



BSI Standards Publication

HVDC Grid Systems and connected Converter Stations — Guideline and Parameter Lists for Functional Specifications

Part 1: Guidelines

National foreword

This Published Document is the UK implementation of CLC/TS 50654-1:2020. It supersedes PD CLC/TS 50654-1:2018, which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee GEL/8, Systems Aspects for Electrical Energy Supply.

A list of organizations represented on this committee can be obtained on request to its secretary.

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Published by BSI Standards Limited 2020

ISBN 978 0 539 06426 1

ICS 29.240.01

Compliance with a British Standard cannot confer immunity from legal obligations.

This Published Document was published under the authority of the Standards Policy and Strategy Committee on 30 June 2020.

Amendments/corrigenda issued since publication

Date	Text affected
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English Version

**HVDC Grid Systems and connected Converter Stations -
Guideline and Parameter Lists for Functional Specifications -
Part 1: Guidelines**

Réseaux CCHT et stations de conversion connectées -
Lignes directrices et listes de paramètres pour les
spécifications fonctionnelles - Partie 1: Lignes directrices

Hochspannungsgleichstrom-Netzsysteme - Leitfaden und
Parameter-Listen für funktionale Spezifikationen - Teil 1:
Leitfaden

This Technical Specification was approved by CENELEC on 2020-04-13.

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European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels

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European foreword

This document (CLC/TS 50654-1:2020) has been prepared by CLC/TC 8X “*System aspects of electrical energy supply*”.

This document supersedes CLC/TS 50654-1:2018.

CLC/TS 50654-1:2020 includes the following significant technical changes with respect to CLC/TS 50654-1:2018:

- new content concerning AC/DC converter stations;
- new content concerning HVDC Grid System installations, including DC switching stations;
- new content concerning HVDC Grid System integration tests.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC shall not be held responsible for identifying any or all such patent rights.

Introduction

HVDC Grid Systems are a new field of technology. There are very few systems with a small number of converter stations in operation; some more are in execution or in detailed planning.

The Guidelines and Parameter Lists to Functional Specifications are presented featuring planning, specification and execution of multi-vendor HVDC Grid Systems in Europe. Being elaborated by a team of experts from leading vendors of HVDC technology, Transmission System Operators (TSO's), Academia and Institutions in Europe, the present document provides a commonly agreed basis for an open market of compatible equipment and solutions for HVDC Grid Systems. Executing such systems and gaining operational experience is seen an important prerequisite for developing corresponding technical standards in the future.

By elaborating 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. The physical phenomena are categorized in order to show the mutual dependence of the individual parameters and ensure completeness of the physical aspects to be considered. Based on a clearly defined common language describing the functionalities requested, existing technologies can be applied, or new dedicated technical solutions can be developed.

Reflecting the early stage of technology, these Guidelines and Parameter Lists to Functional Specifications need comprehensive explanations and background information for the technical parameters. This dual character of the content will be represented by two corresponding parts:

- Part I “Guidelines” containing the explanations and the background information in context with the Parameter Lists.
- Part II “Parameter Lists” containing the essential lists of parameters and values describing properties of the AC respectively DC system (operating conditions) and parameters describing the performance of the newly installed component (performance requirements).

1 Scope

1.1 General

These Guidelines and Parameter Lists to Functional Specifications describe specific functional requirements for HVDC Grid Systems. The terminology “HVDC Grid Systems” is used here describing HVDC systems for power transmission having more than two converter stations connected to a common DC circuit.

While this document focuses on requirements, that are specific for HVDC Grid Systems, some requirements are considered applicable to all HVDC systems in general, i.e. including point-to-point HVDC systems. Existing IEC, Cigré or other documents relevant 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. having typically nominal DC voltages higher than 50 kV with respect to earth are considered in this document.

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

Both parts have the same outline and headlines to aid the reader.

1.2 About the Present Release

The present release of the Guidelines and Parameter Lists for Functional Specifications describes technical guidelines and specifications for HVDC Grid Systems which are characterized by having exactly one single connection between two converter stations, often referred to as radial systems. When developing the requirements for radial systems, care is taken not to build up potential showstoppers for meshed systems. Meshed HVDC Grid Systems can be included into this specification at a later point in time.

The Guidelines and Parameter List to the Functional Specification of HVDC Grid Systems cover technical aspects of:

- coordination of HVDC grid and AC systems
- HVDC Grid System characteristics
- HVDC Grid System control
- HVDC Grid System protection
- AC/DC converter stations
- HVDC Grid System installations, including DC switching stations
- models and validation
- HVDC Grid System integration tests

Beyond the present scope, the following content is proposed for future work:

- transmission lines and transition stations
- DC/DC converter stations
- DC line power flow controllers

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.

EN 60909 (series), *Short-circuit currents in three-phase AC systems*

EN 61660-1:1997, *Short-circuit currents in DC auxiliary installations in power plants and substations — Part 1: Calculation of short-circuit currents*

IEC 60050, *International Electrotechnical Vocabulary*

IEC/TR 60919-1:2010¹, *Performance of high-voltage direct current (HVDC) systems with line-commutated converters – Part 1: Steady-state conditions*

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

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

IEC 62747:2014², *Terminology for voltage-sourced converters (VSC) for high-voltage direct current (HVDC) systems*

IEV 351-45-27, *International electrotechnical vocabulary, control technology*

¹ As impacted by IEC/TR 60919-1:2010/A1:2013, IEC/TR 60919-1:2010/A2:2017.

² As impacted by IEC 62747:2014/A1:2019.

3 Terms, definitions and abbreviations

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply. ISO and IEC maintain terminological databases for use in standardization at the following addresses:

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

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 converter transformers, control equipment, essential protective and switching devices and auxiliaries, if any, used for conversion

[SOURCE: EN 62747:2014², modified – The definition was neutralised with respect to technology (not only VSC converters) and uses the terms PoC as defined in the present 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: EN 62747:2014², 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 the present 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

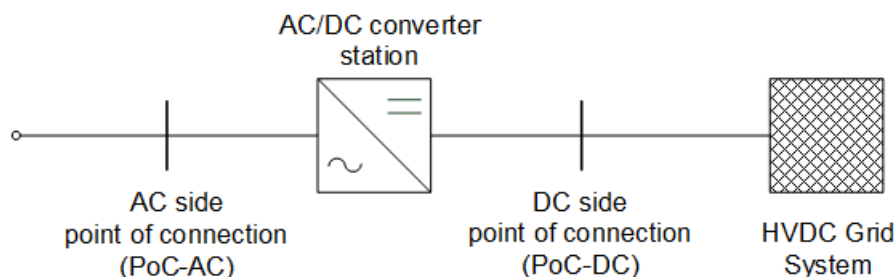


Figure 1 — Definition of the Point of Connection-AC and the Point of Connection-DC at an AC/DC converter station

3.1.5

DC/DC converter unit

indivisible operative unit comprising all equipment between the points of connection to the HVDC Grid System, essentially one or more converters, together with converter transformers, if any, control equipment, essential protective and switching devices and auxiliaries, if any, used for conversion

3.1.6**DC/DC converter station**

part of an HVDC Grid System 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 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

3.1.8**DC switching station**

part of an HVDC Grid System which consists of one or more DC switches, but no AC/DC or DC/DC converter units, installed in a single location together with buildings, reactors, filters, control, monitoring, protective, measuring and auxiliary equipment, if any

3.1.9**HVDC Grid System**

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 sub-systems needed for operation

3.1.10**meshed HVDC Grid System**

HVDC Grid System having more than one direct current connection between at least two converter stations

3.1.11**radial HVDC Grid System**

HVDC Grid System having exactly one direct current connection between two arbitrary converter stations

3.1.12**DC protection zone**

physical part of a HVDC Grid System with a distinct DC fault handling sequence

3.1.13**rigid bipolar (HVDC) system**

bipolar (HVDC) system without dedicated return path or electrodes as illustrated in Figure 2

NOTE 1 to entry Monopolar operation is possible by means of bypass switches during a converter pole outage, but not during an HVDC conductor outage. A short bipolar outage will follow a converter pole outage before bypass operation can be established.

