC pole voltage range parameters at a PoC-DC of an HVDC station, temporary overvolatges)

shall be specified.

8.4.2.3 DC insulation Levels

The values according to Table 24 shall be specified.

8.4.2.4 DC fault ride through behaviour

The behaviour at the PoC-AC in response to an insulation fault appearing at the PoC-DC of the converter station shall be specified according to one of the following fault separation concepts:

- permanent stop PQ ☐
- permanent stop P ☐
- temporary stop PQ ☐ maximum time: ______s
- temporary stop P ☐ maximum time: ______s
- continued operation ☐

The repetition of DC fault events and recovery attempts shall be specified according to Table 56.

Table 56 – Repetition of DC fault events and recovery attempts

Symbol	Parameter	Characteristic	Value	Unit
$n_{DCfault}$	number of events	number of subsequent fault events		integer
$n_{DCrecovery}$	repetition	number of recovery attempts for each DC fault		integer
$t_{ACrecovery}$	restoration time	maximum time to restore full DC fault ride through capabilities		min

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

No parameters identified.

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 in addition to the parameters in Table 57:

- equivalent circuit of the system to be de-energised including, if any, OHLs, cables and other converter stations;
- equivalent impedances of all relevant components, especially its capacitances.

Table 57 – DC circuit energisation

Symbol	Parameter	Characteristic	Value	Unit
U_{DCres_en}	residual voltage	residual DC voltage prior to energization		kV DC
U_{DCmin_en}	lower voltage limit	lower voltage limit of target voltage band for energisation		kV DC
U_{DCmax_en}	upper voltage limit	upper voltage limit of target voltage band for energisation		kV DC
$U_{DCtempOV\_en}$	temporary overvoltage	maximum temporary overvoltage limit for energisation		kV DC
$U_{DCtempUV\_en}$	temporary undervoltage	maximum temporary undervoltage limit for energisation		kV DC
t_{min_en}	time	minimum time to bring the DC voltage within the target voltage band		s
t_{max_en}	time	maximum time to bring the DC voltage within the target voltage band		s
$\hat{I}_{ch\_max\_en}$	charging current	maximum charging current		kA peak
$E_{ch\_max\_en}$	energy	maximum charging energy		W
n_{max_en}	repetition	maximum number of repetitive energisation events		integer

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

The parameter listed in Table 58 shall be specified.

Table 58 – Connecting the AC/DC converter station

Symbol	Parameter	Characteristic	Value	Unit
ΔU_{DCconn}	voltage	maximum voltage across open contacts of switching device before connecting		kV DC

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

The parameter listed in Table 59 shall be specified.

Table 59 – Disconnecting the AC/DC converter station

Symbol	Parameter	Characteristic	Value	Unit
ΔI_{DCres}	current	maximum residual DC current through switching device before disconnecting		A DC

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 in addition to the parameters in Table 60:

- equivalent circuit of the system to be de-energised including, if any, OHLs, cables and other converter 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 keep the DC voltage within the target minimum voltage band;
- maximum discharging current (peak value).

Table 60 – DC circuit de-energisation

Symbol	Parameter	Characteristic	Value	Unit
$U_{DCres\_max\_de}$	residual voltage	maximum residual voltage after de-energisation		kV DC
U_{DCrev_de}	voltage reversal	maximum DC voltage reversal due to discharging the DC circuit		kV peak
t_{min_de}	time	minimum time to bring the DC voltage below the maximum residual voltage after de-energisation		s
t_{max_de}	time	maximum time to bring the DC voltage below the maximum residual voltage after de-energisation		s
$\hat{I}_{dch\_max\ \_de}$	discharging current	maximum discharging current		kA peak
$E_{ch\_max\_de}$	energy	maximum discharging energy		kW
n_{max_de}	repetition	maximum number of repetitive de-energisation events		boolean

8.4.2.5.2 Breaking DC fault currents

The DC fault current breaking capabilities shall be specified according to 5.6. In addition, the following information is required as a minimum set of requirements:

- equivalent circuit of the DC system,
- equivalent impedances of all relevant components,
- number of consecutive faults (see Table 56),
- number of recovery attempts (see Table 56),
- the possibility of AC/DC intersystem faults, if any, together with the relevant AC system data, such as AC system short-circuit current or nominal AC system voltage.

