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TECHNICAL REPORT

colour inside

Performance of voltage sourced converter (VSC) based high-voltage direct current (HVDC) transmission –
Part 1: Steady-state conditions

IEC TR 63363-1:2022-05(en)

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Performance of voltage sourced converter (VSC) based high-voltage direct current (HVDC) transmission – Part 1: Steady-state conditions

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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PERFORMANCE OF VOLTAGE SOURCED CONVERTER (VSC) BASED HIGH-VOLTAGE DIRECT CURRENT (HVDC) TRANSMISSION –

Part 1: Steady-state conditions

FOREWORD

IEC TR 63363-1 has been prepared by IEC technical committee 115: High Voltage Direct Current (HVDC) transmission for DC voltages above 100 kV and IEC subcommittee 22F: Power electronics for electrical transmission and distribution systems. It is a Technical Report.

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

Draft	Report on voting
115/281/DTR	115/298/RVDTR

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 Report is English.

A list of all parts in the IEC 63363 series, published under the general title *Performance of voltage sourced converter (VSC) based high-voltage direct current (HVDC) transmission*, can be found on the IEC website.

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

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

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- withdrawn,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

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INTRODUCTION

High-voltage direct current (HVDC) is an established technology that has been in commercial use for more than 60 years. With the changes in demands due to evolving environmental needs, installation of HVDC systems has increased dramatically in the last 30 years and almost half of the world's HVDC projects were commissioned after the year 2000. HVDC has become a common tool in the design of future global transmission systems.

An HVDC system transmits more electrical power over longer distances than a similar alternating current (AC) transmission system, which means fewer transmission lines are needed, saving both money and land and simplifying approvals. In addition to significantly lowering electrical losses over long distances, HVDC transmission is also very stable and easily controlled, and can stabilize and interconnect AC power networks that are otherwise incompatible. Typically, an HVDC system provides unique or superior capabilities in the following aspects:

– long distance bulk power transmission;
– asynchronous interconnections;
– long distance cable;
– controllability;
– lower losses;
– environmental concerns;
– limitation of short-circuit currents.

The voltage sourced converter (VSC) HVDC transmission system is a new generation of HVDC transmission technology, which can increase the reliability of power grids and provide an alternative to connecting wind farms or solar farms to power grids, providing power to islands, connecting asynchronous grids and building direct current (DC) grids. VSC HVDC can provide:

– independent decoupled control of active and reactive power;
– power supply for weak or even passive networks without a need for AC network to provide commutating voltage;
– simultaneous support of both active and reactive power to the AC power systems, which is beneficial for enhancing system reliability and improving power quality.

Simply due to these technical merits, the market demand for VSC HVDC transmission technology is spreading widely over the world. VSC HVDC has been selected for a number of transmission projects aimed at exchanging energy between areas and connection of remote renewable energy sources such as offshore wind farms to onshore.

With the fast development of the VSC HVDC power transmission industry, IEC standardization work has been carried out accordingly. Up to the time of writing, more than four IEC documents, related to VSC DC equipment and systems have been published. Among these, IEC 62747, IEC TR 62543, IEC 62501, and the IEC TS 62751 series provide essential information for the design and operation of VSC HVDC transmission systems.

This document provides, as a supplement to above publications, a basic guide in VSC HVDC transmission system design and operation.

This document is part one of a series of three intended technical reports, covering steady-state performance, while parts two and three (yet to be published) are intended to cover transient performance and dynamic performance, respectively.

PERFORMANCE OF VOLTAGE SOURCED CONVERTER (VSC) BASED HIGH-VOLTAGE DIRECT CURRENT (HVDC) TRANSMISSION –

Part 1: Steady-state conditions

1 Scope

The objective of this Technical Report is to present the "state of the art" with respect to general guidance on the steady-state performance demands of VSC HVDC transmission systems. It concerns the steady-state performance of two-terminal VSC HVDC transmission systems utilizing converters with power flow capability in both directions.

Different configurations of a VSC HVDC transmission system are covered in this document, including the symmetrical monopolar, asymmetrical monopolar, bipolar with earth return, bipolar with dedicated metallic return and rigid bipolar configurations.

There are many variations between different VSC HVDC transmission systems. This document does not consider these in detail; consequently, it cannot be used directly as a specification for a particular project, but rather to provide the general basis for the system steady-state performance demands.

Normally, the performance specifications are based on a complete system including two VSC HVDC converter stations. However, sometimes a VSC HVDC transmission system can also be separately specified and purchased from multiple vendors instead of single turnkey vendor. In such cases, due consideration can be given to the coordination of each part with the overall VSC HVDC system performance objectives and the interface of each with the system can be clearly defined. The major components of the VSC HVDC transmission system are presented in IEC 62747.

Referring to IEC 62747, an HVDC substation/converter station is defined as that part of the VSC HVDC transmission system which consists of one or more VSC converter units installed in a single location together with buildings, reactors, filters, reactive power supply, control, monitoring, protective, measuring and auxiliary equipment. The AC substations are not covered in this document.

This document provides guidance and supporting information on the procedure for system design and the technical issues involved in the system design of VSC HVDC transmission projects for both owners and contractors. This document can be used as the basis for drafting a procurement specification and as a guide during project implementation.

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

3 Terms, definitions, and abbreviated terms

For the purposes of this document, the terms, definitions and abbreviated terms given in IEC 62747 and the following apply.

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

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

3.1 Terms and definitions

3.1.1
VSC phase unit
equipment used to connect the two DC terminals to one AC terminal

Note 1 to entry: In the simplest implementation, the VSC phase unit consists of two VSC valves, and in some case, it can include also valve reactors. The VSC phase unit can also include control and protection equipment, and other components.

[SOURCE: IEC 62747:2014, 7.7]

3.1.2
VSC unit
three VSC phase units, together with VSC unit control equipment, essential protective and switching devices, DC storage capacitors, phase reactors and auxiliaries, if any, used for conversion

[SOURCE: IEC 62747:2014, 7.6]

3.1.3
VSC converter unit
indivisible operative unit comprising all equipment between the point of connection on the AC side and the point of connection on the DC side, essentially one or more VSC converters, together with one or more interface transformers, converter unit control equipment, essential protective and switching devices and auxiliaries, if any, used for conversion

[SOURCE: IEC 62747:2014, 7.5, modified – Addition of "VSC" to the term "converter unit" and in the definition replacement of "common coupling" with "connection" and "VSC units" with "VSC converters".]

3.1.4
VSC converter station
part of an VSC HVDC system which consists of one or more VSC converter units including DC switchgear, 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

3.1.5
VSC HVDC system
high-voltage direct current transmission system connecting two VSC converter stations transferring energy in the form of HVDC including related transmission lines and/or cables, switching stations, if any, as well as other equipment and sub-systems needed for operation

3.2 Abbreviated terms

The following abbreviated terms are used in the document.

AC	alternating current
AM	amplitude modulation
ASMP	asymmetrical monopole
BPS	bypass switch
BtB	back-to-back
BES	battery energy storage
C&P	control and protection
CPS	converter paralleling switch
DC	direct current
DCCT	current transformer for DC application
DCVT	voltage transformer for DC application
DG	diesel generator
DMR	dedicated metallic return
DMRTS	dedicated metallic return transfer switch
EMC	electromagnetic compatibility
ERTS	earth return transfer switch
FACTS	flexible AC transmission systems
FB	full-bridge
GIL	gas-insulated transmission line
GIS	gas-insulated metal enclosed switchgear
HB	half-bridge
HV	high voltage
HVDC	high-voltage direct current
IGBT	insulated-gate bipolar transistor
ITU	international telecommunication union
LCC	line-commutated converter
MMC	modular multi-level converter
MV	medium voltage
NBS	neutral bus switch
NBES	neutral bus earthing switch
PCC	point of common coupling
PLC	power line carrier
p.u.	per unit
RF	radio frequency
RFI	radio frequency interference
RMS	root mean square
SCADA	supervisory control and data acquisition
SCL	short-circuit level
SCR	short-circuit ratio
SMP	symmetrical monopole

SNR	signal-to-noise ratio
SSTI	sub-synchronous torsional interaction
STATCOM	static synchronous reactive power compensator
UPS	uninterruptible power system
VCU	valve control units
VBC	valve base controller
VBE	valve base electronics
VSC	voltage sourced converter

4 Classifications of VSC HVDC systems

4.1 General

Generally, in studies of projects of the classifications of VSC HVDC systems, this document focuses on the two-terminal point-to-point configuration. The economic considerations can take into account the capital costs, the cost of losses, cost of outages and other expected annual expenses. The voltage and current ratings for a given power rating can be optimized to achieve the lowest system cost, including the evaluated cost of losses. Ordinarily, the user does not need to specify the direct voltage and current ratings, unless there are specific reasons to do so, for example, for compatibility with an already existing station, to provide for a future extension or for some other reasons.

The VSC HVDC system can be operated in different configurations such as with or without transmission lines, monopolar or bipolar configurations, etc., which are further divided and shown below:

– symmetrical monopolar HVDC system,
– asymmetrical monopolar HVDC system,
– bipolar HVDC system,
– back-to-back HVDC system.

In each configuration above, the VSC HVDC system can also be classified in terms of:

– series and parallel connections of the VSC converter units,
– interface transformer arrangements.

4.2 Symmetrical monopolar HVDC system

In a symmetrical monopole (SMP), the HVDC system employs one VSC converter per station feeding a symmetrical transmission line with equal line to ground voltages on the positive and negative poles and no low impedance ground connection. One of the advantages is that the interface transformers are not exposed to DC voltage under normal operating conditions hence their design is similar to that of conventional high voltage AC transmission transformers. A defined impedance to ground is needed at DC side or AC side in order to control the DC voltages to ground including balancing the positive and negative pole DC voltages. Figure 1 shows a simplified illustration of an SMP system with AC side earthing impedance.

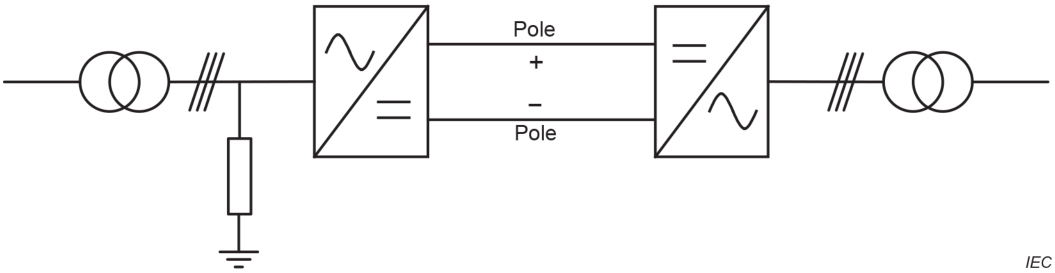


Figure 1 – Symmetrical monopolar VSC HVDC system

4.3 Asymmetrical monopolar HVDC system

4.3.1 General

With an asymmetrical monopole (ASMP), the asymmetrical monopolar configuration can be the first stage in the development of a bipolar scheme. An ASMP HVDC system typically features one converter at each end of the transmission line. Voltages of the two DC output terminals of the converter are asymmetrical. One end of the converter can be grounded directly on the DC side, through an impedance or through the electrode transmission line. The DC side configuration of an ASMP system can be with earth return or metallic return, as shown in Figure 2 and Figure 3.

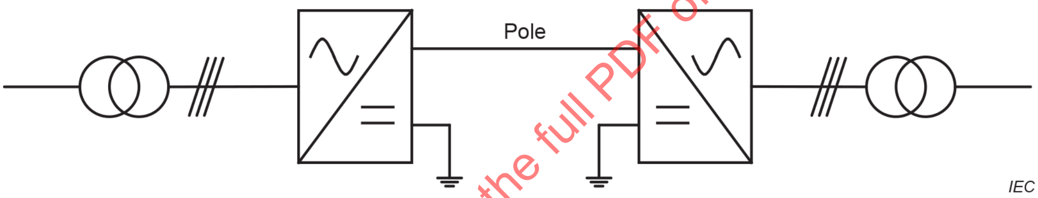


Figure 2 – Asymmetrical monopolar VSC HVDC system with earth return

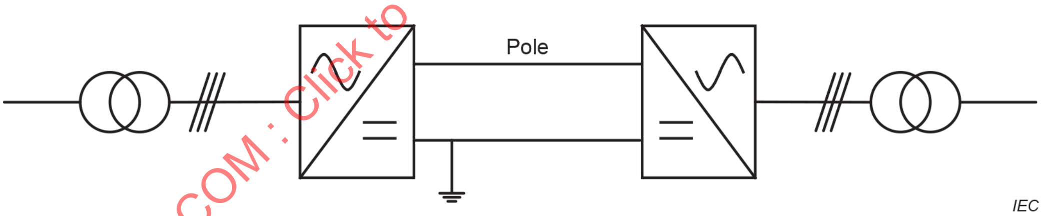


Figure 3 – Asymmetrical monopolar VSC HVDC system with metallic return

4.3.2 ASMP with earth return

For an ASMP with earth return scheme, as illustrated in Figure 2, the system also needs an earth electrode line and continuously operable earth electrodes at the two ends of the transmission. The presence of current through the earth involves issues such as corrosion, magnetic field effects, etc., covered in IEC TS 62334.

4.3.3 ASMP with metallic return

For an ASMP with metallic return scheme, as illustrated in Figure 3, the metallic return configuration can generally be used for technical and/or economical optimization such as:

a) as the first stage in the construction of a bipolar system and if long-term flow of earth current is undesirable during the interim period. In such circumstances, the return path can be through the other pole line, or;

b) if the transmission line length is short enough to make it uneconomical and undesirable to build earth electrode lines and earth electrodes, or;

c) if the earth resistivity is high enough to impose an unreasonable economic penalty, or;

d) if long-term flow of earth current is unsuitable, e.g., because of environmental and safety regulations.

This metallic return configuration utilizes one pole conductor and one dedicated metallic return conductor. The neutral is connected at one of the two HVDC substations to its station earth either directly or via an impedance or, alternatively, to the associated earth electrode. The other HVDC substation neutral can be connected to its station earth through a capacitor or an arrester or both.