[SOURCE: IEC/TR 60919-1:2010]¹

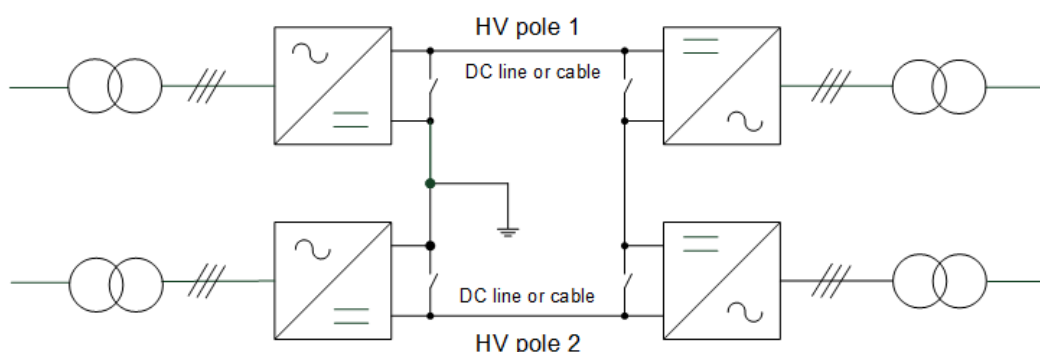


Figure 2 — Rigid Bipolar HVDC system

3.2 Abbreviations

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)
DPS	dynamic performance studies
DPT	dynamic performance tests
EMT	electromagnetic transients
ENTSO-E	European Network of Transmission System Operators for Electricity
ERTS	earth return transfer switch
FAT	factory acceptance tests
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
IEEE	Institute of Electrical and Electronics Engineers
LAT	laboratory acceptance test
MMC	modular multilevel converter
MRTS	metallic return transfer switch
NBGS	neutral bus grounding switch
NBS	neutral bus switch
NC	Network Code
OHL	overhead line
OP	operating point
OPF	optimum power flow
OVRT	over-voltage ride through
PoC	point of connection
POD	power oscillation damping
STATCOM	static synchronous compensator
SRAS	System Recovery Ancillary Service
T	terminal
THD	total harmonic distortion
TSO	transmission system operator

UVRT	under-voltage ride through
VSC	voltage-sourced converter

4 Coordination of HVDC Grid System and AC Systems

4.1 General

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

- DC switching station
- transmission line (overhead line, cable or combinations thereof)
- DC/DC converter station
- DC line power flow controller.

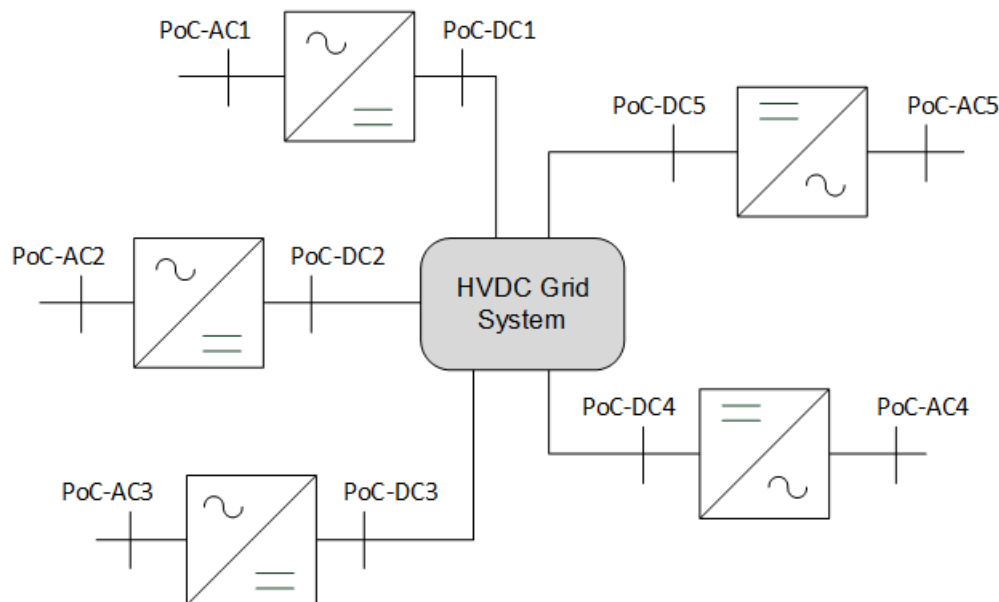


Figure 3 — Principle structure of an HVDC Grid System

The topologies of the AC/DC converter stations as well as the various installations of the HVDC Grid System shall be coordinated and specified as described in chapter 5.1 “HVDC Circuit Topologies”.

Within the boundaries of the given topologies, each AC/DC converter station or HVDC Grid System installation can be operated in different DC connection modes as described for AC/DC converter stations in chapter 8.4.2.1 “DC Connection” and for DC switching stations in chapter 9.2.2.2.1 “DC Connection”. The individual connection modes and their application needs to be coordinated throughout the HVDC Grid System any time when operating.

4.2 Purpose of the HVDC Grid System and Power Network Diagram

To provide an overall understanding of the HVDC Grid System, the purposes and basic functions of the HVDC Grid System including all AC/DC converter stations shall be explained.

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

- AC networks showing the connection of each AC/DC converter station to the synchronous areas
- HVDC Grid System topology and converter station topology for each AC/DC converter 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
- fault separation devices
- 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

4.3 AC/DC Power Flow Optimisation

The behaviour of an HVDC Grid System and its AC/DC converter stations within their AC system environment is typically described in corresponding network codes for the respective AC systems. This chapter describes typical requirements from the AC system perspective with respect to their implications on the design of HVDC Grid Systems.

An HVDC Grid System with more than two AC/DC converter stations in operation requires superordinate coordination of the power flow between the individual converter stations. The requirements for such coordination are described in chapter 6 “HVDC Grid System Control”.

The steady-state active and reactive power capabilities of an AC/DC converter station are described by the maximum and minimum active vs. reactive power exchange capability charts depending on the AC voltage at the PoC-AC (U_{AC}) of each station as shown in Figure 4.

The power flow shall be specified such that the power exchange of a 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.