8.4.2.6 Fault current levels

8.4.2.6.1 Contribution to short-circuit currents

The maximum contribution and the minimum contribution, if any, to DC short-circuit currents shall be specified according to 5.6.

8.4.2.6.2 Short-circuit current withstand capability

The maximum pre-existing DC short-circuit current level for the PoC-DC shall be specified according to Table 30.

The maximum required total DC short-circuit current withstand capability for the PoC-DC, including the AC/DC converter station, shall be specified according to Table 30.

As an alternative to the requirements in the above two paragraphs, all relevant parameters of each individual grid component of the whole HVDC grid shall be specified for the calculation of the relevant short-circuit current withstand capability as described in 5.6.

8.4.2.7 DC side system restoration

The capabilities of the AC/DC converter station to restore the HVDC grid or parts thereof after blackout shall be specified using a simplified representative test network.

The following information shall be specified for the representative test network:

- philosophy and procedures including sequences for restoring the real network including all relevant scenarios until reaching the normal operating state;
- 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.

8.4.2.8 Steady-state DC voltage and current distortions

The steady-state DC voltage and current distortions shall be specified according to 5.7.

8.4.3 AC side

8.4.3.1 AC voltages

The AC voltage profile shall be specified according to 4.5.2.3.

8.4.3.2 AC fault ride through behaviour

The AC overvoltage and undervoltage fault ride through profiles are typically defined by the AC grid codes. The profiles shall be specified by a voltage versus time characteristic as described in 4.5.2.3.

8.4.3.3 AC frequency

The response in active power to frequency deviations in frequency sensitive mode (FSM), limited frequency sensitive mode – over-frequency (LFSM-O) and limited frequency sensitive mode – under-frequency (LFSM-U) shall be specified according to Table 11.

8.4.3.4 AC side fault current contribution

The AC fault current contribution required from the converter station shall be specified according to the corresponding AC grid code requirements.

8.4.3.5 Capability of switching and breaking AC currents

The relevant data for designing the switching devices (CBs, disconnectors and earthing switches) shall be specified according to Table 6.

8.5 HVDC grid control and protection interface

The C&P equipment of the AC/DC converter station shall be provided with the necessary interfaces to subsystems such as:

- control equipment,
- operator controls,
- switching devices,
- measuring system,

- fault recorder.

The following information is relevant:

- Table 43, General interface (signal list) defining "converter schedules";
- Table 45, General signal interface (physical quantities) of the "station information";
- Table 46, General signal interface (control parameters) of the "station information".

8.6 Controls

8.6.1 General

8.6.2 Automated vs manual operation

Table 61 summarises the most important parameters that shall be specified for the communication abilities of each AC/DC converter station.

Table 61 – Parameters for the automatic control interface of the AC/DC converter station according to standard protocols

Symbol	Parameter	Characteristic	Value	Unit
no symbol	protocol	information on standard protocol types to be used for communication (i.e. Ethernet/LAN, IEC 61850 or else). Any degrees of freedom on the actual implementation of such protocols shall be defined further (e.g. sampling rate, header sizes, package lengths, coding/protection methods etc.)	N/A	various

Table 62 lists parameters used for the automatic control interface of an AC/DC converter station according to proprietary protocols.