NOTE The metallic return conductor can be either a dedicated neutral conductor or another high voltage conductor.

4.4 Bipolar HVDC system

4.4.1 General

For a bipolar HVDC system, there are three configurations as given below:

- bipolar HVDC with earth return,
- rigid bipolar configuration,
- bipolar HVDC with dedicated metallic return.

The main advantage of this bipolar configuration is that it retains an availability of 50 % of the transmission capacity in case of one converter outage. In such cases the HVDC system operates as a monopole.

With the bipolar configuration, one pole has positive polarity to earth and the other pole has negative polarity to earth. For power flow direction change, the two poles reverse the directions of their currents rather than the polarities of their voltages. When both poles are in operation, the unbalance current flowing in the earth path can be kept at a very low value.

4.4.2 Bipolar HVDC with earth return

This arrangement is used when a DC transmission line connects two HVDC converter stations with electrodes provided for earth return operation, as shown in Figure 4. It is effectively equivalent to a double-circuit AC transmission. When combined, two monopolar earth return schemes can give a bipolar scheme.

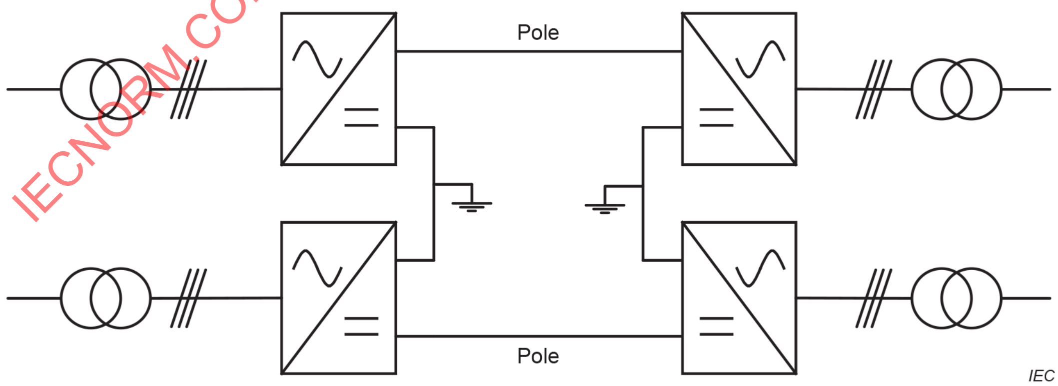


Figure 4 – Bipolar VSC HVDC system with earth return

4.4.3 Rigid bipolar configuration

A rigid bipolar HVDC system configuration is shown in Figure 5. With this scheme, operation is limited to naturally balanced DC current, however, the installation cost can be reduced. In case of outage of one pole line, the entire transmission capacity of the bipolar link is lost. In case of outage of one converter pole, 50 % of the transmission capacity can be restored after reconfiguration by DC switchgear for bypassing DC terminals of the failed converter bridge.

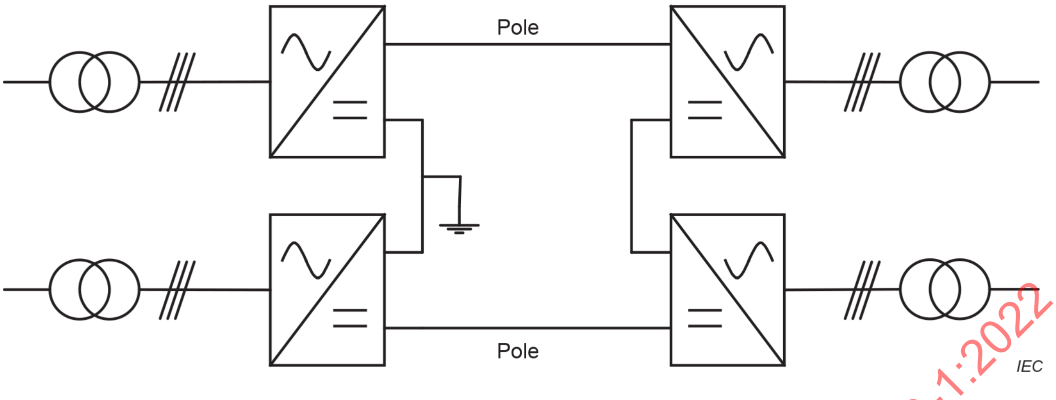


Figure 5 – Rigid bipolar VSC HVDC system

4.4.4 Bipolar HVDC with dedicated metallic return

The bipolar HVDC with dedicated metallic return (DMR) can be constructed with a third conductor, as shown in Figure 6. This third conductor carries unbalanced currents during bipolar operation. It also serves as the return path when one transmission line pole is out of service. This third conductor needs only reduced voltage insulation.

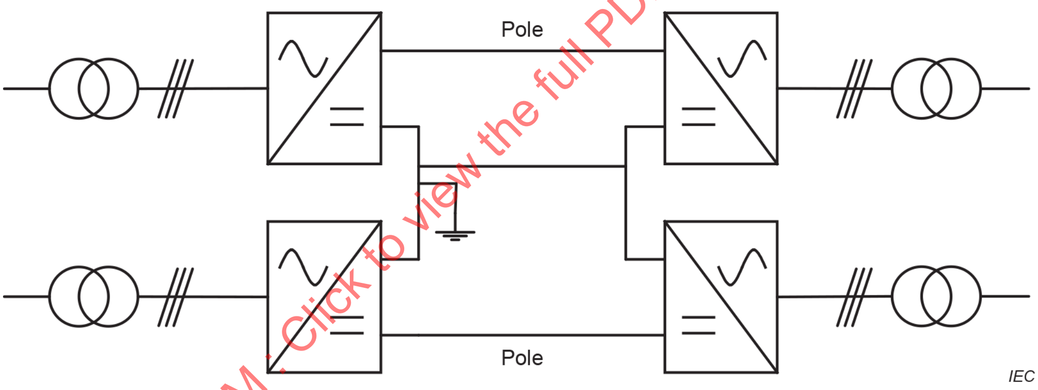


Figure 6 – Bipolar HVDC system with dedicated metallic return

The neutral of one of the two HVDC substations can be earthed, while the neutral at the other end of the transmission can float or be tied to its station earth through an arrester, a capacitor or both.

4.5 Back-to-back HVDC system

The back-to-back (BtB) configuration is a special case of VSC HVDC transmission. In this arrangement, there is no DC transmission line/cable and both converters are located at one site and connected via DC busbars. The converters can be located in one hall, or even in one integrated structure. Similarly, many other items for the two converters, such as the control system, cooling equipment, auxiliary system, etc., can be located in one area or even integrated in layout into configurations common to the two converters. The circuit configurations of the BtB can vary.

4.6 Interface transformer arrangements

Interface transformer is used for coupling of VSC HVDC system to AC network. There are a number of commonly used design alternatives:

- three-phase transformer, or single-phase transformer;
- two-winding transformer, or three-winding transformer, e.g. tertiary winding can be used to supply auxiliary power for the station;
- DC offset or not.

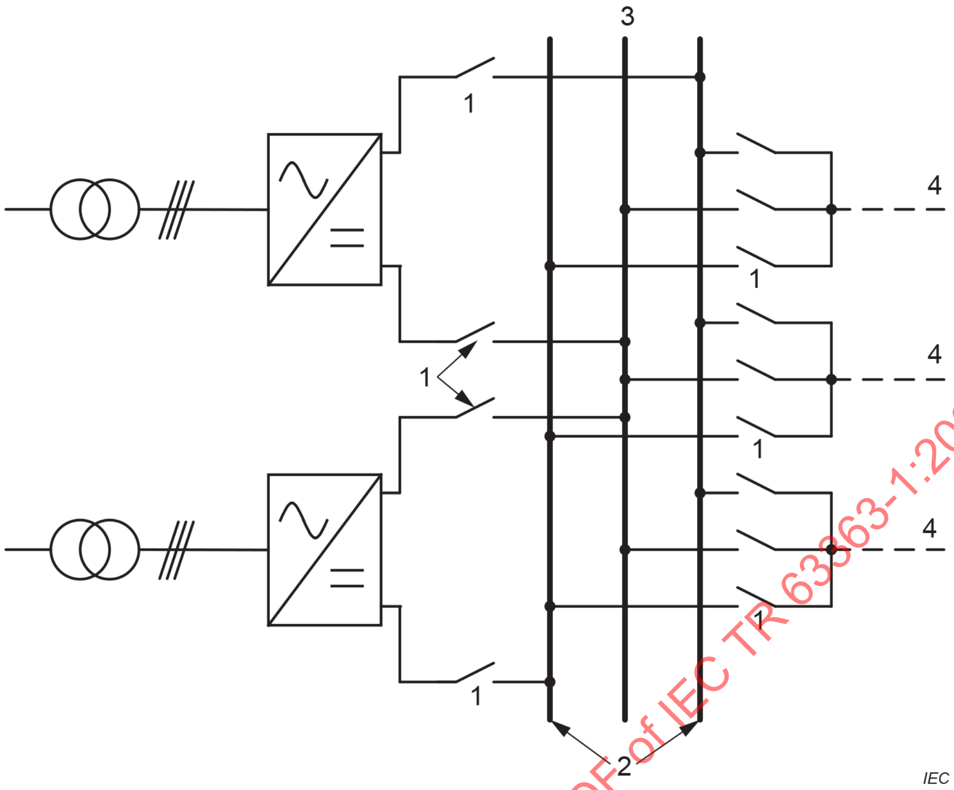
In a symmetrical monopole VSC HVDC system, theoretically, it is possible that the interface transformer cannot be needed. However, in order to mitigate significant stresses due to the overvoltage and the short-circuit current, most projects have employed an interface transformer. And, in the case of a BtB scheme, for selecting optimal DC voltage, the interface transformer is indispensable.

For a bipolar VSC HVDC system, a high insulation level design of the interface transformer can be needed to accommodate the DC stress on the secondary windings due to DC voltage offset.

4.7 Switching and reconfiguration

4.7.1 Converter station and DC yard switching

In bipolar systems, DC switching can be provided, as shown in Figure 7, so that any conductor can be used for connection to any substation pole or to neutral. This can increase HVDC system availability by operating in monopole metallic return operation in the event of a fault in any cable. This arrangement is useful for a scheme involving cables and where a fully insulated spare cable is available or cables are connected in parallel. If one substation pole is out of service, the cables can be paralleled to reduce line losses. Generally, DC buses are fixed in relation to converters, with two pole buses and a neutral bus. This can prevent connection of the two substation poles in parallel.



Key

1 DC switches

2 DC bus

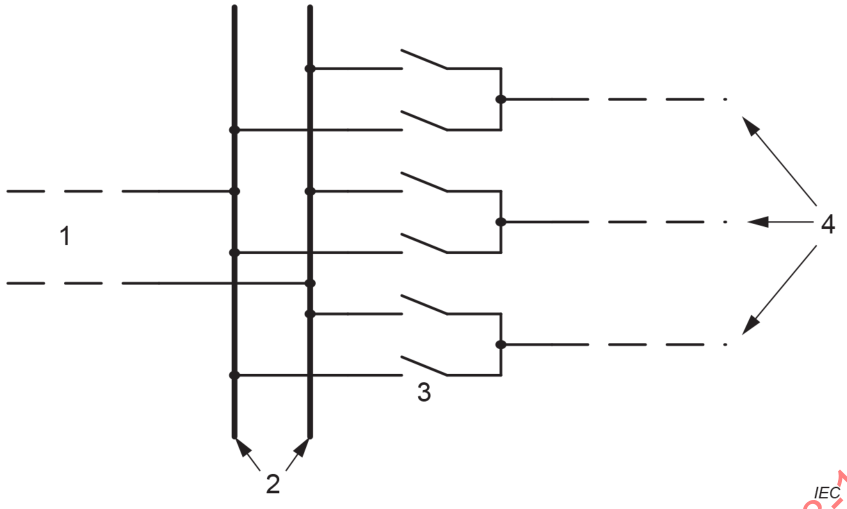
3 Neutral bus

4 DC line/cable

Figure 7 – DC switching of line conductors

4.7.2 Transition station switching

If the HVDC transmission system includes both overhead lines and cable sections, the overhead line and cable switching arrangement (transition) such as in Figure 8 can be used at the junction of the overhead lines and cable sections.