This diagram can be specified for different AC voltage levels. For one AC voltage level the boundaries under temporary conditions, e.g. overload operation can be represented by different graphs in Figure 4.

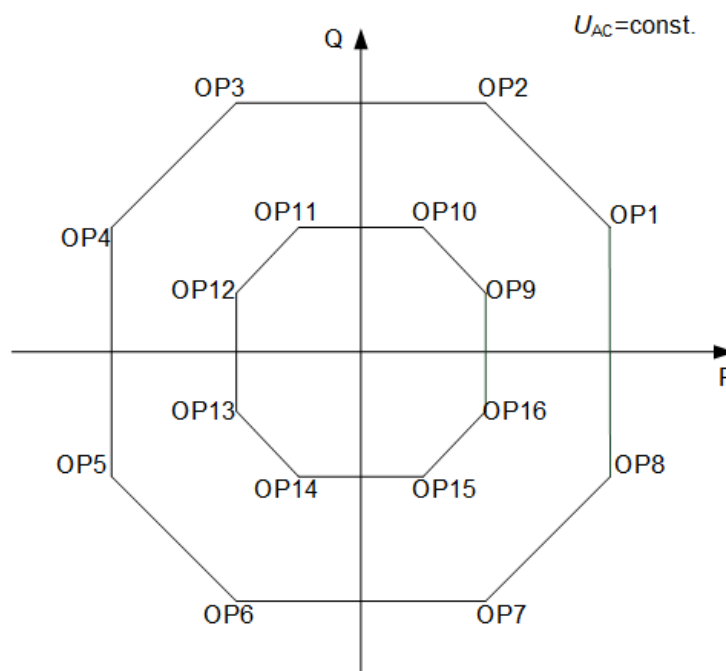


Figure 4 — Example of a PQ-diagram showing maximum and minimum active vs. reactive power exchange capability of an AC/DC converter station for a given AC voltage level

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

4.4 Converter Operational Functions

4.4.1 General

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

4.4.2 Basic Operation Functions – Converter Normal Operation State

4.4.2.1 General

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

- active power exchange
- reactive power exchange

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

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

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

The basic operating functions are specified by as follows:

- AC system frequency by a frequency / power droop (s_{PF})
- DC voltage by a DC voltage / DC power droop (s_{P_UDC}) or a DC voltage / DC current droop (s_{IDC_UDC})

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

- reactive power control
- AC voltage magnitude control

These functions are described under subchapter Ancillary Services.

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

The capabilities and requirements of all converter stations connected to an HVDC Grid System have to be coordinated with the AC system needs.

4.4.2.2 AC System Frequency by a Frequency / Power Droop

The AC system frequency by frequency power droop describes the change of active power in response to a deviation of the AC system frequency from its reference value. It is defined by

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

where:

Δf is the frequency change

f_{nom} is the nominal AC system frequency

ΔP is the change of the active power output of the converter station

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

There are two extreme cases:

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

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

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

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

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

4.4.2.3 DC Voltage / DC Power Droop

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

$$s_{P_UDC} = (\Delta U_{DC} / U_{DCnom}) / (\Delta P / P_n)$$

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

$$s_{IDC_UDC} = (\Delta U_{DC} / U_{DCnom}) / (\Delta I_{DC} / I_{DCnom})$$

There are two extreme cases:

- a) scheduled power, $s_{P_UDC} = \infty$, $s_{IDC_UDC} = \infty$

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

- b) constant DC voltage, $s_{P_UDC} = 0$, $s_{IDC_UDC} = 0$

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

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

The above droop characteristics are the most common, but there could be others along with all other control modes as defined in 6.2.3 in sub-section "Converter Control Modes" where it is explained that droop constants could be a function of active power, DC voltage, etc. Several droop constants $s(P)$ could be used to model dead bands etc.

4.4.3 Basic Operation Functions – Converter Abnormal Operation State

4.4.3.1 General

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

4.4.3.2 Network Conditions and Power Flow Requirements

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

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

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

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

During an AC fault the current contribution by a converter station can be specified with respect to the positive, negative and zero sequence voltage content. The active and reactive power flow requirements during a fault condition may depend on the residual AC voltage level. Various current levels can be specified for different voltage levels.

4.4.3.3 Abnormal AC Voltage Conditions

The operational requirements for abnormal AC voltage conditions are specified by AC Under-Voltage Ride Through (UVRT), also known as AC Low-Voltage Ride Through Capability (LVRT); as well as AC Over-Voltage Ride Through (OVRT),