Table 62 – Parameters for the automatic control interface of the AC/DC converter station according to proprietary protocols

Symbol	Parameter	Characteristic	Value	Unit
no symbol	communication rate	The data sampling rate for communication has to be specified (i.e. how often new values are generated and received). This shall be taken into account for the design of the "Converter Schedule".	N/A	Hz
no symbol	data package sizes and data type(s)	The size and resolution of all transmitted data packages shall be agreed upon.	N/A	various

In addition to this, the following information is relevant:

- definition of "converter schedule" (see Table 43);
- definition of "station information" (see Table 45).

8.6.3 Control modes and support of coordination

Table 63 outlines the possible control modes that can be provided by an AC/DC converter station. It shall be specified whether the station shall be able to operate in all these modes (depending on technology, etc.). Availability of options may therefore be indicated by checkboxes.

Table 63 – Parameters for the available control modes of the AC/DC converter station

Symbol	Parameter	Characteristic	Value	Unit
no symbol	active power control modes	This information defines a list of (core) control modes related to active power regulation at the converter station's PoC-AC or PoC-DC. These modes may comprise: • constant DC voltage • constant DC current • constant DC power • constant AC active power • DC voltage / current droop • DC voltage / power droop • DC voltage / AC active power droop • constant AC frequency • AC active power / frequency droop	N/A	boolean
no symbol	reactive power control modes	This information defines a list of (core) control modes for regulation of reactive power at the PoC-AC of the station. These modes may comprise: • constant AC reactive power (Q) • constant power factor (cosϕ) • AC reactive power / voltage droop	N/A	boolean
no symbol	supporting controls	Information on availability of controls supporting the coordination within the HVDC grid (e.g. for damping functions): • "delta P" modulation (active power) • "delta Q" modulation (reactive power)	N/A	boolean

8.6.4 Limitation strategies

The parameters are listed in Table 64.

Table 64 – Limitation strategies

Symbol	Parameter	Characteristic	Value	Unit
no symbol	priority mode	• 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 • symmetrical: constant cos(ϕ) • asymmetrical: weighting factors	N/A	N/A
no symbol	criteria	applicable criteria for entering and leaving the limiting strategy.	N/A	N/A

8.6.5 Operating sequences for AC/DC converter station

Required parameters for specification of operating sequences are summarised in Table 65.

Table 65 – Operating states and transitions for the AC/DC converter station

Symbol	Parameter	Characteristic	Value	Unit
$t_{\mathrm{min},X}$	minimum duration in state "X"	This time defines the minimum time for remaining in a given state X, if applicable	N/A	s
$t_{\mathrm{max},X}$	maximum duration in state "X"	This time defines the maximum allowed duration for remaining in a given state X NOTE For some states, $t_{\mathrm{max},X}$ can also be unlimited	N/A	s
Fallback$_X$	fallback state	For each state X, a corresponding fallback state has to be specified that will be attained in case of error during state X (e.g. after the maximum duration for that state is exceeded)	N/A	integer

8.6.6 Dynamic behaviour

8.6.6.1 Step responses

The requirements for the dynamic behaviour of the AC/DC converter station 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

The necessary tests conditions shall be specified in order to demonstrate stability of the AC/DC converter station when operated in the respective HVDC grid. The requirements shall be defined in line with 10.2.3.

8.7 Protection

8.7.1 General

8.7.2 Configuration requirements

The protection zones and the configuration of the FSDs with respect to these zones shall be specified.

8.7.3 Function requirements

8.7.3.1 Converter unit protection zone

The fault locations to be selectively detected as a minimum shall be specified.

8.7.3.2 DC line protection zone

The fault locations to be selectively detected as a minimum shall be specified.

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.

8.7.5 Coordination of the DC protection with the HVDC grid

The protection coordination of an AC/DC converter station and the HVDC grid shall be specified according to Table 66.

Table 66 – Protection coordination of the AC/DC converter station and the 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 requirement	Sep. concept (FSD)	Detection requirement	Sep. concept (FSD)	Detection requirement	Sep. concept (FSD)	Detection requirement
Zone 1								
Zone 2								
…								
Zone n								

8.7.6 Example for coordination of the DC protection with the HVDC grid

No parameters identified.