Key

1 DC overhead lines

2 DC bus

3 DC switches

4 DC cables (two poles, one spare if needed)

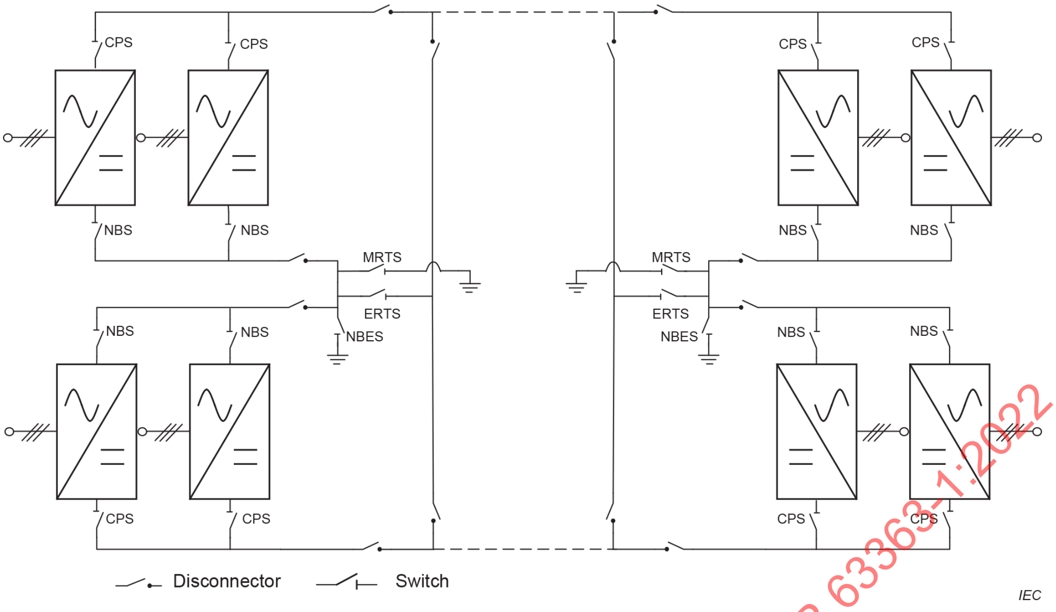
Figure 8 – DC switching – Overhead line to cable

4.7.3 Connecting multiple converters

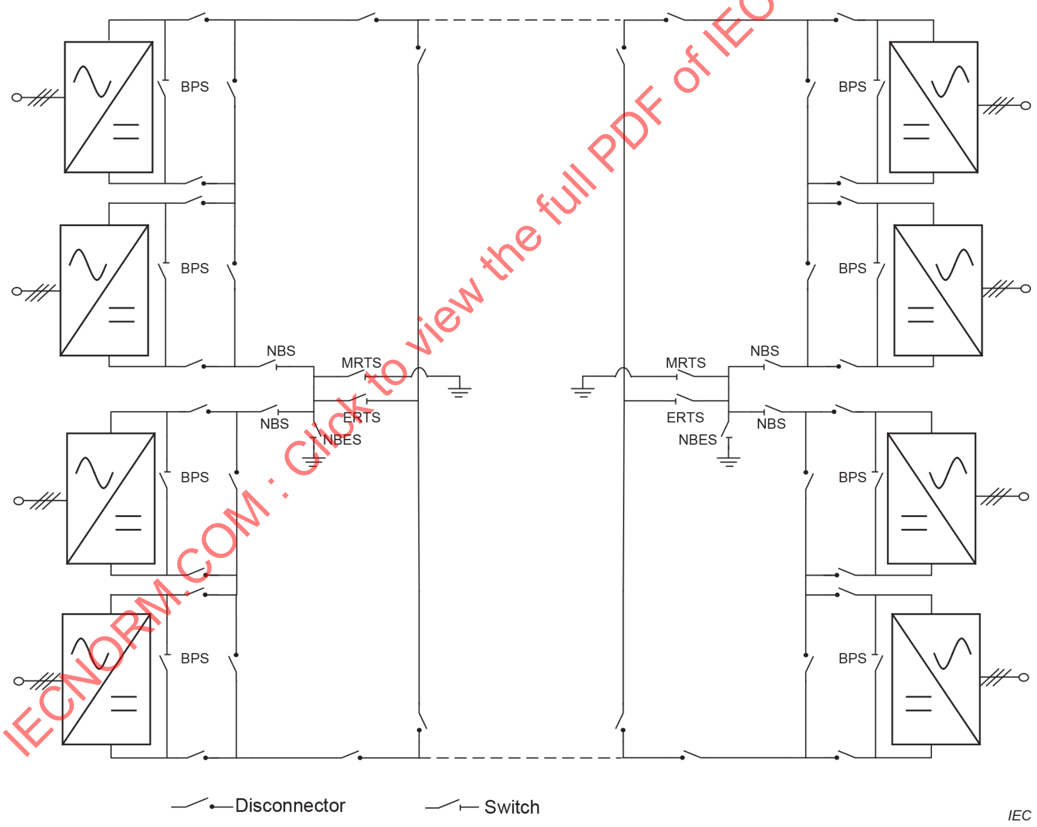
4.7.3.1 General

On the DC side, more than two VSC converter units can be connected in parallel or in series. However, the increased complexity of multiple converter units needs to be evaluated with regard to project-specific demands.

Figure 9 gives the examples of the DC switchyard for a bipolar VSC HVDC system with two VSC converter units in parallel (Figure 9 a)) and series (Figure 9 b)) connections per pole.



a) Two VSC converter units in parallel connection per pole



b) Two VSC converter units in series connection per pole

Key

CPS Converter paralleling switch

BPS Bypass switch

ERTS Earth return transfer switch

MRTS Metallic return transfer switch

NBS Neutral bus switch

NBES Neutral bus earthing switch

Figure 9 – Examples of VSC HVDC system with two converter units per pole

The bipolar configuration offers a number of operating modes. Consequently, the following demands can be considered in the specifications.

a) During an outage of one HVDC transmission line, the converter equipment of the other pole can be capable of operation with earth return or using the DMR. Note that this option is unavailable with the rigid bipole configuration.

b) During an outage of one or more HVDC converter stations of one pole, if long-term flow of earth current is undesirable and if the defective line pole still retains some low voltage insulating capability, the bipolar system can be capable of operation in the monopole metallic return mode. To switch into this emergency operating mode, the conductor of the out-of-service pole is first connected in parallel with the earth path and then the earth path is interrupted to transfer the current to the metallic path (through the conductor of the out-of-service pole). Load transfer without interruption needs a metallic return transfer switch (MRTS) at one terminal of the DC transmission. If the power flow can be interrupted shortly, it is possible that the MRTS is unneeded. The neutral equipment at the MRTS end of the HVDC transmission system can be insulated from earth for a somewhat higher voltage than at the other end of the system.

c) During maintenance of the earth electrode(s) or the earth electrode line(s), operation of the bipolar system can be with the station neutral(s) connected to the station earth at one or both HVDC substations as long as the unbalance current between the two poles entering the station earth(s) is kept at a reasonable value. In this arrangement when one transmission line of a substation pole is lost, both poles can be blocked automatically.

d) In bipolar operation with both earth electrodes connected, the two poles of the HVDC system can be capable of operation with substantially different currents in each pole. This can be needed if loss of cooling or some other unusual condition prevents the operation of one pole with full current. Note that this option is unavailable with the rigid bipolar configuration.

e) In the event of the loss of one transmission line pole, the two substation poles can also theoretically be connected in parallel by using appropriate switches for polarity reversal in at least one station pole enabling both poles to operate in the monopole earth return mode. This, however, needs that both DC terminals of both converters be insulated for the full pole voltage and that the line and the earth electrode can be thermally capable of carrying a current higher than the nominal current.

If the HVDC system includes an overhead line, DC filters (e.g. power line carriers, PLCs) can be needed to eliminate the impacts of radio-frequency interferences generated in converter stations on the DC lines.

The switch and disconnector in Figure 9 are as defined in IEC 62271-1:2017, 3.4.1 and 3.4.2.

4.7.3.2 Converter paralleling switch (CPS)

If the HVDC transmission system has two converters connected in parallel in each pole, as shown in Figure 9 a), the converter paralleling switch (CPS) can be used to increase the system flexibility. Such a switch can isolate converters that are faulty or need maintenance without affecting the normal operation of other equipment.

4.7.3.3 High speed bypass switch (BPS)

For an HVDC system with two converters connected in series in each pole, as shown in Figure 9 b), the high speed bypass switch (BPS) can be used to decrease the pole contingency rate and increase the system availability. The switches mentioned here are optional.

In the case of a half-bridge (HB) VSC HVDC system, in order to avoid a short-circuit between the DC terminals of the converter unit with large short-circuit current, the AC side circuit breaker needs to be opened before closing DC BPS for DC current commutation.

4.7.3.4 Neutral bus switch (NBS)

Within a bipolar HVDC system, to transfer between various operation configurations and increase utilization of the whole HVDC system, the high-speed DC switches, such as a neutral bus switch (NBS), can be used. The NBS connected in series with the neutral bus on a bipolar HVDC scheme is designed to commutate current from the pole conductor or neutral bus to the electrode line or dedicated metallic return conductor in the event of a pole to earth fault or neutral bus to earth fault during bipolar operation.

4.7.3.5 Neutral bus earthing switch (NBES)

A neutral bus earthing (grounding) switch (NBES) can be installed to further increase the reliability and availability of the HVDC system.

For the application with earth return, the NBES is installed on the neutral bus at both ends and is open in normal operation. The NBES can be closed automatically if grounding connection is lost in the balanced bipolar operation mode. The NBES cannot be assumed to have a significant current transfer capability, but is capable of opening during bipolar operation hence transferring the unbalanced current to the earth electrode.

For the application with dedicated metallic return (DMR) line, the NBES is installed at the insulated end of the neutral circuit and is open in normal operation. During bipole operation with balanced current, the NBES can be closed automatically when the DMR is out of service. When an earthing fault occurs at the DMR line, especially in monopole operation, part of the DC current of the DMR line can flow to the fault location. In order to protect insulators, the NBES is closed within several hundred milliseconds to transfer the fault current from the DMR line insulator surface path to the converter station grounding mesh. After the expected time when the fault current is extinguished and deionized, the NBES is opened to commutate the DC current from the path of the earthing mesh to the original neutral circuit. In this application, the NBES is assumed to have a significant current transfer capability.

4.7.3.6 Earth return transfer switch (ERTS)

For a bipolar system with earth as return circuit, an earth return transfer switch (ERTS) can be installed when it is needed to transfer the configuration from a monopole metallic return to an earth return without interrupting power transfer.

4.7.3.7 Metallic return transfer switch (MRTS)

For a bipolar system using an earth electrode or dedicated metallic return (DMR) as the return path, one of the converter stations can be equipped with a metallic return transfer switch (MRTS). In a DMR application, the MRTS is also called the dedicated metallic return transfer switch (DMRTS). The MRTS is used for current transfer from monopole earth return or DMR return to another return circuit, i.e., a pole line without interrupting power transfer when it is needed.

If the commutation current level is beyond the capability of the DC switches when switching between configurations, the HVDC transmission power can be temporarily reduced within the commutation capability of the switches as long as there is no significant disturbance to system operation, and thereafter increased to the maximum as needed. In a DMR scheme, the DC fault current can flow into the AC system and come back through neutral point of transformers installed in the converter station. This current can lead to the malfunction of protective relays installed in nearby stations, because of saturation due to DC current. To prevent such malfunctions, insertion of neutral grounding resistors (small resistance) to transformers in the converter station can be effective.

4.7.4 DC gas-insulated metal enclosed switchgear (DC GIS)

Within the DC switchyard, normally air-insulated equipment is used. However, the DC gas-insulated metal enclosed switchgear (DC GIS) can be of particular interest for space-saving where space comes at a high premium.

The DC GIS can comprise at least the following equipment: busbars/busducts, disconnectors, earthing switches, DCCTs (i.e. current transformers for DC application, refer to IEC 61869-14), DCVTs (i.e. voltage transformers for DC application, refer to IEC 61869-15), bushings, and appropriate insulation medium and enclosure. In addition, connections and sensors can be provided to facilitate monitoring and testing of partial discharges.

The DC switchyard configurations of the VSC HVDC system are the same or similar to line-commutated converter (LCC). For further information, refer to IEC TR 63127.

5 Environmental information

The location and the information listed in Table 1 can be supplied for each HVDC converter station.

Table 1 – Information supplied for HVDC substation

Parameter	Unit		Examples of use and comments
Height above sea-level	m		For the design of air-cooling systems and for air clearances
Outdoor air temperature	°C		The maximum temperatures are given for rating purposes and the low temperatures for overload capability demands. If the user intends to overload the equipment and accept a corresponding loss-of-life expectancy, this can be stated and the essential information supplied
	For low temperature capability	For rated power capability	If preferred, curves showing how these parameters vary over the year, on a monthly basis, can be provided instead
Maximum dry-bulb temperature	°C	°C	Valve cooling, oil insulated transformer and air-cored reactor design
Maximum wet-bulb temperature	°C	°C	Evaporative cooling system design and of valve hall relative humidity
Maximum average dry-bulb temperature for a period of 24 h	°C	°C	Oil insulated transformer and air-cored reactor design
Minimum average dry-bulb temperature for a period of 24 h	°C	-	Oil insulated transformer, air-cored reactor and disconnector switch design and building heating needs
Minimum dry-bulb temperature	°C	-	Oil insulated transformer, air-cored reactor and disconnector switch design and building heating needs
Maximum and minimum indoor air temperatures and relative humidity	°C %	°C %	Usually determined by the valve designer for the valve hall and by the control designer for the control room
Indoor air temperatures and relative humidity during maintenance and maximum transition time after shutdown	°C %	°C %	Specified if indoor temperature extremes are too great for maintenance personnel
Maximum incident solar radiation			Building cooling, ratings of transformers, reactors, buses, etc.
Horizontal surface	W/m^2		
Vertical surface	W/m^2		

Parameter	Unit		Examples of use and comments
Wind conditions			
Maximum continuous velocity	m/s		Equipment support and building design
Maximum gust velocity	m/s		Equipment support and building design
Maximum velocity at a minimum temperature ….. °C	m/s		Conductor, strain insulator and tower design
Ice and snow covering load			
Maximum ice thickness with no wind	mm		Equipment and structure design, for example, disconnector/switch, conductor, etc.
Maximum ice thickness with a maximum wind of …..m/s	mm		Equipment and structure design, for example, disconnector/switch, conductor, etc.
Maximum snow load	N/m^2		Building design
Maximum depth of snow	mm		Equipment height above snow for safety purposes
Rainfall			Building and site drainage
Annual average	mm		
Maximum in a period of 1 h	mm		
Maximum in a period of 5 min	mm		
Fog and contamination Utility practice for insulator washing and greasing			To determine demands for insulation and air-cooled equipment. An estimated equivalent salt deposit density level can be specified for equipment design
Keraunic level at the station and the first 5 km to 10 km of the line	Strokes/km²/year (substation) Strokes/100 km/year(line)		Station lightning protection design
Seismic conditions			Equipment, structure and foundation design
Maximum horizontal acceleration	m/s^2		
frequency range of horizontal oscillations	Hz		
Maximum vertical acceleration	m/s^2		
frequency range of vertical oscillations	Hz		
Duration of seismic event	s		
Cooling water available at the site (if used for secondary cooling)			Secondary cooling water can be used either for make-up and blow-down of evaporative coolers or for once-through cooling. Evaporative cooling towers can be a source of high humidity for the insulators and can be carefully located
Source of water			Reservoir, well, etc. If preferred, curves showing how these parameters vary over the year on a monthly basis can be provided instead.
	For low temperature capability	For rated power capability	
Maximum continuous flow rate	m^3/s	m^3/s	Needed for cooling system design
Maximum flow rate for a period of 24 h	m^3/s	m^3/s	Needed for cooling system design
Minimum continuous flow rate	m^3/s	m^3/s	Needed for cooling system design
Minimum flow rate for a period of 24 h	m^3/s	m^3/s	Needed for cooling system design
Maximum water temperature	-	°C	Needed for cooling system design
Minimum water temperature	°C	-	Needed for cooling system design

Parameter	Unit	Examples of use and comments
Maximum allowable water temperature to drain pH level	°C °C	Needed for cooling system design Design of water treatment plant
   Conductivity of water Type of dissolved solids Quantity of dissolved solids Type of undissolved solids Quantity of undissolved solids	 μ Siemens/m g/m^3 g/m^3	Parameters apply only in the case where well water is used for evaporative cooling Design of water treatment plant Design of water treatment plant Design of water treatment plant Design of water treatment plant Design of water treatment plant
Maximum earth resistivity at the HVDC substation – Depth of water table – Site soil conditions	Ωm m	Station earth design Foundation design Bore hole information (for example, rocks) and any special conditions, such as maximum frost depths, foundation design
– Site accessibility – Weight and size limitations for transportation	 kg, m	To determine installation and delivery costs Equipment design – especially transformers and reactors
– Local profile limitations on equipment and buildings – Environmental considerations		Influence on equipment, bus and building design Audible noise limits, aesthetic demands – architectural treatment, landscaping, etc.
Any special conditions not listed above, for instance, related regulations, transportation limitations, etc. which influence system performance can be given.		