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

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

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

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

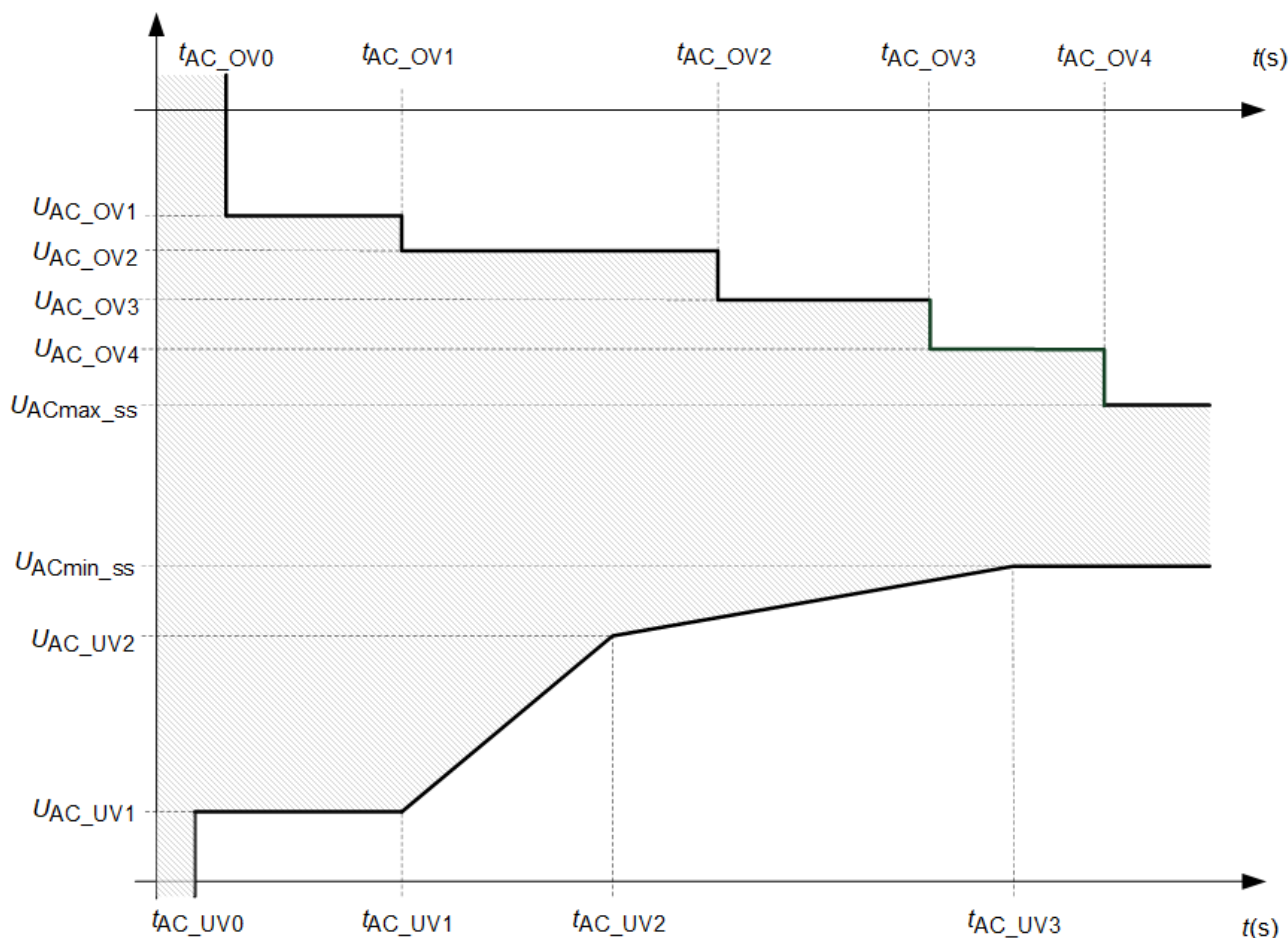


Figure 5 — Exemplary generic AC Over- and Under Voltage Ride Through profile of an AC/DC converter station.

4.4.4 Ancillary Services

4.4.4.1 General

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

- frequency control related services
- AC Voltage control related services
- power oscillation damping service
- system restoration service

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

4.4.4.2 Frequency Control Related Services

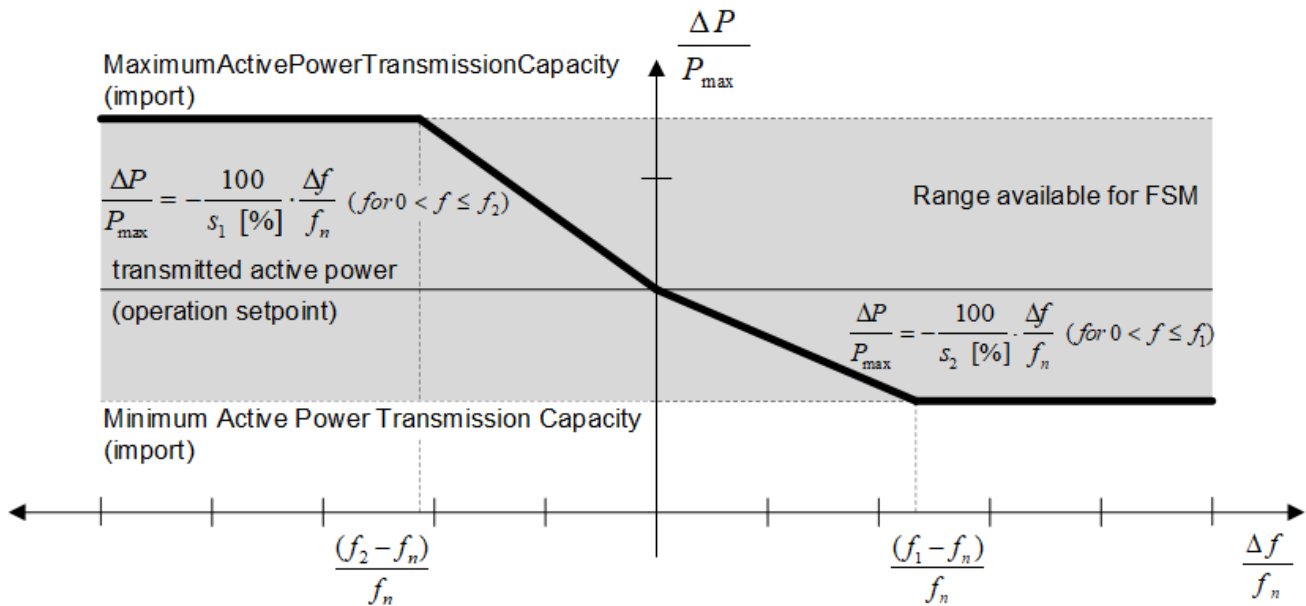
4.4.4.2.1 Synthetic Inertia (Differential Frequency Control)

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

4.4.4.2.2 Frequency Containment Reserve (Primary Frequency Control)

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

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



Key

- ΔP : Change in P_{SETPOINT} triggered by the step change in frequency (MW)
- Δf : Frequency change in AC network(s) where the HVDC is connected to, measured continuously by the average of the rate of change of the AC network frequency (df/dt) for a defined time span; (Hz)
- P_{max} : Maximum HVDC Active Power Transmission Capacity (MW)
- f_n : Target frequency in the AC network (Hz)
- $f_{\text{DEADBAND}} = [f_{\text{min}}, f_{\text{max}}]$: Frequency Response Dead-band (indicative range 0 – ± 500 mHz)
- s_1 : upward regulation 'droop' (indicative value ≥ 0,1 %)
- s_2 : downward regulation 'droop' (indicative value ≥ 0,1 %)
- f_1 : Over-frequency threshold (Hz)
- f_2 : Under-frequency threshold (Hz)
- Frequency response insensitivity: ≤ 30 mHz

Figure 6 — Active power frequency response capability of an AC/DC converter station in Frequency Sensitive Mode (FSM) with zero deadband and insensitivity with a positive active power setpoint (based on Commission Regulation (EU) 2016/1447, 26 August 2016)
FSM in this figure shall be understood as FCR

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

- droop value s_{PF} , see 4.4.2.2 AC System Frequency by a Frequency / Power Droop
- minimum step response time t_{FCRact} , to coordinate with inertia
- maximum provision time $t_{FCRprov}$, to coordinate with Frequency Restoration Reserve (FRR)
- frequency dead band $f_{DEADBAND}$, to limit the activation to exceptional situations

In order to support the frequency containment reserve process of at least one synchronous area, the frequency containment reserve provision by an HVDC Grid System adapts the active power infeed from the HVDC Grid System to at least one synchronous area (receiving area(s)). It further modulates the active power drawn by the HVDC Grid System from at least one synchronous area (sending area(s)). The sending areas and receiving areas shall not be synchronously operated. This is inherently ensured by the application of the same Synthetic Inertia algorithm

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

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

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

Where

- $K_{FCR,i,j}$ is the FCR-distribution coefficient (dimensionless) indicating the amount of active power drawn from the sending area j and fed into the receiving area i
- $\Delta P_{RZ,j}$ is the active power fed into receiving area j
- $\Delta P_{SZ,i}$ is the active power drawn from sending area i
- n_R is the number of asynchronous AC grid zones which are receiving areas
- n_S is the number of asynchronous AC grid zones which are sending areas

4.4.4.2.3 Frequency Restoration Reserve (Secondary Active Power Control)

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

4.4.4.2.4 Replacement Reserves (Tertiary Control)

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

4.4.4.3 AC Voltage Control Related Services

AC Voltage control related services can be:

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

4.4.4.4 Power Oscillation Damping Services

4.4.4.4.1 General

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

4.4.4.4.2 Electromechanical Oscillations

Electromechanical oscillations can be damped by active power:

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

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

4.4.4.4.3 Sub-Synchronous Torsional Interactions

HVDC control loops introduce sub-synchronous frequencies in the AC network, through the voltages applied on the stator windings of the generator. Electromagnetic torque disturbances (e.g. abrupt change of the topology of the electrical network further to fault elimination) can also initiate the phenomenon of sub-synchronous oscillations. The sub-synchronous frequencies can then excite those of the turbine generator shaft and produce very high torsional torques. [2][3]

4.4.4.5 System Restoration Services

4.4.4.5.1 General

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

4.4.4.5.2 Restoration from Blackout

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

AC system restoration services comprise two steps:

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

NOTE The start-up of a converter station from a connected AC system, DC system or an internal power source like a diesel generator is considered an energisation process and not a system restoration service. Energisation of a converter station is described in 8.4.2.5.1 "Energisation and De-Energisation, Connection and Disconnection of DC Circuits".