9 HVDC grid installations

9.1 General

No parameters identified.

9.2 DC switching station

9.2.1 Purpose

A specification of each DC switching station in the HVDC grid shall be provided.

The electrical connections to be provided by a DC switching station shall be specified using an equivalent circuit diagram.

Besides the mandatory functions, all required optional functionality shall be specified.

9.2.2 Overall requirements

9.2.2.1 Coordination and communication

Except for local protection functions, all switching and reconfiguration actions at the DC switching station shall be coordinated with the surrounding HVDC grid.

9.2.2.2 Availability and reliability

For the reliability as well as availability calculation method, reference is made to Cigre Technical Brochure 713 [12].

9.2.3 Main circuit design

9.2.3.1 General characteristics

9.2.3.1.1 Topology

The DC switching station topology shall be specified by the station code as shown in Table 67 according to the following criteria:

- 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).

Table 67 – DC switching station topology

Criteria	Connection to pole	Neutral return path	Station earthing
options	"1" pole 1 "2" pole 2 "B" both	"O" none "R" return conductor "E" earth electrode	"O" none "Z" impedance "E" direct
station code			

9.2.3.1.2 Active power characteristics

Refer to 9.2.3.1.4.

9.2.3.1.3 Energisation of the DC switching station

The requirement regarding the energy source for the energisation shall be specified:

- energisation from DC side,
- energisation with auxiliary power.

Further requirements for energisation are:

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

9.2.3.1.4 Energy dissipation and absorption capability

A DC switching station can be equipped with additional devices providing temporary active power exchange with the HVDC grid. In this case the information listed in Table 68 shall be specified as a minimum requirement.

Table 68 – Temporary energy dissipation/absorption capability of the DC switching station

Symbol	Parameter	Characteristic	Value	Unit
$E_{D/A}$	power versus time P=f(t) integrated	worst case power versus time characteristic integrated to outline energy dissipation/absorption capability requirement		MWs
$n_{max\_D/A}$	number of consecutive events	maximum number of consecutive energy dissipation/absorption events		integer
$\Delta t_{min\_D/A}$	minimum time	minimum time between consecutive energy dissipation/absorption events		min

DC line power flow controllers can be used in a DC SU to modulate the DC voltage at the PoC-DC for the purpose of controlling the power flow through the connected line in steady state and dynamically. In this case the information listed in Table 69 shall be specified as a minimum requirement.

The power flow control function in one SU may be coordinated with one or more other Sus of the DC switching station to balance the power exchange inside the HVDC grid. Any such requirement shall be specified.

Table 69 – Power flow controlling capability of a DC SU

Symbol	Parameter	Characteristic	Value	Unit
U_{mod_pos}	voltage increase	maximum value of the DC voltage modulation at the PoC-DC in positive direction, i.e. increasing the DC voltage, for steady-state and dynamic power flow control		kV DC
U_{mod_neg}	voltage decrease	maximum value of the DC voltage modulation at the PoC-DC in negative direction, i.e. decreasing the DC voltage, for steady-state and dynamic power flow control		kV DC
$\Delta u_{mod}/\Delta t$	voltage gradient	maximum value of the rate of change of the DC voltage for power flow control at the PoC-DC		kV/ms

In addition, the configuration around the power flow controller may require equipment for connection, isolation, energization, de-energization, protection, earthing, bypassing, which shall be specified.

9.2.3.2 DC side

9.2.3.2.1 DC connection

9.2.3.2.1.1 HV poles

The topology of each SU of the DC switching station shall be specified according to Table 67. A given SU 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 and shall be specified using Table 70.

The busbars of the DC switching station are described by the following nomenclature:

BB-P*y* 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-DC*x* P*y* station DC PoC *x*, *x* being the number of the PoC-DC with HV pole P*y*, *y* being 1 or 2

PoC-DC*x* R*y* 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 (R*y*, *y* being 1 or 2).