6 Rated power, current and voltage

6.1 Rated power

Rated power is the active power which the VSC HVDC transmission system is able to operate continuously, over the range of ambient conditions specified, with all equipment in service, but with or without the need to utilize redundant components depending on the specification; the VSC HVDC system voltage and frequency being in their steady state ranges.

Because the VSC HVDC transmission system in general consists of three sections, that is the two VSC HVDC substations and the transmission line, each of which produces losses, the point and the method of determination of rated power can be specified.

Normally, the rated power of the VSC HVDC transmission system can be defined either at DC or AC side and either at sending or receiving end. If the same power rating is need in both directions, such as with system ties for power exchange, this can be stated. Where power flow is primarily in one direction, such as with systems fed from remote generation, rated power can be specified only for that direction to optimize the system cost.

6.2 Rated DC current

Rated DC current is the mean value of the direct current that the system is able to transmit continuously for all ambient conditions specified and without time limitations.

6.3 Rated DC voltage

Rated DC voltage is the maximum continuous mean operating direct voltage of the VSC, excluding harmonics and ripples for which the equipment is designed.

For long distance HVDC transmission systems, the rated DC voltage is generally specified at the sending end. If the voltage capability of the HVDC transmission line is higher than the rated DC voltage, then this can be stated.

7 Steady-state operation

7.1 General

In the VSC HVDC system, each VSC converter station is able to control the reactive power independently from the active power within the rated values. The exchange of reactive power between a VSC converter station and the AC system can be controlled by the amplitude of the VSC output voltage in relation to the voltage of the AC system.

The reactive power flow can however be limited by the voltage and current capabilities of the VSC converter. Voltage and current levels and reactive power flow need to be coordinated to let the VSC HVDC system operate within reasonable limits.

The tap position of interface transformers equipped with an on-load tap changer as well as the sources of reactive power included in the VSC converter station, such as shunt capacitors, shunt reactors, series capacitors, static synchronous reactive power compensators (STATCOMs) can be considered in the active and reactive power capability of the VSC HVDC system.

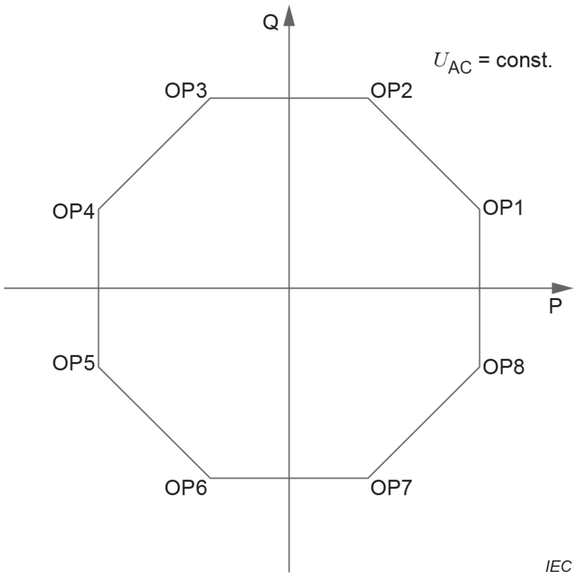
In STATCOM mode of operation, the VSC converter can only exchange reactive power to the AC terminals and without energy transfer on the DC lines or cables except the losses.

7.2 PQ diagram

The PQ diagram of the VSC HVDC system defines its possible steady-state active and reactive powers operating regime. The diagram normally gives the capability at the AC interface point. When active output power P is positive, the VSC is operated as an inverter, either in capacitive mode, when Q is positive, or in inductive mode when Q is negative. When P is negative, the VSC is operated as a rectifier, either in capacitive or inductive mode. The VSC can be operated within all four quadrants of the PQ plane.

The steady-state active and reactive power capabilities of the VSC HVDC system are described by the maximum and minimum reactive power exchange capabilities (inductive and capacitive) depending on active power and AC voltage at the PCC. These can be specified in the PQ diagrams for different AC voltage levels (i.e. U_{AC} = const.).

Figure 10 gives an example of the PQ diagram, showing the maximum and minimum reactive power (inductive and capacitive) exchange capabilities of the VSC converter. In the diagram, a number of operating points (e.g. OP1-OP8) of the VSC converter can be defined as needed.



Key

U_{AC} AC voltage at PCC

OPi Operating points of the VSC converter (i = 1, 2, 3, ---, 8)

Figure 10 – Example of PQ diagram of the VSC converter

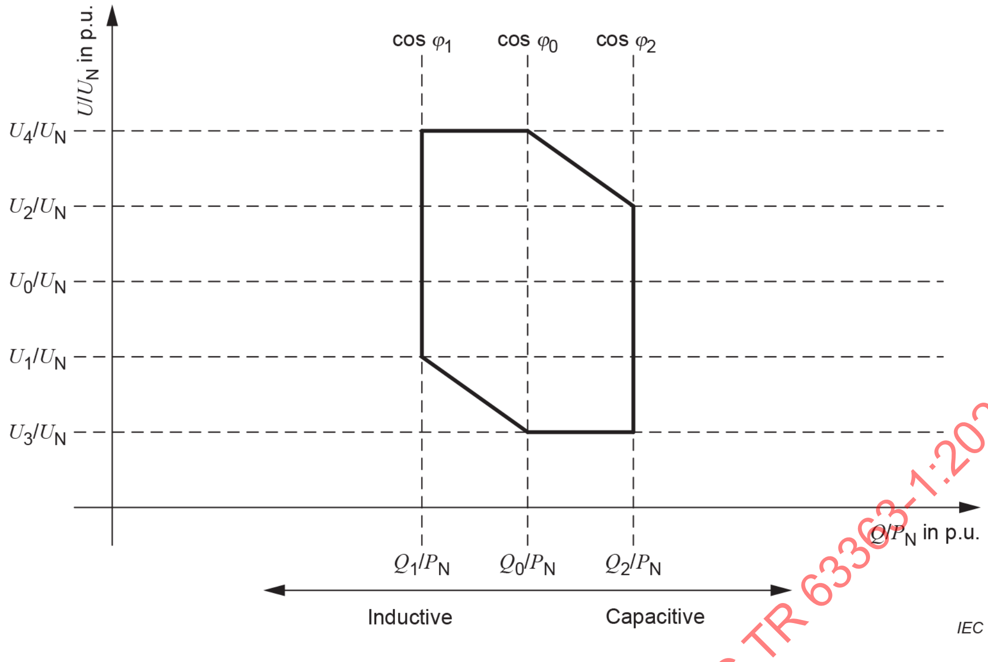
Figure 10 shows that the active and reactive power capabilities of the VSC converter depend on the AC grid voltage. The PQ diagram can be given for a specified AC voltage range (e.g. a range between maximum and minimum AC voltages). However, at a lower AC voltage, a higher current is needed to produce a given output power, and the output capability is limited by the current capability of the VSC converter and with half-bridge converters, also by the DC voltage. Therefore, if an interface transformer is provided, the transformer ratio can be used to optimize the PQ diagram. With an on-load tap changer, the transformer ratio can be continuously optimized to maximize the steady-state power capability of the VSC converter.

If the PQ diagram is built from different tap positions of the interface transformer or reactive power supply from other devices, additional PQ diagrams can be provided to identify the areas of dynamic control.

NOTE The fundamental PQ equations and typical power-circle diagrams of the VSC converter can be found in Annex A.

7.3 UQ diagram

The UQ diagram of the VSC HVDC system gives its possible steady-state AC voltage and reactive power operating regime. The reactive power exchange of the VSC converter can be affected by both power factor and the AC voltage. The minimum demands for the exchange of reactive power depending on the AC voltage are determined by the UQ profile as an example shown in Figure 11.



Key

U_N	Nominal AC voltage at PCC
P_N	Nominal active power (i.e. maximum transmitted active power of the VSC converter)
U_i	Operating AC voltages (i = 0, 1, 2, 3, 4, ---) at PCC
Q_i	Exchanged reactive powers (i = 0, 1, 2, ---) at PCC
cosφ_i	Power factors ((i = 0, 1, 2, ---) at PCC

Figure 11 – Example of UQ diagram of the VSC converter

The VSC converter can be capable of reaching every operation point within its UQ diagram within a specific time duration. The operation point within the UQ diagram is determined by the VSC reactive power control.

NOTE Areas of the UQ diagram which are not part of the normal operating range can be explored by fast dynamic voltage support functions.

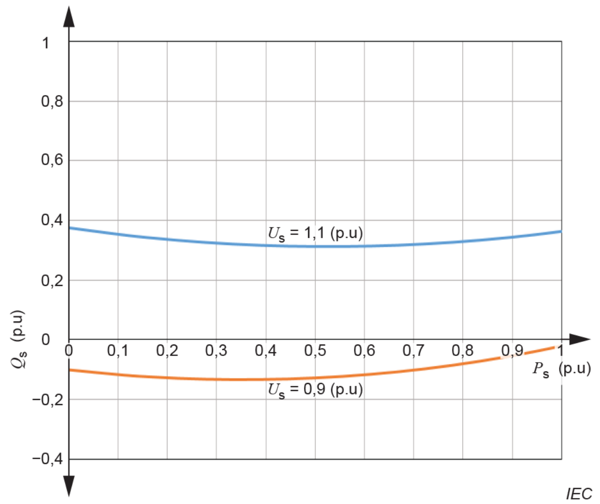
The sources of reactive power supply to meet a set of demands can include the most economical combination of VSC converters, shunt capacitors, shunt reactors, series capacitors, STATCOMs that meets the steady-state performance criteria.

If the UQ diagram is built from different tap positions of the interface transformer or reactive power supply from other devices, additional UQ diagrams can be provided to identify the areas of dynamic control.

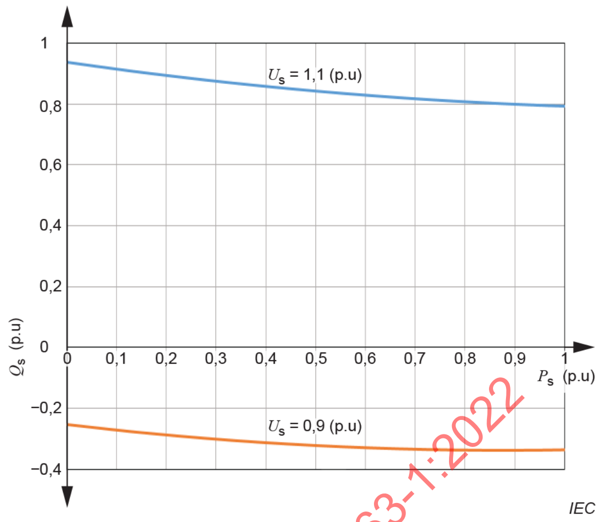
7.4 Reactive power exchange

The reactive power exchange of the VSC HVDC system with the AC system is limited or influenced by the characteristics of the AC grid connection, especially on the equivalent short-circuit level (SCL) impedance at PCC of the VSC converter. The maximum and minimum SCLs at PCC of the VSC converter station can be considered in the design of the VSC converter capability.

Figure 12 presents an example of the reactive power exchanges of the VSC converter station with the AC system in different short-circuit ratios (e.g. SCR = 2,0 and SCR = 5,0) at PCC.



a) SCR = 2,0



b) SCR = 5,0

Figure 12 – Reactive power exchanges of the VSC converter station at PCC

The SCR is here defined as a ratio of the AC network SCL (in MVA) at 1,0 p.u. voltage at the PCC to the HVDC substation AC bus, to the rated DC power of the HVDC substation (in MW).

NOTE The relationship of reactive power exchange of the VSC converter with the AC network SCL impedance can be found in Annex B.

8 Overload and equipment capability

8.1 Overload

Overload, which is related to an operation of the HVDC substation, usually refers to direct current flow above the level corresponding to the rated value of active power transmission. Overload demand sometimes also includes reactive power. Overload capability can only be available when the needed overload current is included in the equipment capability, including the transmission line, for safe operation. Consideration can be given to suitable reduction in life expectancy of equipment (for example, due to thermal ageing), use of redundancy, and low ambient temperatures.

As a consequence, in order to meet the overload demand, over-dimensioning of equipment can be needed. For a more economical design, overload demands can be specified in detail, such as in terms of duration and magnitude in percentage of overload. However, some constraints can be observed for the HVDC substation equipment. Thermal time constants range from one second to some hours. Longer duration overload demands of high magnitude can, therefore, result in an effectively increased rating of equipment and thus impose a greater cost or a reduction of life expectancy. These factors can be weighed against system benefits when specifying overload.

The frequency and time intervals between such overload cycles can be specified as well.

8.2 Equipment capability

8.2.1 General

This is defined as the ability of the HVDC substation equipment to transmit power greater than rated, with reasonable loss of equipment life expectancy. It depends on operating conditions as well as on the design criteria for individual components. Implications resulting from the design criteria for individual components are discussed in subsequent subclauses with respect to their bearing on overload specifications.