The limits of the AC voltage at the PoC-AC shall be defined based on the AC voltage profile given in 4.4.2.3, "Abnormal AC Voltage Conditions". The frequency limits shall be defined based on the requirements of the AC system restoration process.

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

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

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

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

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

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

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

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

4.4.4.5.3 Post AC Fault Active Power Recovery

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

- $P_{\text{POST-FAULT}}$ Post fault active power recovery: (example 90 % of pre-fault active power transmission)
- $t_{\text{POST-FAULT}}$ Time in which to recover P: (example 0,2 s)

5 HVDC Grid System Characteristics

5.1 HVDC Circuit Topologies

5.1.1 Availability and Reliability

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

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

5.1.2 Basic Characteristics and Nomenclature

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

Attributes characterizing the HVDC Grid System are:

- number of HV poles
- DC circuit earthing

Attributes characterizing a station are:

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

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

The characteristics of the HVDC Grid System and a station are expressed by the nomenclature of the HVDC circuit topologies given in Table 1.

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

Table 1 — Nomenclature of HVDC circuit topologies

Characteristics of the HVDC Grid System			-	Characteristics of a station		
Number of HV poles	DC	DC circuit earthing	-	connection to pole	connection to neutral return path	station earthing
1 2	DC	"z" not effectively earthed "e" <u>e</u> ffectively earthed	-	"1" pole <u>1</u> "2" pole <u>2</u> "B" <u>b</u> oth	"O" <u>n</u> one "R" <u>r</u> eturn conductor "E" earth or sea <u>e</u> lectrode	"O" <u>n</u> one "Z" <u>i</u> mpedance "E" <u>d</u> irect

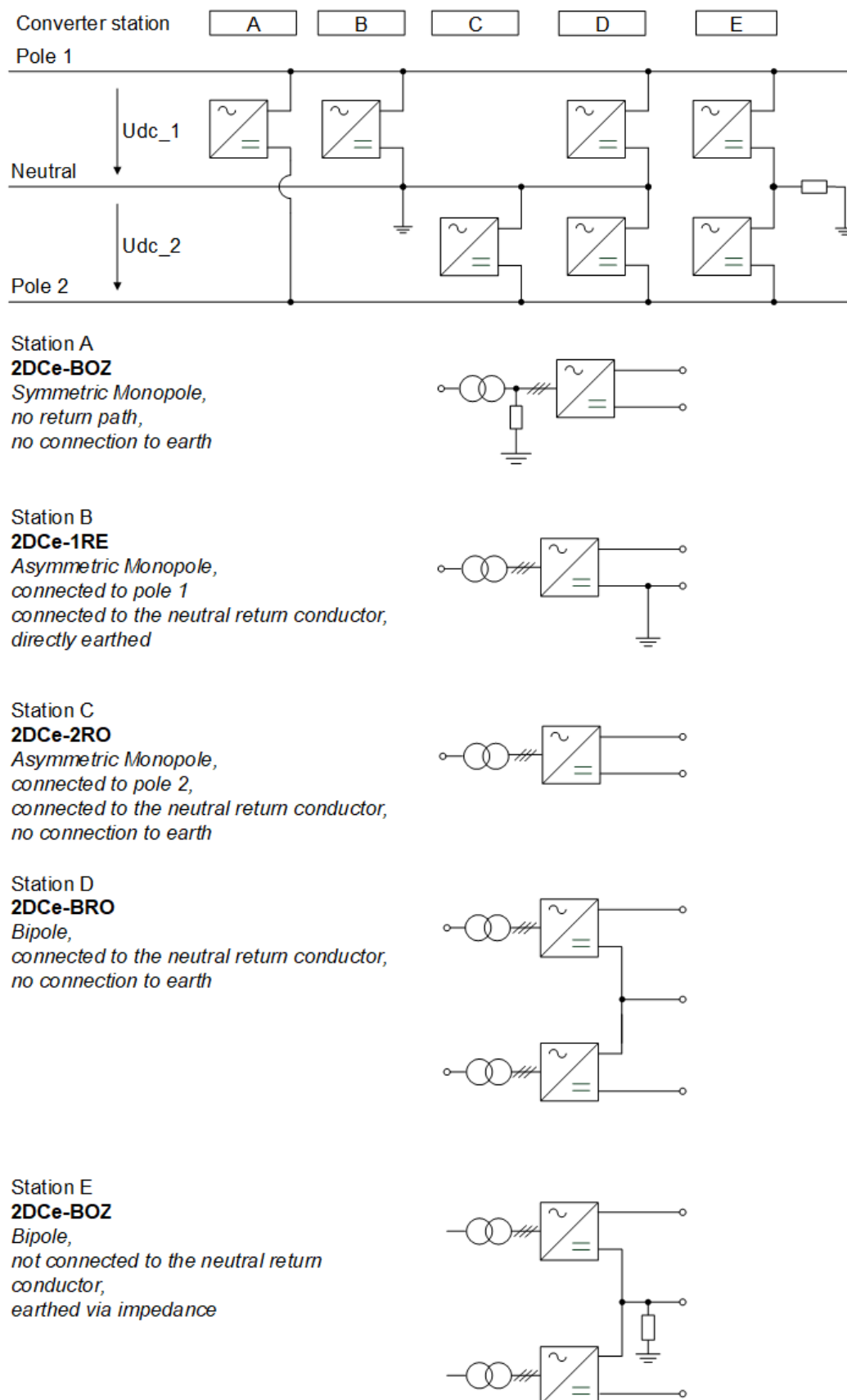
Table 2 — HVDC circuit topologies – HVDC Grid System characteristics

number of HV poles		1DC (Monopole)	2DC (Bipole)	
DC earthing		effectively earthed 1DCe	effectively earthed 2DCe	isolated 2DCz