Table 70 – DC connection modes of a DC SU for PoC-DCx

Connection mode		BB-P1	BB-N	....	BB-P2
Mode 1	*name*				
Mode 2	*name*				
Mode 3	*name*				
…					
Mode *n*	*name*				

The required DC connection modes can also be specified in the form of single line diagrams showing the connections between the individual terminals of the DC switching station including the necessary switchgear.

The maximum transition time requirements for reconfiguration 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 in accordance with Table 71.

Table 71 – DC circuit re-configuration time requirements

Previous connection mode S_x	Next connection mode S_y				
	Mode 1	**Mode 2**	**Mode 3**	**…**	**Mode *n***
Mode 1		t_{max12}	t_{max13}	…	t_{max1n}
Mode 2	t_{max21}		t_{max23}	…	t_{max2n}
Mode 3	t_{max31}	t_{max32}		…	t_{max3n}
…	…	…	…		…
Mode *n*	t_{maxn1}	t_{maxn2}	t_{maxn3}	…	
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

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

Electrical characteristics of the earthing branch shall be specified according to the parameters outlined in 5.1.4.2. The parameters of the earthing branch shall be specified according to Table 26.

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 [13].

9.2.3.2.2 DC voltages

The values according to:

- Table 19, nominal DC system voltage;
- Table 20, DC pole voltage range parameters at a PoC-DC of an HVDC station, steady-state;
- Table 21, DC pole voltage range parameters at a PoC-DC of an HVDC station, undervoltages;
- Table 22, DC pole voltage range parameters at a PoC-DC of an HVDC station, overvoltages,

shall be specified.

9.2.3.2.3 DC insulation levels

The values according to Table 24 shall be specified.

9.2.3.2.4 DC fault ride through behaviour

A DC switching station can be equipped with additional devices providing active power exchange with the HVDC grid. In this case the DC switching station can be required to provide a certain fault ride through behaviour at a PoC-DC in response to an insulation fault appearing at another PoC-DC of the DC switching station.

The required behaviour shall be specified according to one of the following fault separation concepts:

- permanent stop PQ ☐
- permanent stop P ☐
- temporary stop PQ ☐ maximum time: ______s
- temporary stop P ☐ maximum time: ______s
- continued operation ☐

The repetition of DC fault events and recovery attempts shall be specified according to Table 72.

Table 72 – Repetition of DC fault events and recovery attempts

Symbol	Parameter	Characteristic	Value	Unit
$n_{DCfault}$	fault repetition	number of subsequent fault events		integer
$n_{DCrecovery}$	recovery repetition	number of recovery attempts for each DC fault		integer
$t_{DCrecovery}$	time	maximum time to restore full DC fault ride through capabilities		min

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

No parameters identified.

9.2.3.2.5.1.2 Energisation of a DC circuit

When the HVDC grid or parts thereof are to be energised from the DC switching station, the following shall be specified as a minimum set of requirements in addition to the parameters in Table 73:

- equivalent circuit diagram of the system to be energised including, if any, OHLs, cables and other converter stations;
- equivalent impedances of all relevant components, especially its capacitances.

Table 73 – DC circuit energisation

Symbol	Parameter	Characteristic	Value	Unit
$U_{\text{DCres\_en}}$	residual voltage	residual DC voltage prior to energization		kV DC
$U_{\text{DCmin\_en}}$	lower voltage limit	lower voltage limit of target voltage band for energisation		kV DC
$U_{\text{DCmax\_en}}$	upper voltage limit	upper voltage limit of target voltage band for energisation		kV DC
$U_{\text{DCtempOV\_en}}$	temporary overvoltage	maximum temporary overvoltage limit for energisation		kV DC
$U_{\text{DCtempUV\_en}}$	temporary undervoltage	maximum temporary undervoltage limit for energisation		kV DC
$t_{\text{min\_en}}$	time	minimum time to bring the DC voltage within the target voltage band[a]		s
$t_{\text{max\_en}}$	time	maximum time to bring the DC voltage within the target voltage band[b]		s
$\hat{I}_{\text{ch\_max\_en\_}X}$	charging current	maximum charging current at PoC-DCX		kA peak
$E_{\text{ch\_max\_en}}$	energy	maximum charging energy at PoC-DCX		MJ
$n_{\text{max\_en}}$	repetition	maximum number of repetitive energisation events at PoC-DCX		integer