Ambient temperature is an important factor. Power equipment is designed to perform at rated loading under the most adverse ambient conditions specified. However, these conditions normally prevail for only limited time periods. At low ambient temperatures, some margin can be available for increased capability, if the constraints listed in 8.2.4 can be overcome. This margin depends on the design chosen for the particular equipment and can differ for various HVDC substation components. An enveloping curve of transmission capability versus ambient temperature can be specified along with the AC system conditions to be met. This can be specified in terms of wet-bulb and dry-bulb ambient temperatures.

8.2.2 Converter valve capability

The thermal time constant of the power semi-conductor heat-sink combination in a VSC valve is rather small (several seconds up to a few minutes). Overloads following continuous operation at rated current and at maximum ambient temperatures increase the power semiconductor junction temperature. This can be considered with respect to the designed maximum operating junction temperature of the VSC valve. Consequently, VSC valve cooling can be designed so that safe operating temperatures are not exceeded even during specified overload operation.

If redundancy is provided in the valve cooling circuit, the VSC valves are normally designed such that the specified rating can be met under the most adverse ambient conditions and loss of power semiconductor cooling equipment redundancy. If additional capability is needed when redundant cooling is unavailable, this can be explicitly specified.

On the other hand, with redundant cooling equipment in service, extra thermal capability can be available. The resulting greater-than-normal current capabilities depend on the thermal design of the valve and on the cooling system.

In view of the above, converter overload specifications can state the magnitude and duration of overload. The converter suppliers can comply with design calculations taking the cooling equipment status and ambient temperatures into consideration.

8.2.3 Capability of oil-cooled transformers and dry type reactors

Suppliers of transformers and reactors can confirm the thermal time constants of the transformer or reactor windings, as well as equipment's overload capabilities and impact of loss-of-life expectancy.

8.2.4 Capability of other converter station equipment

All other converter station equipment, including busbar, switchgear, converter control and protection system as well as auxiliary systems, need to be designed for the specified overload capability.

9 Converter station types and operation modes

9.1 Converter station types

Five general types (Type A, Type B, Type C, Type D and Type E) of AC/DC converter station are defined differentiating a converter station's operating range with respect to DC voltage and DC current, as shown in Figure 13.

NOTE The rectangular shapes of the different types are indicative only. The technical and economic aspects can lead to different shapes.

- Type A:

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

- Type B:

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

- Type C:

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

- Type D:

  The converter station that can operate continuously in quadrants 1 and 2 at any DC voltage level. This type of converter station can extinguish DC fault currents by operating transiently in quadrants 3 and 4, expressed by the dash-dotted line in Figure 13, e.g. like a MMC based on hybrid half-bridge (HB) and full-bridge (FB) modules.

- Type E:

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

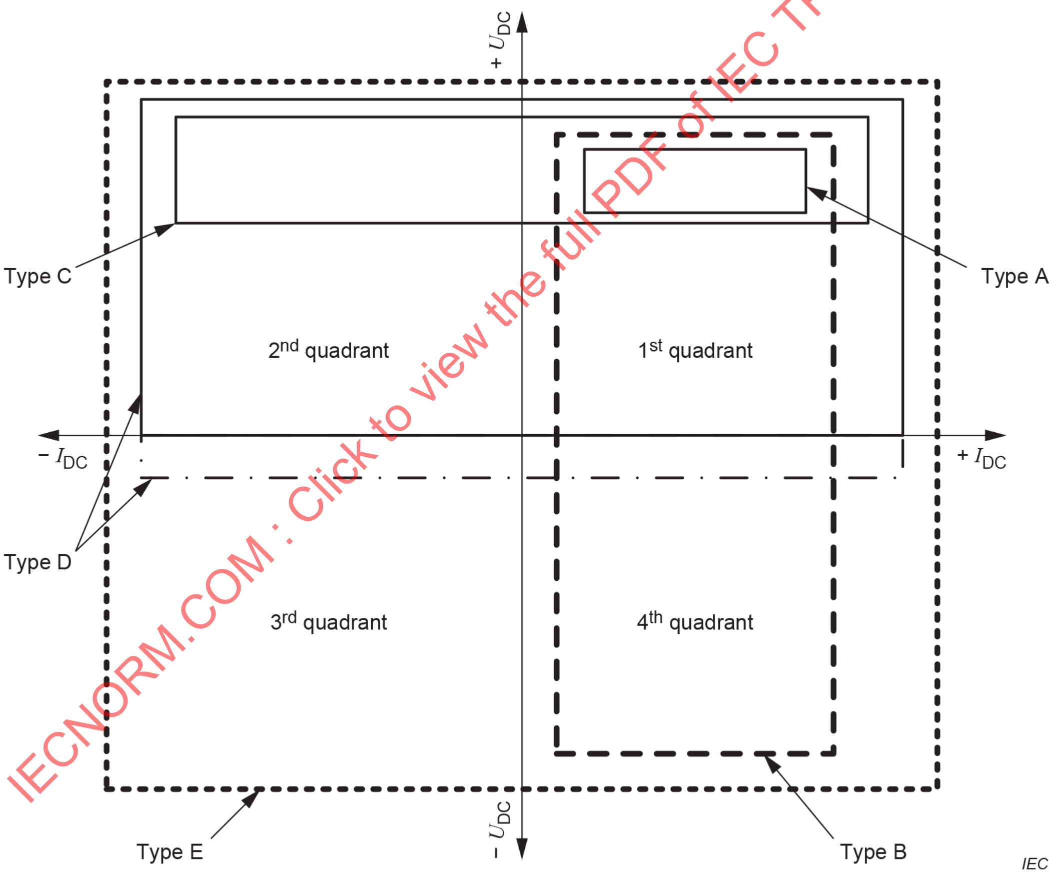


Figure 13 – AC/DC converter station types in the U/I diagram

The VSC converter station can be one of three types (Type C, Type D or Type E).

For further information, refer to CLC/TS 50654-1.

9.2 Operation modes

9.2.1 Reduced direct voltage operation

Under contamination conditions, often in combination with unfavourable weather conditions, operation of an overhead DC transmission line cannot be at its rated voltage. However, the HVDC converter can be designed to continue power flow at reduced transmission voltages. This reduced DC voltage operation depends on converter types and the projects case by case.

The VSC converter types C to E have different capabilities to operate with DC voltage variation. Type C converter has the ability to regulate DC voltage within a limited area. The type C converter can also be designed to normally operate with a reduced modulation index, in this case reduced voltage can be achieved by increasing the modulation index. This demand can mean a special valve design and thus increases valve costs and losses in normal conditions. Type D can operate continuously in quadrants 1 and 2 and transiently in quadrants 3 and 4 at different DC voltage levels. Type E converter can operate in all four quadrants and therefore fully control the DC voltage.

It is noted that operating at reduced voltage and modulation index implies that either the VSC converter needs to be operated at a higher current than normal and also that the losses can increase (for which it can need to be designed) or the real and reactive power orders can need to be reduced.

One possibility for all converter types is that the transformer tap changer can be moved to the position resulting in the lowest AC voltage for the converter. Other possibilities are that the tap changer range can be increased, or where the HVDC system is fed from an isolated power station, a reduction of AC bus voltage can also be considered.

The practical value for reduced DC voltage operation is at minimum 80 % of rated voltage, perhaps, with reduced performance.

9.2.2 Full direct voltage operation

The VSC HVDC system can operate with full DC voltage in several different operating states from "NOT ready" to be connected to the AC and DC systems, depending on availability of other parts of the HVDC system and objective of operation.

9.2.3 Operating sequences

9.2.3.1 General

The fundamental operating sequences of the VSC HVDC system describe the transition between the individual operating states of the HVDC system, sub-system or installation.

It can be emphasized that operating states and thus also respective sequences always relate to a specific grid component that can be either a single device (e.g. switch) or a group of devices (e.g. VSC converter units).

The operating sequences of the VSC HVDC system are defined as below:

– to start (from 'NOT ready' to 'Ready to energize')
– to energize (from 'Ready to energize' to 'Energized')
– to synchronize (from 'Energized' to 'Ready to connect')
– to connect (from 'Ready to connect' to 'Ready to transmit')
– to operate (from 'Ready to transmit' to 'In operation', switch)
– to unload (from 'In operation' to 'Ready to transmit')
– to disconnect (from 'Ready to transmit' to 'Ready to connect')

– to decouple (from 'Ready to connect' to 'Energized')
– to de-energize (from 'Energized' to 'Ready to energize')
– to emergency shut-down (from any state to 'NOT ready' → can be enforced by protective actions).

The operating sequence transitions of the VSC HVDC system can be as shown in Figure 14.

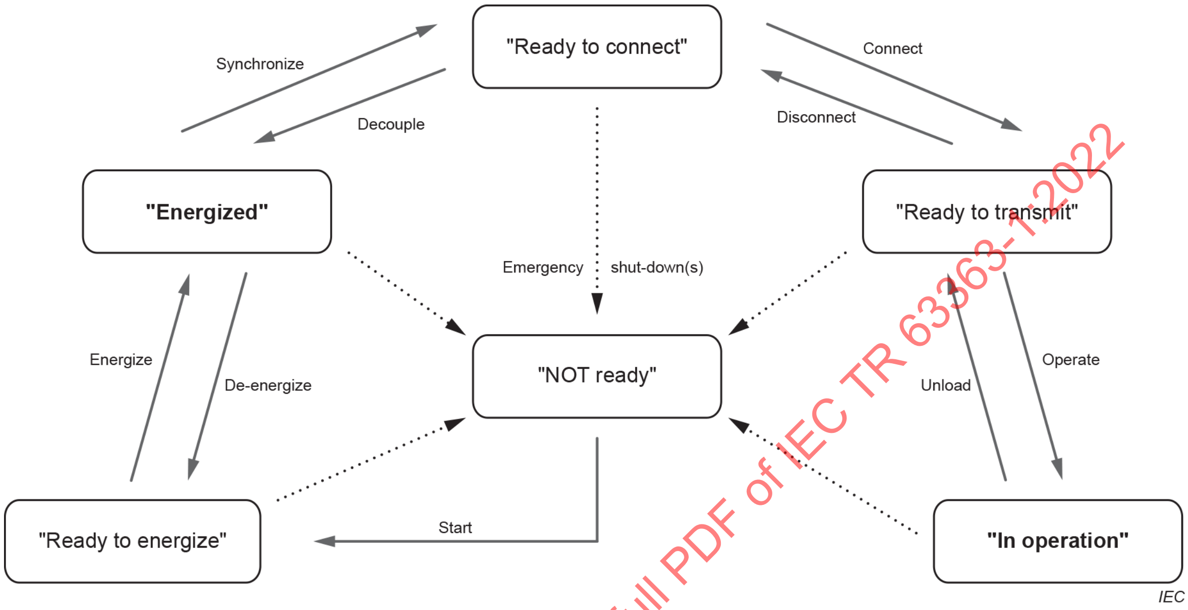


Figure 14 – Operating sequence transitions of the VSC HVDC system

Different operation modes, such as STATCOM mode, can be achieved by selecting which part of the system to connect in the sequence.

For further information, refer to CLC/TS 50654-1.

9.2.3.2 Energized – No-load operating state

In the energized/no-load operating state, the VSC HVDC substation is energized when the AC circuit breaker is closed. A definition of the status of various equipment can be specified to determine the no-load losses of the VSC HVDC substation, if operation in the no-load stand-by state is planned. The converter can be energized either as a stand-alone unit or connected to the DC system and other converters.

The interface transformers are energized or de-energized, depending on the user's policies with respect to losses. In the latter case, account can be taken of the time needed for inrush currents to decay. Oil pumps and coolers can be in operation on a minimum level, as appropriate to the design of the transformers.

Depending on the start-up concept of the VSC transmission scheme, a circuit breaker can be equipped with a closing resistor, or a separate pre-insertion resistor, with either a circuit breaker or disconnector in parallel with it, can be provided in series with the main circuit breaker. The resistor reduces the inrush current of charging VSC converters, resulting in smaller temporary AC system disturbances and lower charging current stresses on the free-wheeling diodes during energization. However, the power losses in the circuit breaker are normally neglected. The resistor does not contribute to steady-state losses and need not be considered in the loss evaluation.

Due to the anti-parallel free-wheeling diodes in the VSC half-bridge topology, there is a DC voltage present at the DC terminals of the converter once the converter is energized. There are scenarios where the transformers can be left de-energized, typically if the valve is energized from the DC side.

The no-load operating state of the VSC converter is defined in IEC 62751 (all parts).

9.2.3.3 Energized – Idling operating state

While operated in idling operating state, the VSC HVDC substation is energized and the semiconductor devices are deblocked but with no active or reactive power output at the point of common connection to the AC network.

The "idling operating" and "no-load" conditions are similar but from the no-load state, several seconds can be needed before power can be transmitted, while from the idling operating state, power transmission can be commenced almost immediately (less than a few power frequency cycles). In the idling operating state, the converter is capable of actively controlling the DC voltage, in contrast to the no-load state, where the behaviour of the converter is essentially "passive". Losses can generally be slightly lower in the no-load state than in the idling operating state.

The idling operating state of the VSC converter is defined in IEC 62751 (all parts).

9.2.3.4 In operation

The VSC converter station can be operated in power transmission mode or STATCOM, if reactive power support is needed by the AC system.

In power transmission operation, the VSC converter station is operational and capable of transmitting the active power and exchange reactive power. The VSC converter station operates together with another end converter station to transmit active power on the DC circuit.

In STATCOM operation, the VSC converter station is fully operational and capable of controlling the exchanged reactive power of the converter. The VSC converter station operates as a stand-alone converter not transmitting active power on the DC circuit. The VSC converter station can be connected in the following three modes:

– without DC line or cable;
– with DC line or cable connected;
– with the other converter substation connected.

10 AC system

10.1 General

The following can be specified for AC systems at both ends for each stage of development as well as for expected future changes. Different values can be specified for performance and rating purposes. The arrangement of the AC switchgear to which the converter units and filters (if supplied) are connected, including AC lines, can be described. This can also be done for the planned operating schemes of the switch yard.

Specific data can be made available for generators, converters and flexible AC transmission systems (FACTS) devices in the close vicinity, particularly if the major load for the generators is served through the converter. Often all data pertinent to system study items, such as load flow and short-circuit studies are also needed.