Table 3 — HVDC circuit topologies – AC/DC converter station characteristics

Number of HV poles		one	two	two
connection to HV poles		pole 1 or pole 2 1DCe-1 or 1DCe-2 <i>Asymmetric Monopole</i>	both poles 2DCe-B <i>Bipole</i>	both poles 2DCz-B
neutral return path	dedicated return conductor	1DCe-xR <i>Asymmetric Monopole with Dedicated Metallic Return, connected to pole x (1 or 2)</i>	2DCe-BR <i>Bipole with Dedicated Metallic Return</i>	2DCz-BR <i>Bipole with Dedicated Metallic Return, impedance earthed</i>
	earth or sea electrode	1DCe-xE <i>Asymmetric Monopole, connected to pole x (1 or 2), connected to earth or sea electrode</i>	2DCe-BE <i>Bipole, connected to earth or sea electrodes</i>	
	none		2DCe-BO <i>Rigid Bipole</i>	2DCz-BO <i>Rigid Bipole or Symmetric Monopole</i>
station earthing	direct	1DCe-xEE or 1DCe-xRE <i>Asymmetric Monopole, connected to pole x (1 or 2), connected to earth or sea electrode, alternatively neutral return conductor, directly earthed</i>	2DCe-BxE <i>Bipole, directly earthed; x: either connected to earth or sea electrodes, neutral return conductor or no neutral return path</i>	
	impedance	1DCe-xRZ <i>Asymmetric Monopole, connected to pole x (1 or 2), connected to return conductor, impedance earthed</i>	2DCe-BRZ <i>Bipole, connected to neutral return conductor, impedance earthed</i> or 2DCe-BOZ <i>Rigid Bipole, impedance earthed</i>	2DCz-BRZ <i>Bipole, connected to neutral return conductor, impedance earthed</i> or 2DCz-BOZ <i>Rigid Bipole or Symmetric Monopole, impedance earthed</i>

Number of HV poles		one	two	two
	none	1DCe-xRO <i>Asymmetric Monopole, connected to pole x (1 or 2), connected to return conductor, no connection to earth</i>	2DCe-BRO <i>Bipole, connected to neutral return conductor, no connection to earth</i> or 2DCe-BOO <i>Rigid Bipole, no connection to earth</i>	2DCz-BRO <i>Bipole, connected to neutral return conductor, no connection to earth</i> or 2DCz-BOO <i>Rigid Bipole or Symmetric Monopole, no connection to earth</i>



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

Figure 7 — Example of an HVDC Grid System in 2DCe topology with different AC/DC converter station topologies.

5.1.3 Attributes of HVDC Grid Systems or HVDC Grid Sub-Systems

5.1.3.1 Number of HV Poles

The topologies of the HVDC Grid Systems differentiate regarding the number of HV pole conductors. Systems can have:

- one HV pole, so-called Monopoles
- two HV poles, so-called Bipoles or Symmetric Monopoles

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

5.1.3.2 DC Circuit Earthing

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

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

- effectively earthed
- not effectively earthed

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

HVDC Grid Systems that are effectively earthed are built either in 2DCe topology (so-called Bipoles) or in 1DCe, (so-called Asymmetric Monopoles). A DC circuit in 2DCe topology can be considered consisting of two 1DCe circuits having opposite DC voltage polarity to earth. 2DCe HVDC Grid Systems or parts thereof can be operated as 1DCe in case one DC pole is out of operation.

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

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

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

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

5.1.4 Attributes of a Station

5.1.4.1 Connection to HV Poles

A station can be connected to HV pole 1, HV pole 2 or both.

For AC/DC converter stations, the terms Symmetric Monopole, Asymmetric Monopole and Bipole are also used.

An AC/DC converter station connected to either HV pole 1 or HV pole 2 is also called an Asymmetric Monopole station.

An AC/DC converter station connected to both HV poles is also called a Bipole station or Symmetric Monopole station. A Bipole station comprises at least two separate converter units connected in series between both HV poles, a Symmetric Monopole station connects both HV poles by just one converter unit. Both options are shown in Figure 7 for Station A with just one converter unit (Symmetric Monopole) and Station E with two series connected converter units (Bipole). In case of an isolated HVDC Grid System, the number of series connected converter units between (one or two) poles shall be specified.

Converters with unidirectional DC current, i.e. type 1 converters as described in 8.2 “AC/DC Converter Station Types”, can be complemented by dedicated switchgear to connect the terminals of the converter to either HV pole of the HVDC Grid System. This possibility is not reflected in the nomenclature of the converter topologies.

5.1.4.2 Neutral Return Path

The options for the neutral return path are:

- dedicated metallic return conductor – DMR
- HV pole conductor used for the return path (metallic return)
- earth or sea electrode
- no return path

1DCe topologies can use dedicated neutral return conductors (1DCe-xR³) or the earth or the sea electrodes (1DCe-xE) for the DC current to return.

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

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

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

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

³ 1DCe-xR: The x represents the connection of the respective converter station to the HV poles. The variable x can be 1 or 2.

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

5.1.4.3 Station Earthing

The options for earthing a station are:

- direct earthing
- impedance earthing
- no connection to earth

The neutral point of a station can be directly connected to earth. Stations operated using earth or sea electrodes are always directly earthed.

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

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

5.2 Connection Modes

Within the boundaries of the given topologies, each AC/DC converter station or HVDC Grid System installation can be operated in different DC connection modes as described for AC/DC converter stations in 8.4.2.1 “DC Connection” and for DC switching stations in 9.2.2.2.1 “DC Connection”. The individual connection modes and their application needs to be coordinated throughout the HVDC Grid System any time when operating.

5.3 Grid Operating States

5.3.1 General

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

5.3.2 Normal State

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

5.3.3 Alert State

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

- AC system constraints
- HVDC Grid System constraints

5.3.4 Emergency State

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

5.3.5 Blackout State

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

5.3.6 Restoration

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

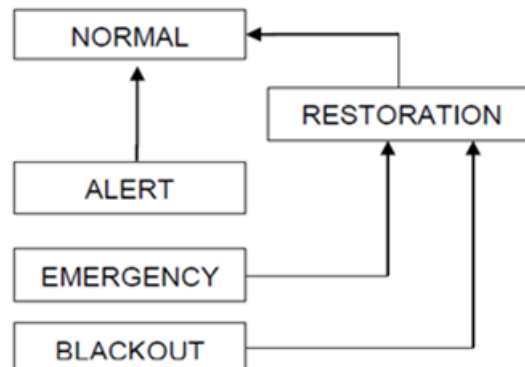


Figure 8 — Operating states (Source: Operating Handbook Continental Europe [5])

5.4 DC Voltages

5.4.1 General

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

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

5.4.2 Nominal DC System Voltage

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

5.4.3 Steady-State DC Voltage

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

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

Also, the maximum DC voltages applicable to the neutral bus, dedicated metallic return conductors and electrode lines need to be defined. Both, the DC pole voltage to earth as well as the DC neutral voltage to earth need to be considered when defining the DC voltage across the converter. Operation at reduced DC voltage levels may be considered taking into account reduced DC insulation capabilities, e.g. due to harsh weather conditions.

5.4.4 Temporary DC Voltage

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

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

The following example of a temporary voltage profile for the DC voltage shown in Figure 9 below is taken from CIGRÉ TB 657 [4]. In order to derive a specific representation several aspects are to be considered, such as:

- AC and DC system power flow changes
- AC and DC system harmonics
- AC system transients and fault scenarios
- DC system transients and fault scenarios

The time and DC voltage limits depend on technology and topology of the HVDC Grid System. The scales are used for illustration only.