[a] Only relevant if the DC switching station contains devices capable of exchanging power in the HVDC grid system.

[B] Only relevant if the DC switching station contains devices capable of exchanging power in the HVDC grid system.

9.2.3.2.5.1.3 Connecting the DC switching station to an energised HVDC grid

The parameter listed in Table 74 shall be specified.

Table 74 – Connecting the DC switching station

Symbol	Parameter	Characteristic	Value	Unit
$\Delta U_{\text{DCconn\_}X}$	voltage	maximum voltage across open contacts of switching device at PoC-DCX before connecting		kV DC

9.2.3.2.5.1.4 Disconnecting the DC switching station from the HVDC grid

The parameter listed in Table 75 shall be specified.

Table 75 – Disconnecting the DC switching station

Symbol	Parameter	Characteristic	Value	Unit
$\Delta I_{\text{DCres\_}X}$	current	maximum residual DC current through switching device at PoC-DCX before disconnecting		A DC

9.2.3.2.5.1.5 De-energisation of a DC circuit

When the HVDC grid or parts thereof are to be de-energised through the DC switching station, the following shall be specified for each de-energisation scenario as a minimum set of requirements in addition to the parameters in Table 76:

- equivalent circuit of the system to be de-energised including, if any, OHLs, cables and other converter stations,
- equivalent impedances of all relevant components, especially its capacitances.

Table 76 – DC circuit de-energisation

Symbol	Parameter	Characteristic	Value	Unit
$U_{\text{DCres\_max\_de}X}$	residual voltage	maximum residual voltage after de-energisation at PoC-DCX		
$U_{\text{DCrev\_de}X}$	voltage reversal	maximum DC voltage reversal due to discharging the DC circuit at PoC-DCX		kV peak
$t_{\text{min\_de}X}$	time	minimum time to bring the DC voltage below the maximum residual voltage after de-energisation at PoC-DCX		s
$t_{\text{max\_de}X}$	time	maximum time to bring the DC voltage below the maximum residual voltage after de-energisation at PoC-DCX		s
$\hat{I}_{\text{dch\_max \_de}X}$	discharging current	maximum discharging current at PoC-DCX		kA peak
$E_{\text{ch\_max \_de}X}$	energy	maximum discharging energy at PoC-DCX		MJ
$n_{\text{max\_de}X}$	repetition	maximum number of repetitive de-energisation events at PoC-DCX		integer

9.2.3.2.5.2 Breaking DC fault currents

The DC fault current breaking capabilities for each PoC-DC shall be specified according to 5.6. In addition, the following information is required as a minimum set of requirements:

- equivalent circuit of the DC system,
- equivalent impedances of all relevant components,
- number of consecutive faults (see Table 56),
- number of recovery attempts (see Table 56),
- the possibility of AC/DC intersystem faults, if any, together with the relevant AC system data, such as AC system short-circuit current or nominal AC system voltage.

9.2.3.2.6 Fault current levels

9.2.3.2.6.1 Contribution to short-circuit currents

A DC switching station can be equipped with additional devices capable of exchanging power in the HVDC grid. In this case the DC switching station can be required to contribute to short-circuit currents.

The maximum contribution and the minimum contribution, if any, to DC short-circuit currents shall be specified for each PoC-DC according to 5.6.