Local grid codes need to be considered where applicable.

10.2 AC voltage

10.2.1 Steady-state voltage range

10.2.1.1 General

The steady-state voltage range is a range over which the VSC system is capable to transmit rated power and over which all performance demands are met, unless stated otherwise. Any special performance demands beyond the limits of the steady-state range can be specified. These can affect the design of main equipment such as converter valves, interface transformers, filters (if supplied), auxiliary equipment, etc.

10.2.1.2 Short-term voltage range

There can be situations under which the voltage exceeds the normal steady-state operating range but the HVDC system is needed to remain in operation. Under these conditions the VSC system can be designed to operate in a manner whereby no equipment can be at risk of damage, but the performance limits of the system can be relaxed (for harmonics, losses, etc., or even power transmission capability).

The reasonable performance limits can be specified since these can have an effect upon the ratings of equipment. The VSC control system can even be specified to assist in the restoration of the voltage to within the normal operating range if this is appropriate.

10.2.1.3 Voltage variation during emergency

Dynamic overvoltage can determine ratings and protection strategies.

Under extreme circumstances, the AC voltage can exceed even the short-term range, in which case it can be desirable to remove the VSC system from operation in order to protect the equipment. Alternatively, it can rate the VSC converter equipment to operate within these limits, although this can probably need higher cost equipment and degraded performance.

10.2.2 Negative sequence voltage

The negative sequence component of AC voltage, calculated according to the method of symmetrical components, is that balanced set of three-phase voltages whose maxima occur in the opposite order to that of the positive sequence voltages. It is generally expressed as a percentage of the rated voltage.

10.3 Frequency

10.3.1 Rated frequency

The AC network rated frequency can be 50 Hz or 60 Hz.

10.3.2 Steady-state frequency range

Steady-state frequency range is a range, in conjunction with the AC voltage steady-state range, over which the rated power can be transmitted, and all performance demands are met.

The steady-state frequency range can be quoted from the network grid codes.

10.3.3 Short-term frequency variation

Limits and duration of short-term frequency excursions for which system performance is needed can be specified.

The short-term frequency range can be quoted from the network grid codes.

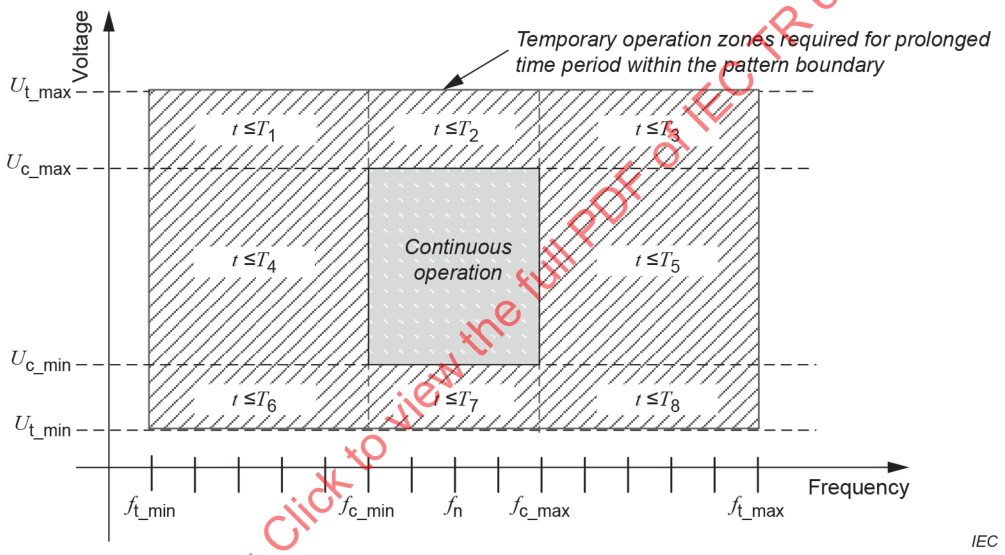
10.3.4 Frequency variation during emergency

During an emergency, the AC system frequency can reach extreme values for limited periods. These values and their expected durations can be specified. In this condition, the equipment can remain in service without damage, but the performance specified cannot to be met. For excursions beyond the specified operating frequency limits, the equipment can be automatically disconnected.

10.4 AC voltage and frequency operation ranges

The VSC system can be capable of operating continuously within the voltage and frequency variation limits encountered in normal operating conditions. In addition, it can remain in operation in case of frequency deviations outside the normal operating limits for a specified time, and in some cases with a specific active power output.

For a general demand, taking also into account the voltage range level at which the frequency range is needed, the AC voltage-frequency profiles are combined to produce the operation ranges, as shown in Figure 15.



Key

U_{t_max}	Maximum temporary operation AC voltage (kV or p.u.)
U_{t_min}	Minimum temporary operation AC voltage (kV or p.u.)
U_{c_max}	Maximum continuous operation AC voltage (kV or p.u.)
U_{c_min}	Minimum continuous operation AC voltage (kV or p.u.)
f_n	Rated frequency (e.g. 50 Hz or 60 Hz)
f_{t_max}	Maximum temporary operation frequency (Hz)
f_{t_min}	Minimum temporary operation frequency (Hz)
f_{c_max}	Maximum continuous operation frequency (Hz)
f_{c_min}	Minimum continuous operation frequency (Hz)
T_i	Maximum allowed operating time within temporary operation zones (i = 1, 2, --- 8) (s)

Figure 15 – Example of the AC grid voltage and frequency operation ranges

10.5 System impedance

For the purpose of analysis of the converter harmonic performance, the system impedance at fundamental frequency can be stated. The system impedance at harmonic frequencies (referring to IEC TR 62001-5) is needed for performance evaluations, harmonic stability studies as well as AC filter design (if needed). This impedance can be calculated using the parameters of the lines, transformers, converters, and generators up to several buses away from the converter station. However, this impedance can change considerably under different load conditions and extension stages of the system. Therefore, it is usually more convenient to use resistance and reactance R-X diagrams and to plot the envelope of the loci of the system harmonic impedance under expected system conditions. The values of minimum resistance R_{min} and reactance X_{min} can be included in the diagram of harmonic impedance loci. In practice, this diagram can take various forms such as a circular plot, limited by constant R/X ratio or a combination of both. The polygon diagram is also widely used to define all possible impedances for a single harmonic or a range of harmonics. However, these kinds of diagrams are unlikely to correspond to any actual network and are therefore not suitable to be used for any detailed harmonic studies.

Due to a lack of system inputs, some users can specify maximum and minimum harmonic impedance based on corresponding fundamental impedance according to methods provided by CIGRE TBs 766 and 798.

Resonances can occur because of critical contingencies as well as harmonics in the AC system. The resonance scanning can be done to determine the harmonic frequency characteristics of the AC system and VSC system and to investigate the risk of resonances. If such resonances exist, mitigation methods such as AC filters, active filtering controls, active damping controls and filtering inserted in the control loop can be designed and verified.

10.6 Positive and zero-sequence surge impedance

The positive and zero-sequence surge impedance is needed for all AC lines going into the station for evaluation of interference from converters in the carrier frequency band and for design of appropriate filters.

10.7 Other sources of harmonics

Other sources of harmonics electrically close to the HVDC substation or pre-existing harmonic on the coupled bus can be identified. Their influences can be taken into account. Generated harmonics can be stated for the devices, for example FACTS, battery energy storage (BES) systems, wind turbines, etc., connected to the converter station bus or to nearby AC substations.

11 Reactive power

11.1 General

This Clause 11 identifies the considerations relevant to reactive power.

11.2 VSC HVDC systems

VSC HVDC systems can be operated in active power transmission or STATCOM modes. The reactive power exchanged between the AC system and the VSC can be controlled by the VSC independently at both ends of the HVDC system. Normally, appropriate reactive power balance demands are provided by the grid code or the owner. If these reactive power balance demands are not defined, the load flow studies need to be performed and the following considerations can be taken into account:

- the power factor range to be maintained in the AC lines for all operating conditions;
- the operating voltage ranges under light and peak load conditions of the AC system;
- redundancy demands.

The reactive power (capacitive or inductive) of the VSC can be varied according to AC system demands by using appropriate control strategies (e.g. reactive power control and/or AC voltage control).

VSC reactive power control is needed when other nearby controllers are acting to maintain AC voltage. To avoid interference between the various controllers, VSCs not needed for AC voltage can provide reactive power control.

If all VSCs in close proximity are controlling the same quantities, then it can be for each to participate in AC voltage control through a carefully designed droop characteristic. Under these circumstances, reactive power control can be preferable, with the settings either at zero Mvar or other fixed values slowly controlled by a joint VAR controller or by a command from the SCADA system.

Normally, the reactive power of the VSCs can be limited by their PQ and UQ profiles, as defined in 7.1 and 7.2.

12 HVDC transmission line, earth electrode line and earth electrode

12.1 General

This Clause 12 identifies those characteristics of the HVDC transmission line (including overhead line and cable), the earth electrode and the earth electrode line that are relevant to the specification of the steady-state performance of the converter, including power line carrier performance and design demands. It does not provide the information that can be specified for the design of the HVDC transmission line, earth electrode lines or earth electrodes themselves.

Key performance specification data for the HVDC transmission line, the earth electrode line and earth electrode can be determined in advance.

12.2 Overhead line(s)

12.2.1 General

The total length of the line can be given, including details concerning any overhead line and cable sections. Details can be provided of any right-of-way joint uses. Particulars of all crossings and parallelisms need to be given to enable assessment of possible electrical interactions and interference. If the exact length of the line is unknown, the expected range for this length can be stated.

When the transmission corridor and space are limited, the multi-pole lines on the same tower can be an optimal solution for the HVDC transmission using overhead lines. For the multi-pole lines on the same tower, information on the spacing between poles along the complete route are needed.

12.2.2 Electrical parameters

The electrical parameters are as follows:

1) resistance – maximum positive and zero-sequence DC values at minimum current, rated current, maximum overload current with due consideration of the ambient conditions (temperature, radiation, wind velocity, etc.) prevailing during the load condition considered. Curve of frequency dependence up to 49th harmonics of AC side fundamental frequency for rated current.
2) capacitance – positive and zero-sequence capacitance (C_1 and C_0).
3) inductance – positive and zero-sequence inductance (L_1 and L_0), curve of frequency dependence up to two times of the fundamental frequency for rated current.

The positive and zero sequence parameters of the DC line resistance, capacitance and inductance are useful for studies, wherever the transient or harmonic behaviour of the DC line is important.

If the information in 1) to 3) above is unavailable, as an alternative, the essential data to enable its calculation can be given. To calculate these parameters, the following data can be needed:

a) conductor size, type, geometry (including the shield wire);
b) tower outlines, spacing and sag profiles;
c) soil resistivity along the route;
d) tower footing resistance;
e) the worst-case maximum conductor surface gradients to perform calculation for corona effects, for example, if a power line carrier is used;
f) critical impulse flashover level of insulation.

It is important to note that the HVDC transmission line can be adequately shielded from direct lightning strokes for the first 10 km from the HVDC substation and for the HVDC transmission line tower footing resistance to be sufficiently low, for example less than 10 Ω up to 25 Ω, to prevent back flashover.

As a third alternative, in place of sequence components, the information can be provided in the form of self and mutual impedance between conductors and earth.

12.3 Cable(s)

12.3.1 General

Length of sections or total length can be specified as appropriate. Any restrictions on service conditions imposed by the cable supplier can be stated.

Examples of such restrictions can include:

a) limitations on polarity reversal;
b) limitations on discharge rate;
c) limiting voltage and current ripple level;
d) limitations on overvoltage and overcurrent.

12.3.2 Electrical parameters

The electrical parameters are the following:

a) DC resistance of conductor, maximum value at rated current and at maximum overload current, minimum value at minimum current;
b) conductor resistance frequency dependence up to 5 kHz;
c) cable earthing, sheath resistance and frequency dependence up to 5 kHz;
d) inductance and frequency dependence up to 20 kHz;
e) capacitance of conductor to sheath;
f) capacitance of sheath to earth (armour);
g) surge impedance of cable conductor to sheath;
h) attenuation characteristics up to 50 kHz.

Alternatively, as for overhead line, geometrical data can be provided to calculate the electrical parameters.

12.4 Transmission line combined with overhead line and cable section

In the case of hybrid HVDC transmission systems with overhead line and cable section, a transition station can be needed. Dedicated DC current transformers can be installed for distinguishing between faults in overhead lines and faults in cable sections. Protective action such as restarting the overhead line section can be needed.

12.5 Electrode line

The earth electrode line length, as well as the length of any part of it which is on the HVDC transmission line towers can be specified. The earth electrode line resistance (maximum value and ambient temperature assumptions) can be specified. The same parameters of the electrode line can be specified as in 12.2.2 electrical parameters of the overhead line(s) and 12.3.2 electrical parameters of the cable(s). For further information, refer to IEC TS 62344 and CIGRE TB 675.

12.6 Earth electrode

The maximum resistance of the earth electrode relative to the remote earth can be indicated. It is noted that this resistance can increase with time and environmental and/or load conditions. More information on HVDC earth electrode is available in IEC TS 62344.

12.7 Gas insulated line

For the same reasons and with similar demands as in AC transmission line system applications, gas-insulated DC transmission lines (DC GIL) can be applied to higher voltage class and larger capacity HVDC systems having relatively short distance transmission lines as an alternative to cables. The DC GIL installation route, structure and insulation gases are evaluated and selected within the suitable design conditions and environmental demands.

The DC GIL installations can be used in a feasible layout in any direction angle change while carrying high power ratings without requiring multiple circuits.

The DC GIL can be part of a gas-insulated system for HVDC. For further information, refer to CIGRE TB 506.

13 Reliability

The reliability of an HVDC system is the ability to transmit a defined energy within a defined time under specified system and environmental conditions.

Reference is made to IEC TR 62672 which deals with a reporting procedure of specific failures and overall availability of HVDC systems in operation, and to IEC TR 60919-1. Although the scope of IEC TR 62672 differs from that of IEC TR 60919-1, the basic reliability terms used and their definitions are common to both documents.

It is noted that the reliability demands in a VSC HVDC project are subject to agreement between purchaser and supplier.

14 HVDC control

14.1 General

This Clause 14 discusses VSC HVDC controls, whilst the protections will be described in detail in IEC TR 63363-2. It is a document that is under consideration (i.e. not yet published).

14.2 Control objectives

The advantages of the VSC HVDC system very much depend on the utilization of its controllability in ensuring maximum flexibility, reliability and adaptability for different system demands. The objective of the VSC HVDC control system can be to provide efficient operation and maximum flexibility of power control in magnitude, rate of change and direction without compromising the safety of the equipment, while maintaining the maximum independence of each pole. The control system can be suitable for high-speed control in such a way that it can effectively respond to disturbances in the AC and VSC HVDC systems. It is recognized that long-distance transmission needs a high-speed telecommunication system for the most effective operation. However, the VSC HVDC system can be operable without telecommunication, and, for this case, the performance can be maximized to the extent possible.

The control system can be adaptable for:

a) active power control;
b) reactive power control;
c) AC voltage control;
d) frequency control;
e) active and reactive power modulation;
f) sub-synchronous torsional interaction (SSTI) damping;
g) remote operation;
h) black start;
i) emergency power control.

14.3 Control structure

14.3.1 General

The various control functions of a VSC HVDC substation are generally structured in a hierarchical manner. The main control functions are dispersed to a lower level as far as possible to improve the system reliability and availability. They normally operate fully automatically and can be controlled from stations either locally or remotely. An example of HVDC control hierarchy is shown in Figure 16.

The HVDC control core functions normally include:

- HVDC bipole/station control,
- HVDC pole control,
- converter control,
- valve control, including:
  a) valve control level – set of valve control units (VCU),
  b) valve electronics control level – set of valve base electronics (VBE),
  c) VCU and VBE can be combined in one – valve base controller (VBC).

In addition, there can be different types of supplementary controls at higher levels, either included in the HVDC control system or external controls such as SCADA systems giving orders to the HVDC.

Examples are:

- integrated AC/DC system control, which can be system operators in dispatch centres;
- HVDC DC grid master control or multi-terminal control, if the converter is connected to a DC grid.

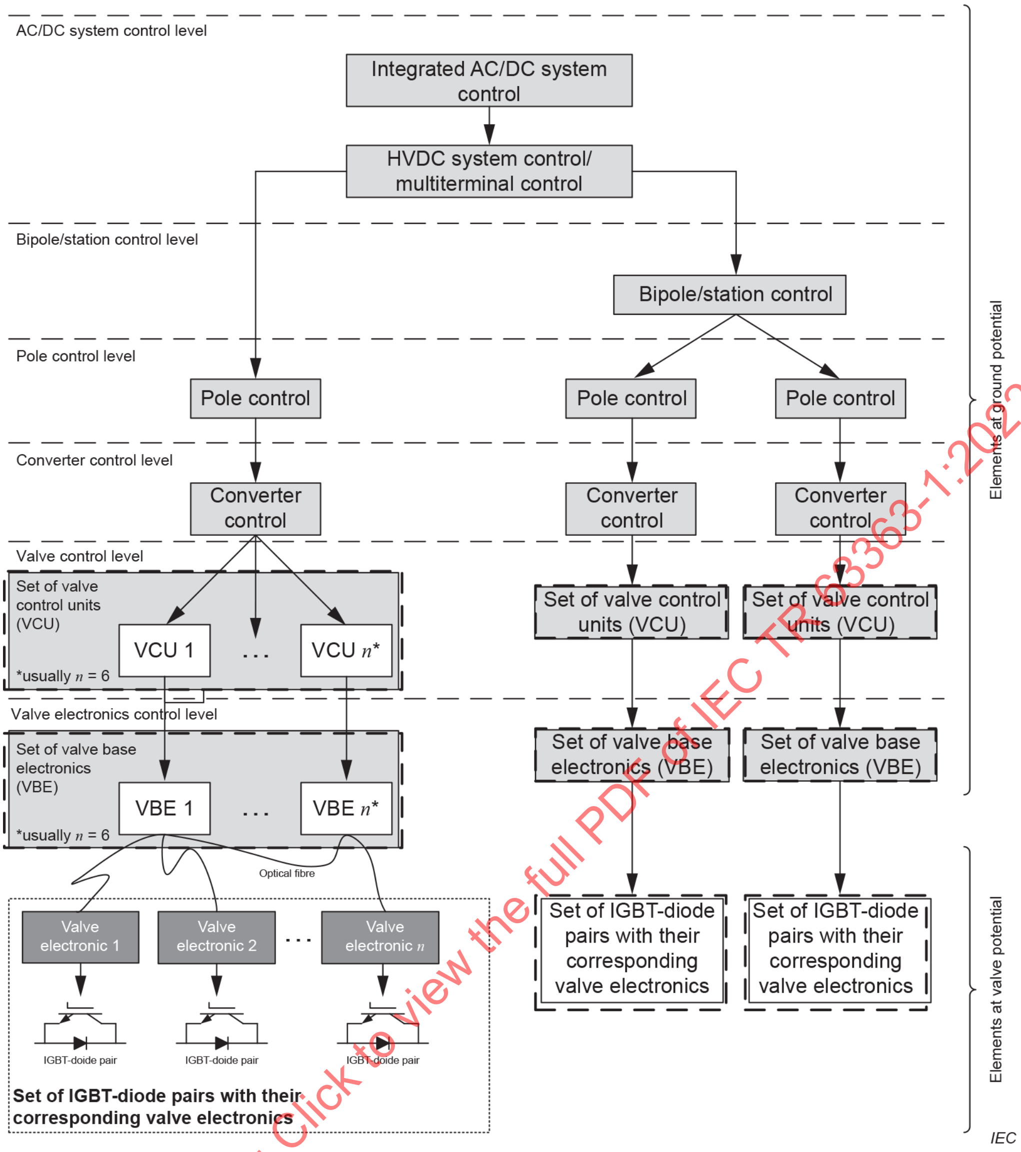


Figure 16 – Hierarchical structure of an HVDC control system

14.3.2 HVDC bipole/station control

The HVDC bipole/station control is normally used in cases where there is more than one pole in the same substation. The primary purpose of the bipole/station control is to coordinate the two, or more, pole controls. One major design criterion for HVDC systems is normally to minimize the equipment at the substation level as much as possible, in order to minimize the impact on the bipole/station in case of a fault at that level. Referring to substation level functions, these control functions can also be realized within pole level hardware.

The bipole/station control functions are primarily described as below.

- The HVDC substation control can be coordinated with control external to the HVDC substation, for example, wind farm controllers and high-level AC/DC interaction controls.
- Pole current balance control can be specified to minimize earth electrode line current (equal to the unbalance current between two poles of a bipolar earth return HVDC system), to avoid earth currents. The unbalance current control limit between the two poles of a bipolar system is primarily depending on the measurement inaccuracy.
- Emergency power controls or run-back and run-up functionalities can be included to support the AC system in case of disturbances.

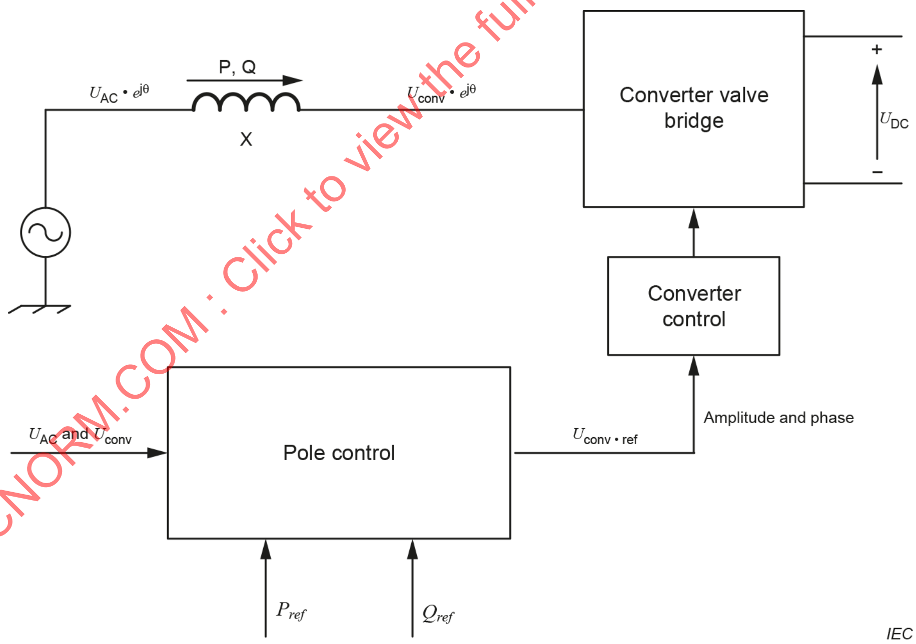
It can be specified which control strategies are intended to be used and at which priority they can be operable under different operating and AC system conditions. The power control tolerance is dependent upon the accuracy of the voltage divider, the current sensor and the resolution of the power order. The output from the bipole/station control is mainly power, DC voltage, reactive power and AC voltage orders to the pole control.

Generally, both converter stations of an HVDC system are equipped with identical control functionality since most HVDC systems are designed to transmit power in both directions. However, only the station control in one location can be in the lead at one time. The setting of the station control order and rate of change are provided manually at the lead station. The changes in order are then executed in the other substation(s) via the telecommunication. Capability of the lead station for setting can also be transferred to a remote location, for example, a dispatch centre.

Change in power direction is normally initiated from the lead substation, but can also be ordered automatically, if emergency reversal is called for, for example, after a disturbance in one of the AC systems.

14.3.3 HVDC pole control

As shown in Figure 17, the analogy of an AC transmission line with generator on one side and the network on the other can be used with the modification that the impedance between the network and generator is the impedance of the VSC converter namely transformer and phase/valve reactor equivalent impedance. Principally, the active and reactive power transfers are determined by the VSC converter voltage created by the converter arm, the AC network voltage and the impedance between the two.



Key

U_{AC}	network AC voltage at PCC
θ	phase angle of the AC voltage at PCC
U_{conv}	converter AC voltage
φ	phase angle of the converter AC voltage
P	active power from PCC to converter
Q	reactive power from PCC to converter
X	equivalent impedance between PCC and converter
U_{DC}	DC voltage at converter DC side
$U_{conv.ref}$	reference voltage (including amplitude and phase angle) for converter control

P_{ref} reference active power for pole control

Q_{ref} reference reactive power for pole control

Figure 17 – HVDC pole control

The pole control provides the reference values per pole for all converter units, if any. Pole control is a closed loop control and includes the basic control functions that are needed for stable operation of the HVDC system, such as AC and DC voltage controls, active and reactive power controls as well as tap changer control. All these control functions have a reference value and an actual value. Some of these reference values can be provided by the pole control (for example, the current reference value, which is calculated out of the requested transmission power), others can be provided by the bipole/station control and/or operator (for example, DC voltage, DC power, frequency).

The selected DC voltage limit in the inverter is lower than that of the rectifier, and the current can be controlled by one station. That is, one station can maintain the voltage, and the other can adjust its voltage until the current becomes equal to the order input, and a stable working point is established.

Special control modes for isolated renewable energy sources can be with the possibility to determine the frequency and voltage or reactive power of the isolated network.

14.3.4 Converter and valve control

The converter control physical parts are directly connected to the pole control at ground potential, controlling the complete converter. Typically, it contains the functions such as the inner-loop current control, active power control, reactive power control and AC voltage control as well as DC voltage control. The converter control produces the reference voltage of each bridge arm. The reference voltages and other interface signals are sent to the valve control level according to the communication protocol between the converter control level and the valve control level.

The valve control can be partly placed at ground potential as valve control units or valve base controls and partly distributed in the valve. Its outputs are the switching pulses to the individual cells or semiconductor devices in the converter unit on high voltage potential.

Switching of semi-conductor devices from the control can be synchronized to the AC system voltage to produce the needed active and reactive power at PCC. From the given reference voltages, the valve control decides the switching patterns.

The functions included in the valve control can be the valve monitoring functions and switchover logics in case redundant systems are used. The valve control can also include a third harmonic injection to boost power output of the converter. The voltage balance control, circulating current control and active damping control can be implemented in valve control as well. The protection systems and these valve control functions can be integrated into the converter control if needed.

14.4 Measurement

Items of interest which are normally measured in a VSC HVDC system are as follows:

- DC current;
- DC voltage;
- AC current;
- converter arm current;
- AC voltage;
- ambient temperature;
- coolant conditions.

The accuracy or tolerance demands can be different according to the function for which the measurement is being made (control, protection, metering, indication, recording, etc.). As an example, the deviation between the set current order and the actual current is dependent upon the tolerance of the current control system and the current sensor.

15 Telecommunication

15.1 Types of telecommunication links

When the two terminals of a HVDC system are located a considerable distance apart, it is possible that having a telecommunication system to exchange information between the two terminals will not always be needed. The most basic information to be exchanged relates to coordination of the two terminals during start and stop sequences. Fast communication between the two terminals can be used to enhance the performance of the HVDC system. The types of telecommunication system used for control and operation of the HVDC transmission can be one or more than one of those listed below:

a) optical fibre communication;

b) telephone;

c) power line carrier (PLC);

d) microwave;

e) radio link.

For further information, refer to IEC TR 60919-1.

15.2 Classification of data to be shared

A list of classes of the major types of information to be transmitted between the HVDC substations and/or remote control centres is given below:

1) signals for continuous control
   a) active power control;
   b) reactive power control;
   c) AC voltage control;
   d) DC voltage control;
   e) frequency control;
   f) damping control.
2) operation modes
   a) change of control mode of operation;
   b) interlocking of protection;
   c) operation of switches;
   d) block/deblock.
3) state indications
   a) position of switches;
   b) number of converters in operation.
4) alarm signals
5) online DC transmission line fault locations

15.3 Fast response telecommunication

Several types of control can need a fast telecommunication between the substations such as:

- active power modulation;
- frequency control;
- emergency power control;
- HVDC transmission line protection.

Speed of the communication depends on the state of art of technologies as well as protocols and functional demands used.

16 Auxiliary systems

16.1 General

Auxiliary power supplies are needed for cooling pumps and fans, control, protection and motorized drives of disconnectors, etc. and for general substation service needs.

To ensure adequate security of supply and freedom from interruption, these supplies are usually derived directly from the high voltage AC network at the substation where a separately and independently energized distribution network supply is available. This supply can be utilized as a backup source to give added protection against failure of medium and low voltage switchgear and supply transformers.

To avoid the auxiliary power interruption, batteries/uninterruptible power supplies (UPS) can be installed.

A diesel generator (DG) can also be needed if the demand for a restart from a de-energized bus (commonly called "black-start") is expected.

The auxiliary systems can be broadly classified in two major groups of the electrical and mechanical auxiliary systems.

16.2 Electrical auxiliary system

16.2.1 General

Electrical auxiliary systems for an HVDC substation are feeding electrical loads in the station mainly including valve cooling systems, controls, protections, data recording systems, telecommunication systems, etc. The loads can be segregated into non-essential and essential categories. The loads that are absolutely essential for operation of the HVDC and emergency functions can be classified as an essential category. All other loads can be classified as a non-essential category. Thus, the electrical auxiliary systems can be classed into two categories of non-essential auxiliary and essential.

16.2.2 Auxiliary power supplies

For the non-essential auxiliary system, the power can be supplied from the main AC power supply for normal operation. The main AC power supply can be made redundant from at least two independent sources. If the main AC power supply is switched off or fails, the power supply can automatically be taken over by the reserve power supply, which is from the local substation medium-voltage distribution network (or reserve diesel generators) of the same power size. The emergency generator can only be used in an emergency, i.e. in case of simultaneous failure of the main and reserve power supplies.

In the essential auxiliary system, the power can be supplied from the DC systems, batteries and UPS. The DC system feeds electrical loads that are supplied uninterruptedly and grid-independently for a defined backup time in case of a complete outage of the non-essential auxiliary power supply. For each DC system, there can be at least two independent chargers connected to individual battery banks with redundancy.

Redundant DC/DC converter and AC/DC inverter systems can be used and installed in the DC system for the essential DC consumers (e.g. control and protection cubicles and fibre optical based telecommunication system) and AC supplies of important and critical AC loads.

The essential auxiliary system can accommodate a very short interruption in its power supplies. For example, it can be supplied from station batteries or, when AC supplies are needed, from an UPS system.

For the important AC loads (e.g. valve cooling systems), UPS systems can be considered. Since the UPS can be always available, the power supply for the UPS systems can be fed from two different sources and have an auto changeover system.

16.2.3 Batteries and uninterruptible power supplies (UPS)

The DC supply system can consist of two independent DC systems with separate charger, battery bank and distribution system for:

- HVDC system control for each pole;
- other substation control and protection;
- telecommunication equipment.

These batteries can usually be of different rated voltages. The time for which each battery can supply its rated load, within the rated voltage range in the event of failure of the charger or its supply, can be specified.

For batteries, it is needed to consider and specify the following:

- nominal voltage,
- load profile and/or rated capacity,
- voltage range from charge (when boost is needed) to discharge,
- kind of battery and/or type,
- temperature conditions,
- ventilation demands.

The charging system needs to meet the demands of the battery and the load.

The UPS for AC loads can be based upon dedicated units, or a common system for the HVDC substation. The latter is usually preferred because it makes the provision of adequate redundancy more realistic. Usually, the UPS includes its own assigned battery, but the station battery can also be utilised, in which case the station battery needs to be adequately sized.

The following can be specified for the UPS:

- rated voltage, number of phases and tolerable distortion,
- voltage, frequency and tolerance,
- rated and maximum load,
- type of load,
- maximum allowable interruption for which the UPS can function.

16.2.4 Emergency supply

If a diesel generator is needed for emergency supply, then consideration can be given to the following when preparing its specification:

- how much of the total auxiliary load can be supplied?

- can start-up, changeover and/or shutdown be automatic?
- if automatic, care can be taken to ensure that conditions causing frequent restarting cannot occur, otherwise the starting battery can become fully discharged,
- how much fuel can be stored on-site?

To ensure reliable operation when needed by emergency conditions, it is desirable that the generator is started and loaded so that it reaches correct operating conditions periodically on a systematic basis. The auxiliary system can be designed to achieve this without putting the transmission at risk in any way by the failure of auxiliary supply equipment to make a correct changeover.

16.3 Mechanical auxiliary system

Mechanical auxiliary systems for HVDC substation include the following important systems: valve cooling, compressed air, fire detection, protection and extinguishing, insulating oil, diesel oil, water supply, drainage and sewage, air conditioning, ventilation and mechanical load handling facilities, etc.

The above mechanical auxiliary systems are normally needed so that full electric power transmission can be maintained on the HVDC system. The valve cooling system is important and critical for the normal operation of converter valves.

The design of the converters determines the type of valve cooling system. Generally, the converter can be liquid cooled. Cooling for a valve group can be dimensioned to handle the power losses from each valve group. Moreover, provision can be made for stand-by or spare components so that the failure or shut-down of a cooling pump, heat exchanger, etc. cannot cause a reduction of DC transmission capacity under any reasonably expected combination of load and ambient conditions (if it cannot utilize the redundant cooling equipment for overload operation).

A supervisory and alarm system can be included to monitor the auxiliary power functions essential for converter valve operation and cooling. Such functions can include (for water-cooled valves): deionized water temperatures from and to the valves; water level in expansion vessels; water conductivity; pressure drop across the valve cooling pipes; low water flow through a valve; water oxygen content if needed; if a cooling tower is used, water temperatures and heat exchanger temperatures; and temperature and humidity of the valve hall air and air handling system.

The supervisory system can be arranged to give alarm warnings for low and high limits of the items described above, as well as for losses of pumps or fans, for low reserves of water and the need for refilling of storage vessels, and for water leakage in the converter valve structures, etc.

It can also give an alarm signal for such excursions from normal as: high temperature of the deionized water from the valves; low water flow through a valve; or loss of too many pumps, for which a trip signal can be initiated by the supervisory system.

Fire detection, protection and extinguishing are important for protection of HVDC assets and system availability aspects. The fire detection and protection systems at HVDC substations can be implemented in accordance with local construction regulations and safety demands. More information on fire prevention measures in HVDC substations is available in IEC TR 62757.

The VSC converter halls can be protected and fitted with fire alarm systems. Interaction with the smoke extraction system is especially relevant in the converter hall and it can be dimensioned by the system installer. The VSC converter halls can be equipped with fire detectors and arcing detectors. In case of a fire, the signals of the fire detectors and arcing detectors can be sent to the HVDC control and protection (C&P) system in real time, the converter valves can be tripped and corresponding fire protection measures can be initiated.

17 Audible noise

17.1 General

Noise from the HVDC substation can be troublesome and incur prescriptive mandatory sanctions which are difficult to resolve once the station is built. Therefore, limiting specifications can be prepared at the start of the project taking into account demands of any applicable regulations or codes of practice. The effects of noise are generally treated as those concerning nuisance to the public outside the boundary of the HVDC substation and noise effects in the working environment. While the latter are important, public nuisance limits are often more difficult to specify.

The impact of HVDC substation noise on the public outside the confines of the substation, and whether or not it is seen as a nuisance, depends upon the noise level, the pre-existing level, and the nature of the surrounding area and the nearness of residential property.

As a first step, the reasonable noise level at the boundary can be specified having regard to the relevant factors. ISO 1996-1 gives a method for determination of a suitable level. Next, the level and spectrum of noise expected from each major source can be defined. These can then be summed to decide whether or not the total noise is suitable. The location of equipment, that is the distance from the property line, is of particular importance. Special noise abatement measures can be used to keep the total to a suitable value.

Other noise-producing equipment can be installed at the same location and, if so, can also be considered, for example, AC system transformers and reactive power compensators. Typical HVDC substation plant items most likely to produce significant noise are discussed below. When very low audible noise levels are specified at the boundary, the noise from other equipment, such as AC filter capacitors, diesel generators, etc., can also be significant.

For further information, refer to ISO 1996-1, ISO 1996-2, ISO 1996-3 and IEC TS 61973.

17.2 Public nuisance

17.2.1 Valves and valve coolers

The noise associated with indoor valves can usually be disregarded so far as the public is concerned, since in most cases the attenuation introduced by the valve hall can adequately suppress it.

The main source of noise can probably be from the fans of outdoor coolers. These can usually be closed-cycle evaporative coolers or forced air coolers drawn from a standard product range and, as such, the cooling equipment manufacturer can supply noise spectrum and level data. Evaporative coolers are generally less noisy than dry air coolers. In both types, the noise level can be reduced by using larger, lower-speed fans. Substantial noise reduction can also be achieved by using screen walls to deflect the noise upwards.

17.2.2 Interface transformers

Interface transformer noise level is likely to be comparable to similarly sized AC system transformers; the tank and cooler noise levels can be reduced by conventional means, if needed, for example, enclosure, mufflers and lower speed fans.

More details about determination of sound levels can be found in IEC 60076-10 and IEC/IEEE 60076-57-129.

17.2.3 Reactors

Reactors applied to VSC HVDC systems, especially DC main circuits and filters (if needed) are air core reactors because the value of their inductance can be almost constant and unrelated to the value of flowing current. However, noise from reactors can be expected to have peaks at ripple frequencies corresponding to the harmonics generated during converter operation.

Generally, three functional categories of air-cored reactors can be seen in the VSC HVDC system: (1) DC reactors (if needed), (2) phase reactors/valve reactors and (3) filter reactors (if needed).

The DC reactor (if applicable) can be an important source of noise. It is probably not practicable to carry out valid factory tests of DC reactor noise. Where low noise levels are needed, special designs including the use of additional sound absorbent shields or indoor installations can be considered for the DC reactor.

In some designs of VSC, the phase reactors can fulfil part of the function of the converter-side high frequency filter. In addition, in some designs of VSC, part of or all of the phase reactor can be built into the three phase units of the VSC unit, as valve reactors. Where low noise levels are needed, a special design of phase reactors/valve reactors, including the use of additional sound absorbent shields, can be considered.

For the filter reactors (if applicable), modern manufacturing methods are available which can be used to reduce the amount of noise produced. Other measures can be taken to reduce the amount of noise propagated, such as careful consideration of the location within the converter station, sound absorbent barrier walls, or even locating the equipment inside buildings.

More details about air-core reactors can be found in IEC 60076-6.

17.3 Noise in working areas

The noise level to which persons working within the boundary of the VSC HVDC substation can be subjected needs to be considered with regard to safety, hearing impairment, and working efficiency.

Many countries have established codes or mandatory regulations which seek to safeguard the hearing of those exposed to high noise levels and these can be examined and incorporated within the specification as appropriate. Problems of this kind are unlikely in VSC HVDC substations other than during maintenance procedures and in the immediate vicinity of certain types of cooling fans or diesel generators. In most cases, it can meet the demands of the regulations if maintenance personnel wear hearing protectors as needed.

The general noise level within the building in the working area can be determined primarily by the rotating machinery such as valve cooling system, pumps and fans, etc., and transformers where these are partially or fully enclosed within the building. In case it is possible to enter the high voltage areas during operation, equipment noise needs to be considered. Low noise levels can be specified where mental concentration is routinely expected, as in control rooms.

For further information about typical performance noise limits, refer to IEC TS 61973:2012, 5.6.

18 AC side harmonics

18.1 General

The main issues associated with AC side harmonics for VSC HVDC transmission are presented in this document. For further information, refer to IEC TR 62001-5 and CIGRE TB 754.

18.2 Harmonic sources

18.2.1 General

To determine the total harmonic distortion at the PCC of a VSC HVDC substation, two aspects can be considered:

– converter-generated harmonic emission;
– pre-existing or network (background) harmonics.

In the calculation of the overall harmonic distortion, the network and converter harmonic sources can generally be considered as independent from each other. In the following, the network is represented as an ideal harmonic voltage source along with its impedance. The same harmonic impedance can be used for the calculations of both the emissions and the amplification of the pre-existing AC network harmonics.

18.2.2 Converter generated harmonics

The impact of the VSC converter harmonic contribution on the overall harmonic distortion at the PCC can be analysed by use of the model, as shown in Figure 18.

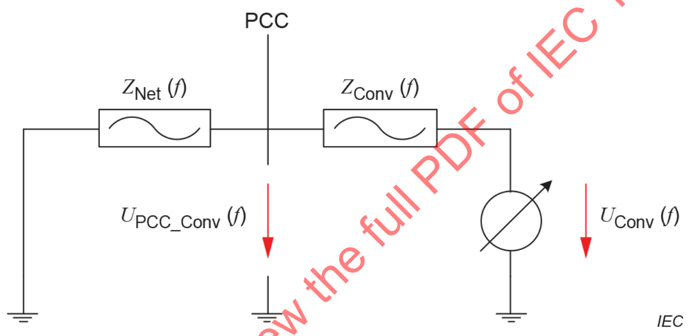


Figure 18 – Harmonic contribution by the VSC converter

In Figure 18, the converter is represented as an ideal harmonic voltage source $U_{Conv}(f)$. In a typical design study, the converter impedance $Z_{Conv}(f)$ which includes both active and passive impedances is defined by the HVDC manufacturer and the network impedance $Z_{Net}(f)$ can be provided by the network operator for the relevant frequency range. The network impedance can have a wide range of possible values depending on configuration and load levels. A suitable calculation algorithm is needed to determine the worst-case network from the specified network impedance loci, i.e. that impedance which maximizes the distortion at the PCC for each individual frequency. The harmonic voltage distortion $U_{PCC\_Conv}(f)$ at PCC is then calculated by Equation (1).

$$\left|U_{PCC\_Conv}(f)\right| = \left|\frac{Z_{Net}(f)}{Z_{Net}(f) + Z_{Conv}(f)}\right| \cdot \left|U_{Conv}(f)\right| \quad (1)$$

where,

$Z_{Net}(f)$ is the AC network harmonic impedance;

$Z_{Conv}(f)$ is the VSC converter harmonic impedance.

18.2.3 Pre-existing network harmonics

The impact of pre-existing (background) harmonics on the total harmonic distortion at the PCC can be analysed by using the same type of model as shown in Figure 19 below.