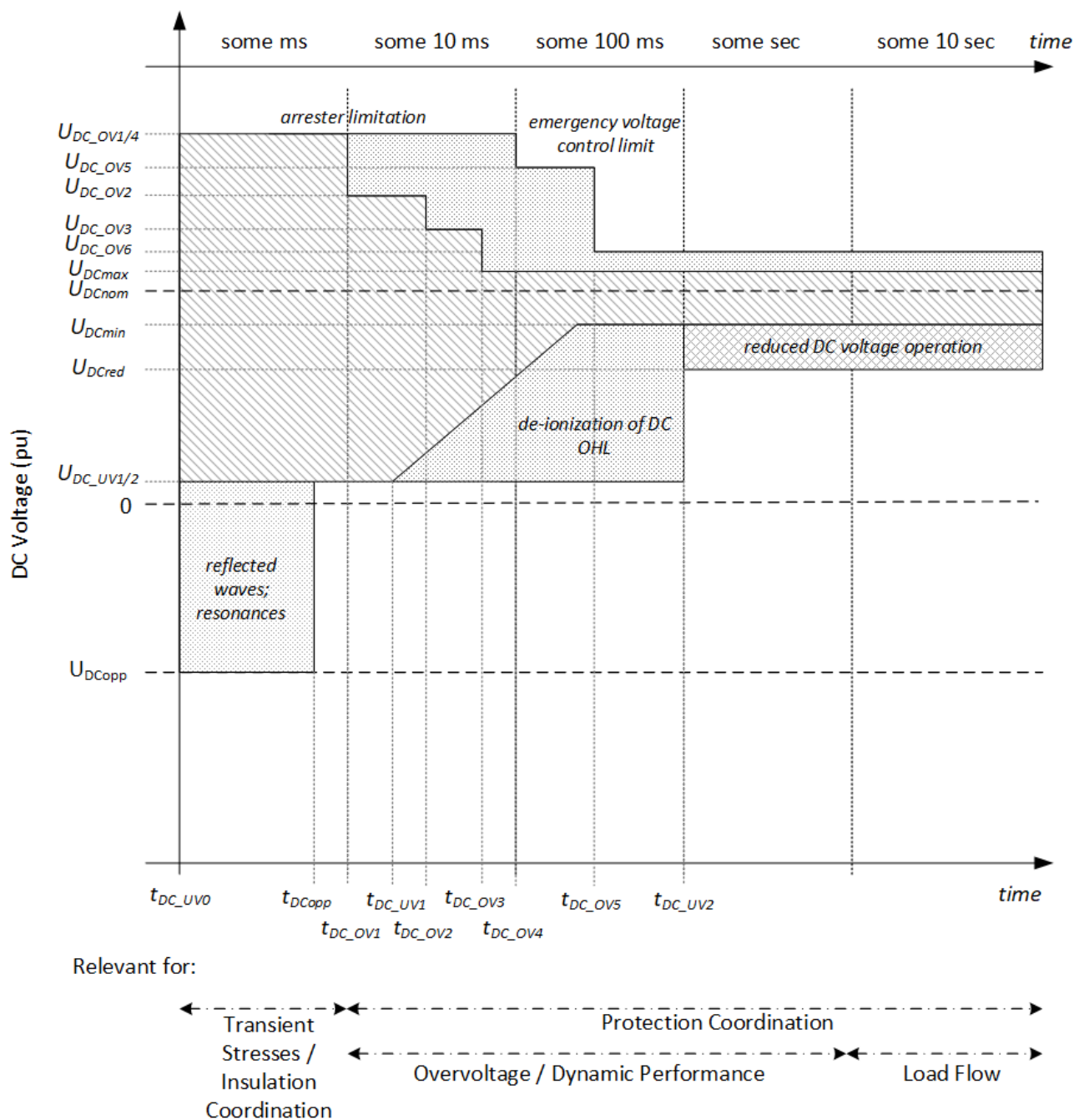


Figure 9 — Temporary DC pole to earth voltage profiles in HVDC Grid Systems
(Source: [4])

5.4.5 Neutral Bus Voltages

The steady state neutral bus DC voltages depend on the topology and concept of operation of the neutral return path as described in 5.1.4.2 “Neutral Return Path”.

Temporary voltages due to operation of DC switches, such as MRTS, ERTS, NBS and NBGS shall be considered in addition to 5.4.4 “Temporary DC Voltage” for all relevant DC system configurations and reconfiguration sequences. It is recommended to consider extra voltage margin for future system expansions or modifications.

5.5 Insulation Coordination

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

5.6 Short-Circuit Characteristics

5.6.1 Calculation of Short-Circuit Currents in HVDC Grid Systems

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

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

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

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

- discharging of overhead lines and cables
- discharging of filters/capacitors
- contribution of the converter stations
- contribution of parts of a HVDC Grid System that are connected via a short-circuit current limiting device

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

- type of converter station, i.e. AC/DC types 1, 2, 3, 4, 5, as described in 8.2 “AC/DC Converter Station Types”.
- short-circuit current limiting devices
- earthing of the DC circuit in case of line to earth short-circuits

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

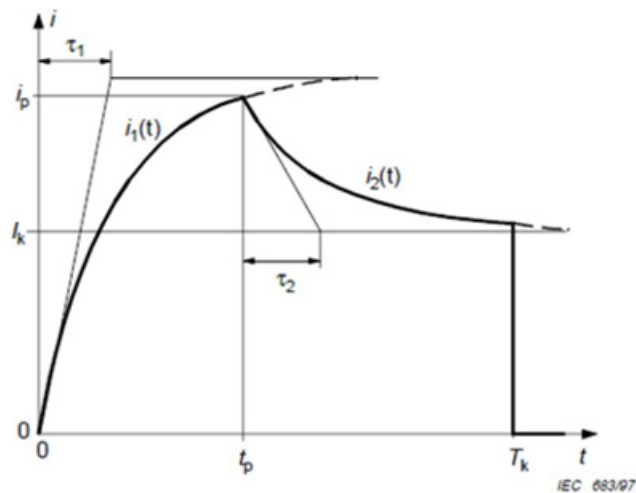
The amplitude of the short-circuit current in case of line to earth faults depends on the earthing of the system. The following steps have to be considered in detail for the determination of short-circuit currents:

- selection of a typical DC system (layout), including earthing and used components which will lead to the maximum/minimum short-circuit current
- configuration of overhead lines and cables (resistance, reactance and capacitance for the calculation of minimum and maximum short-circuit currents)
- definition of system installations or components respectively which contribute to the short-circuit currents (filters, capacitors etc.)
- behaviour of converters during a short-circuit: short-circuit current depending on the fault time (control of the converter stations)

- operating conditions (DC voltage, DC current, power flow) in the HVDC Grid System
- definition of fault types (single pole, pole-to-poles or intersystem faults)

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

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



Key

i_k	steady state short-circuit current
i_p	peak short-circuit current
T_k	short-circuit duration
t_p	time to peak
τ_1	rise-time constant
τ_2	decay-time constant

Figure 10 — Standard approximation function according to EN 61660-1:1997

By calculating the characteristic quantities for the time variation of the short-circuit current according to Figure 10, the mechanical and thermal short-circuit stresses can be ascertained.

5.6.2 Short-Circuit Current Design Requirements

Parameters defining the design of the HVDC Grid System with respect to short-circuit currents shall be specified according to the standard approximation function demonstrated by the wave shape shown in Figure 10, for each part of the HVDC Grid system.

5.7 Steady-State Voltage and Current Distortions

5.7.1 Voltage and Current Distortion Limits

Power electronic converters are designed to generate voltages and currents of predefined characteristics. Due to their principles of operation, real power electronic converters, besides their target voltage and current wave shapes, generate unwanted content which may include conducted as well as radiated electromagnetic emissions. In terms of the HVDC Grid System characteristics, this chapter addresses voltage and current distortions in the frequency range below 9 kHz. These distortions can lead to impermissible emissions, adverse interactions between different HVDC Grid System installations or interference with other technical systems. To

ensure safe and undisturbed operation of the HVDC Grid System tolerable limits of voltage and/or current distortions need to be specified.

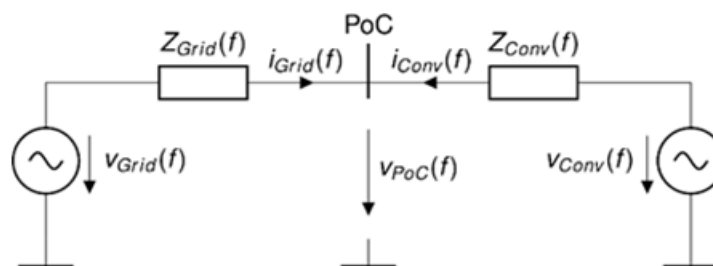
Aspects to be considered when specifying maximum permissible voltage and/or current distortion limits include:

- Dielectric stresses of components, e.g. cables, also considering resonance effects
- Local standards for electromagnetic interference limits including electromagnetic emissions, e.g. interference with telecommunication systems.
- Pre-existing voltage distortions (before operating a new converter), also referred to as “background” distortions

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

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

Voltage and current distortions are related to each other by the effective impedances at the particular frequency as shown in Figure 11. Voltage or current distortion limits shall be specified at the PoC-DC.



Key

- $V_{Grid}(f)$: pre-existing voltage distortion at frequency f in grid
- $i_{Grid}(f)$: distortion current flowing in the grid at frequency f
- $Z_{Grid}(f)$: DC-grid equivalent impedance as seen from the PoC-DC into the grid at frequency f
- $V_{Conv}(f)$: voltage generated by the converter at frequency f
- $i_{Conv}(f)$: distortion current flowing in the grid feeder to the converter station at frequency f
- $Z_{Conv}(f)$: equivalent impedance of the converter station at frequency f

NOTE 1 The equivalent network impedances will be different for different system configurations, e.g. bipolar vs. monopolar conditions, return path configurations, converter station impedances including passive as well as controlled parts.

NOTE 2 Converters with dominating current source characteristics need to be re-calculated into an equivalent voltage source

Figure 11 — Equivalent circuit, defining the relationship between voltage and current distortions

While voltage and/or current distortion limits for AC-systems are defined and well established over the last decades (IEC/TR 61000-4-1), such definitions and limits do not yet exist for HVDC Grid Systems.

The definition of relevant limits is between the poles of technical feasibility and commercial acceptability while providing safe and undisturbed operation of the HVDC Grid System itself and other relevant systems in the environment. Thus, for HVDC Grid Systems the definition of limits can follow the concept described by IEC/TR 61000-1-4 and depicted in Figure 12.

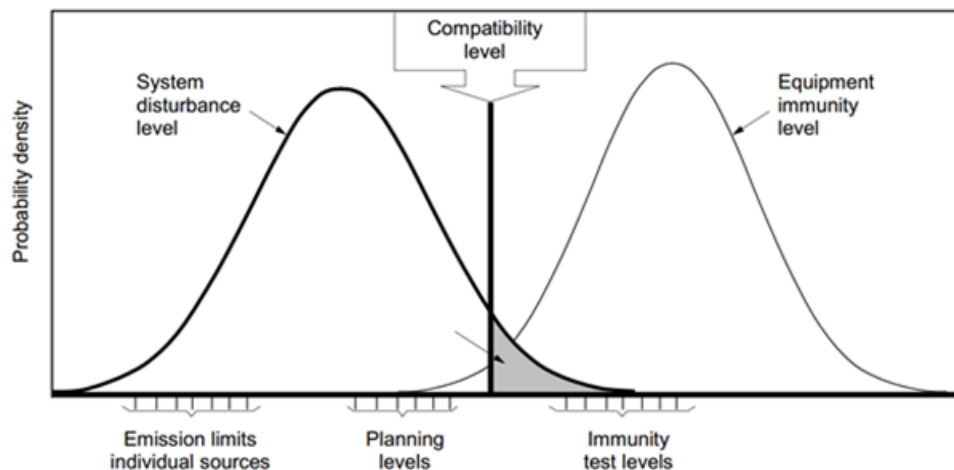


Figure 12 — Disturbance Level [IEC/TR 61000-1-4]

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

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

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

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

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

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

5.7.2 Frequency Dependent DC System Impedance

The frequency-dependent impedances of the HVDC Grid System as seen from the point of connection (PoC-DC) of the new installation shall be specified for the relevant frequency range and frequency step width.

Alternatively, in particular for small HVDC Grid Systems, the harmonic impedances of the individual elements of the HVDC Grid System together with the topology and potential operational configurations of the grid can be specified.

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

5.8 DC System Restoration

5.8.1 General

In case of a fault in the HVDC Grid System, the affected line or grid section needs to be disconnected from the unfaulty part of HVDC Grid System according to assigned DC fault separation concepts in 7.2 “DC Fault Separation”. Depending on the fault separation concepts, post DC fault recovery strategies can require System Recovery Ancillary Service DC (SRAS-DC) by the AC/DC converter stations.

5.8.2 Post DC Fault Recovery

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

Dependent on the capabilities of the involved converter(s) and the assigned protection concept (7.4 “HVDC Grid System Protection Zones”), post DC fault recovery may contain the following options:

- energization, synchronization and re-connection of the disconnected converter stations according to 8.5.5 “Operating Sequences for AC/DC Converter Station”; This applies if the involved converter stations were de-energised and disconnected from the HVDC Grid System.
- synchronization and re-connection of the disconnected converter stations; This applies if the involved converter stations were not blocked but just disconnected from the HVDC Grid System.
- recovery of the DC voltage after fault separation or recovery of the full insulation capability; This applies if the involved converter station can limit and control the fault current by a counter voltage (e.g. using proactive breakers or type 5 converter).
- re-connection and energisation of the faulted line

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

5.8.3 Restoration from Blackout

Major disturbances within the HVDC Grid System can result in a blackout of the entire HVDC Grid System. In these cases, the post fault recovery strategies (see 5.8.2 “Post DC Fault Recovery”) are not applicable. The HVDC Grid System needs to be restored from an AC system. The procedure is also referred to as System Recovery Ancillary Service DC (SRAS-DC). It follows the procedure described in 8.4.2.7 “System Restoration DC Side”. Thereby the HVDC Grid System will be restored and synchronized subsequently section by section. The priority of energisation and connection to the HVDC Grid System needs to be agreed by the involved system operators.

6 HVDC Grid System Control

6.1 Closed-Loop Control Functions

6.1.1 General

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

The effective capacitance can be complemented by: