



BSI Standards Publication

Guideline for the system design of HVDC converter stations with line-commutated converters

National foreword

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TECHNICAL REPORT

Guideline for the system design of HVDC converter stations with line-commutated converters

INTERNATIONAL
ELECTROTECHNICAL
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CONTENTS

FOREWORD.....	6
INTRODUCTION.....	8
1 Scope.....	9
2 Normative references	9
3 Terms and definitions	9
4 Symbols	10
4.1 Letter symbols for variables	10
4.2 Subscripts.....	11
5 Overview of HVDC system design	11
5.1 General.....	11
5.2 Formulation of system design	13
5.2.1 HVDC system ratings.....	13
5.2.2 HVDC system configuration	13
5.2.3 Reactive power compensation and control	13
5.2.4 AC/DC interaction and control.....	13
5.2.5 Insulation coordination.....	14
5.2.6 AC/DC harmonic filtering	14
5.2.7 Environmental considerations	14
5.3 System studies and simulations	14
6 Determination of design conditions and requirements	16
6.1 Environmental conditions and requirements	16
6.2 DC transmission line (cable) and earth electrode	17
6.2.1 Parameters of DC overhead transmission line	17
6.2.2 Parameters of DC cable.....	18
6.2.3 Parameters of electrode line and ground electrode	18
6.3 AC system conditions.....	18
6.3.1 Operating scenarios of AC/DC system	18
6.3.2 AC system modelling	18
6.3.3 Relevant AC system protection	19
6.3.4 Reactive power supply and absorption.....	19
6.3.5 Short-circuit current or capacity	20
6.3.6 AC bus voltage	20
6.3.7 AC system frequency.....	21
6.3.8 Pre-existing harmonic and negative sequence voltage	21
6.4 Requirements for HVDC systems arising from AC/DC interaction	22
6.5 AC system equivalents.....	23
6.5.1 General	23
6.5.2 Equivalent for AC/DC system dynamic or transient simulation	23
6.5.3 Impedance equivalent for AC filter design.....	24
6.5.4 System equivalent for low order harmonic resonance study	25
7 Main circuit design.....	26
7.1 Ratings	26
7.1.1 Rated power	26
7.1.2 Rated voltage	27
7.1.3 Rated current.....	28
7.2 Configurations	28

7.2.1	Pole and return path	28
7.2.2	Converter topology	29
7.2.3	DC switchyard configuration	30
7.2.4	Reactive power equipment.....	38
7.3	Determination of main circuit parameters	38
7.3.1	General	38
7.3.2	Control strategy	39
7.3.3	Tolerances and errors.....	40
7.3.4	Determination of converter transformer impedance	40
7.3.5	Relative inductive voltage drop (d_{xN}) and relative resistive voltage drop (d_{rN})	40
7.3.6	Ideal no-load DC voltage	41
7.3.7	DC voltage and DC current	41
7.3.8	Rated capacity of converter transformer	42
7.3.9	Converter transformer taps	43
7.3.10	Inductance of smoothing reactor	44
8	Insulation coordination.....	44
9	Filter design	45
9.1	General.....	45
9.2	AC filter design	45
9.3	DC filter design	45
9.4	Power line carrier (PLC) filters	46
9.5	Radio frequency interference (RFI)	46
10	Reactive power compensation and control.....	47
10.1	General.....	47
10.2	Reactive power consumption	47
10.2.1	Reactive power consumption calculation.....	47
10.2.2	Maximum reactive power consumption.....	48
10.2.3	Minimum reactive power consumption	48
10.3	Determination of reactive power equipment capacity.....	48
10.3.1	General	48
10.3.2	Capacity of reactive power supply equipment	48
10.3.3	Capacity of reactive power absorption equipment	48
10.3.4	Sizing of reactive power sub-bank	49
10.3.5	Sizing of reactive power bank	49
10.4	Reactive power control	49
10.4.1	General	49
10.4.2	Reactive power exchange control/voltage control	50
10.4.3	Voltage limitation	50
10.5	Temporary overvoltage control.....	51
11	Basic parameters of main equipment	51
11.1	General.....	51
11.2	Converter valves.....	51
11.2.1	General	51
11.2.2	Valve hall environment	51
11.2.3	Current rating	52
11.2.4	Voltage rating	52
11.2.5	Losses of converter valves	53
11.2.6	Testing requirements	53

11.3	Converter transformers	53
11.3.1	General	53
11.3.2	Current rating	54
11.3.3	Voltage rating	54
11.3.4	Other rating	54
11.3.5	Rated loss	54
11.3.6	Test requirements.....	55
11.4	Smoothing reactor.....	55
11.4.1	General	55
11.4.2	Current ratings.....	55
11.4.3	Voltage rating	56
11.4.4	Other ratings	56
11.4.5	Losses.....	56
11.4.6	Test requirements.....	56
11.5	Wall bushings	56
11.5.1	General	56
11.5.2	Current rating	56
11.5.3	Voltage rating	56
11.5.4	Testing requirement.....	56
11.6	AC and DC filter equipment.....	57
11.7	PLC filter equipment	57
11.8	Other equipment in DC yard.....	57
Annex A (informative) Typical control, measurement and equipment manufacturing tolerance in HVDC systems		58
Annex B (informative) Technical parameters for equipment specification		59
B.1	Converter valve.....	59
B.2	Converter transformer.....	61
B.3	Smoothing reactor.....	62
Bibliography.....		63
Figure 1 – System design in an HVDC project.....		12
Figure 2 – Example of schematic diagram of AC system frequency variation range.....		21
Figure 3 – Sector diagram of system harmonic impedance.....		24
Figure 4 – Circle diagram of system harmonic impedance.....		25
Figure 5 – Structure of equivalent network for low order harmonic resonance study.....		26
Figure 6 – Converter transformer connection topology		30
Figure 7 – Sketch maps of the DC yard switches of HVDC system		33
Figure 8 – Schematic diagram of converter parallel connection		33
Figure 9 – Schematic diagram of pole line parallel connection		34
Figure 10 – Procedure of NBS disconnecting DC fault		34
Figure 11 – Current transfer path of the MRTS.....		35
Figure 12 – Current transfer path of ERTS.....		35
Figure 13 – Connection and function of the NBES.....		36
Figure 14 – Commutating process of NBES in case of DMR.....		36
Figure 15 – High speed bypass switch		37
Figure 16 – Converter paralleling switches.....		37

Table 1 – Studies and simulations in HVDC system design	15
Table 2 – Preferred rated voltages for overhead line HVDC power transmission	27
Table 3 – Preferred rated voltages for submarine HVDC power transmission	27
Table A.1 – Tolerance for main circuit calculation	58
Table A.2 – Control parameters for main circuit calculation	58

INTERNATIONAL ELECTROTECHNICAL COMMISSION

GUIDELINE FOR THE SYSTEM DESIGN OF HVDC CONVERTER STATIONS WITH LINE-COMMUTATED CONVERTERS**FOREWORD**

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IEC TR 63127, which is a Technical Report, has been prepared by IEC technical committee 115: High Voltage Direct Current (HVDC) transmission for DC voltages above 100 kV.

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

Enquiry draft	Report on voting
115/195/DTR	115/203/RVDTR

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

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

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

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

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

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 ^{A1} more than half of HVDC projects were commissioned after the year 2000. ^{A1} HVDC has become a common tool in the design of future global transmission systems.

HVDC systems transmit 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 permissions. 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 ^{A1} line-commutated converter (LCC) ^{A1} HVDC systems provide 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.

Simply due to these technical merits, the market demand for HVDC transmission technology is spreading widely over the world. There are many HVDC power transmission systems with a DC voltage from 50 kV up to ^{A1} 1 100 kV ^{A1} in different countries. ^{A1} *Text deleted.* ^{A1}

The fast development of the HVDC power transmission and distribution industry has been accompanied by IEC standardization work. More than 40 IEC documents, from DC equipment to DC systems, have been published. Among these, the IEC TR 60919 series, IEC 60633, IEC 60071-5, the IEC TR 62001 series and the IEC 60700 series provide essential information for the design and operation of HVDC power transmission systems.

However, this document provides only a basic guide and refers to typical numbers and examples. Other points and values may also be valid in particular cases and should also be considered accordingly.

GUIDELINE FOR THE SYSTEM DESIGN OF HVDC CONVERTER STATIONS WITH LINE-COMMUTATED CONVERTERS

1 Scope

System design is the basis of construction and operation of HVDC systems. It defines the overall philosophy for the HVDC transmission system and enables the ratings and specifications for the equipment integrated in the project.

This document focuses on the system design of converter stations. It is applicable to point-to-point and back-to-back HVDC systems based on line-commutated converter (LCC) technology.

This document provides guidance and supporting information on the procedure for system design and the technical issues involved in the system design of HVDC transmission projects for both purchaser and potential suppliers. It 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 60633, *High-voltage direct current (HVDC) transmission – Vocabulary*

3 Terms and definitions

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

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

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

4 Symbols

4.1 Letter symbols for variables

U_d	DC voltage between the pole and the neutral bus at the line side of the smoothing reactor
U_{dL}	DC voltage of pole line to ground at the measuring point
I_d	DC current
U_{dmeas}	measured DC voltage
P_{ref}	power setting at the line side of the smoothing reactor in the rectifier station
X_t	commutation reactance, including converter transformer reactance and other reactance in the commutation circuit that will affect the commutation process
P_u	on-load losses of converter transformer and smoothing reactor when a six-pulse converter is operating at rated capacity
R_{th}	equivalent resistance of the voltage drop of the thyristor valve (current dependent resistance of the thyristors)
U_{dio}	ideal no-load DC voltage of six-pulse converter
U_k	relative converter transformer inductive voltage drop (short-circuit reactance)
U_{plc}	relative voltage drop of AC PLC filter reactors
d_x	relative inductive DC voltage drop of converter
d_r	relative resistance DC voltage drop of converter
U_T	forward voltage drop of converter valve under conducting state
d_{xtotR}	total relative inductive DC voltage drop of converter – contains both commutation circuit reactance and the system impedance converted onto valve side
P_{dc}	active power of converters
Q_{conv}	reactive power consumption of individual converter
Q_f	reactive power supplied by filters
S_{SC}	short-circuit capacity of AC bus
R_d	total resistance of DC transmission line at each pole
R_e	resistance of electrode
R_g	resistance of electrode line
S_n	rated capacity of a three-phase converter transformer connected to a six-pulse valve group
S_{n3w}	rated capacity of a single-phase three-winding converter transformer connected to a 12-pulse valve group
S_{n2w}	rated capacity of a single-phase two-winding converter transformer connected to a 12-pulse valve group
U_v	valve side line voltage of converter transformer
I_v	valve side line current of converter transformer
U_l	line voltage of line side of converter transformer
n_{nom}	rated ratio of converter transformer at normal tap position
η	needed OLTC range of converter transformer
$\Delta\eta$	step size of converter transformer OLTC
L_d	total inductance from DC side
L_{dr}	smoothing reactor inductance
L_{tr}	converter transformer inductance per phase
μ	overlap angle

α	delay angle
γ	extinction angle
Q_{total}	total reactive power supplied by AC filters and shunt capacitors at normal voltage
Q_{sb}	reactive power supplied by the largest AC filter or shunt capacitor sub-bank at normal voltage
Q_{ac}	reactive power supplied by AC system (negative value means the capability to supply reactive power by AC system)
Q_{dc}	reactive power consumption of converters
K_v	voltage correction factor, normally 0,95 to 1,05
Q_r	total reactive power absorbed by the shunt reactors of converter station at normal AC voltage
Q_{fmin}	capacity of the minimum filter combination which shall be switched in to meet the harmonic performance requirement at normal AC voltage
ΔU_{AC}	dynamic voltage change because of sub-bank switching
Q_{filter}	reactive power capacity of the filter or shunt capacitor sub-bank to be switched
ΣQ_{filter}	reactive power capacity of the filter or shunt capacitor sub-banks in operation after switching
ΔQ_{dc}	change of reactive power consumption of converters due to sub-bank switching, which sometimes can be ignored

4.2 Subscripts

N	normal value of the variables
R	value of rectifier side
I	value of inverter side
max	maximum value of the variable
min	minimum value of the variable

5 Overview of HVDC system design

5.1 General

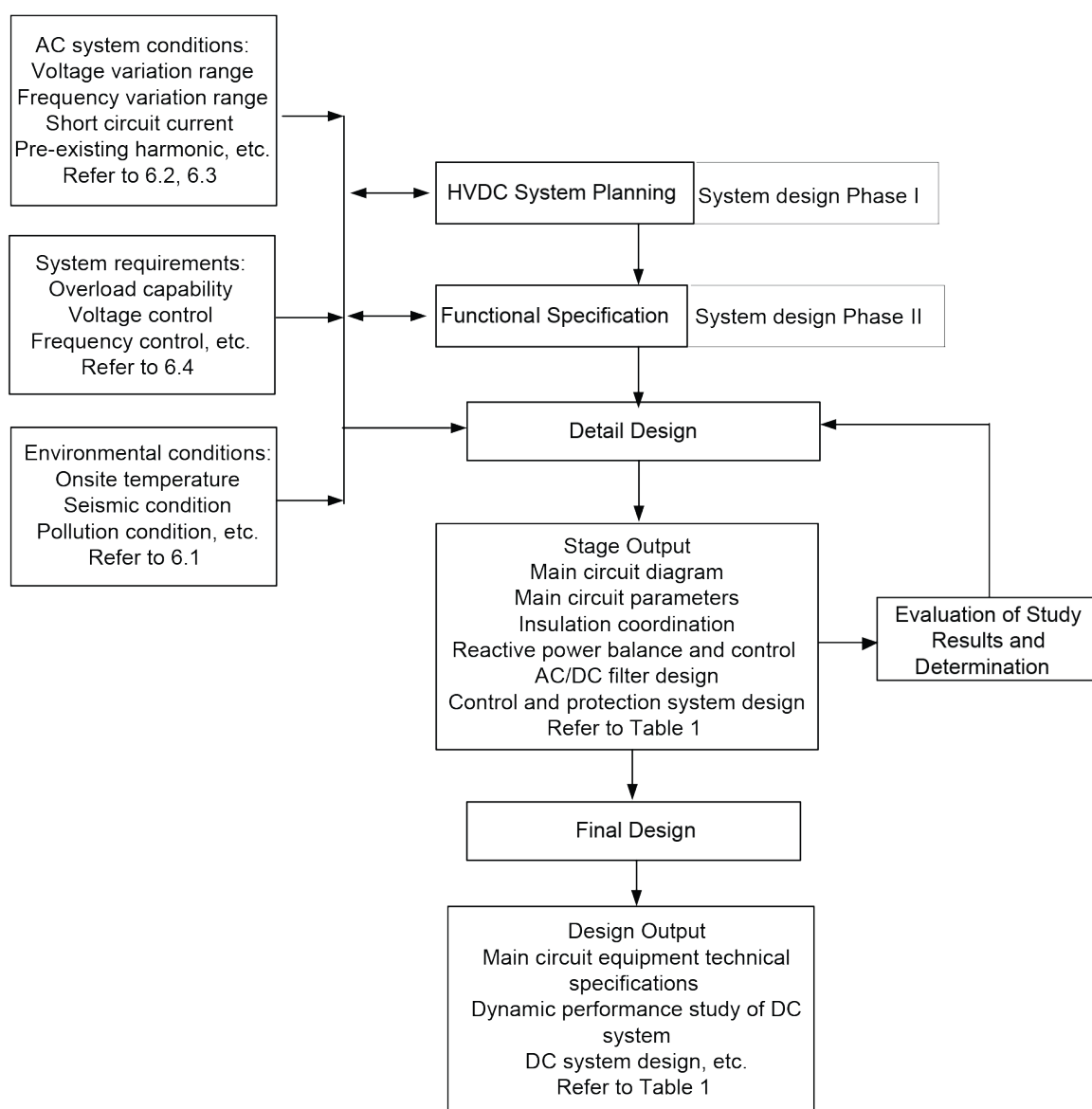
In implementing HVDC projects, the purchaser or the supplier will do preliminary system design work to prepare the various required documents needed by the project. Specific studies and simulations are conducted during the system design to find the optimal project schemes and to demonstrate performance. As a minimum, the following main system features should be determined:

- HVDC system ratings;
- HVDC system operation configurations and control modes;
- reactive power compensation and control;
- harmonic filtering;
- AC/DC interaction and control;
- insulation coordination;
- environmental impacts, such as audible noise, electromagnetic fields, etc.

The system design may be conducted in several phases by different parties, such as purchaser or supplier, during planning, bidding, detailed design stages, for example, as shown in Figure 1. Different tools and models may be introduced in the system design because of different targets or designs at each stage. One should be very careful to adopt the tools and models in a coordinated manner.

A functional specification for the project is usually prepared by the purchaser before the detailed design. It may consist of project objectives and conditions, grid codes, targeted system performance requirements and operation regulations, etc. This functional specification should be treated as both providing inputs and the guide for the system design of an HVDC project. Because the final technology solution is undefined before the detail design stage, it is always necessary to reserve adequate space in the functional specification for further optimization. The owner will issue the specification as a document for bidding if this is a turn-key project. After evaluation of bidding for the specific technology solution, especially for HVDC control, the owner may choose the appropriate solution. Thus, the system features listed above will be studied in more detail based on the chosen technology solution and some additional studies and surveys usually need to be performed to finalize the system design. Finally, all the equipment ratings and specifications will be prepared.

The flowchart of an HVDC system design is summarized in Figure 1.



IEC

Figure 1 – System design in an HVDC project

5.2 Formulation of system design

5.2.1 HVDC system ratings

HVDC system ratings are defined by transmission capacity, DC voltage and DC current. These ratings are evaluated and selected according to considerations such as the exploitation and the market of energy, the conditions and requirements of power grids, the grid code, the transmission distance, the transportation of bulk equipment, the amount and payback of investment together with the environmental conditions, etc.

The capacity is the first item which the purchaser decides on in the planning stage as well as the DC voltage for a long-distance transmission project. Other ratings can be optimized and finalized in the following design stages.

5.2.2 HVDC system configuration

The HVDC system configuration is normally chosen according to the function and rating of the HVDC system, the environmental requirements, the reliability and availability requirements and other similar high-level functional requirements. A preliminary configuration will be suggested prior to other system design work and the final single line diagram of the converter station will be finalized by the detail design.

5.2.3 Reactive power compensation and control

The converter consumes reactive power in operation. It is necessary to design the reactive power compensation scheme along with the HVDC equipment and control strategy to align with the AC system conditions and requirements. This compensation scheme will be estimated and proposed during planning and then formulated and verified during the detail design together with the related control strategy.

Although most of the reactive power to be compensated is inside the converter station, there will still be some reactive power exchange with the AC system. The capability of the AC system to exchange reactive power needs to be specified in the planning.

5.2.4 AC/DC interaction and control

The AC/DC interaction study should be conducted in different phases to demonstrate stable operation and performance of the power grid after integrating the HVDC link. The power flow and stability study should include at least

- starting and stopping of HVDC system,
- steady-state operation,
- AC system faults, and
- DC system faults.

Especially when the short-circuit ratio (SCR) is low, the commutation failure and recovery procedure of the HVDC system after faults should also be carefully studied. The use of capacitor commutated converters (CCC) or controlled series compensated capacitors (CSCC) may be considered as an option for improvement of HVDC operational performance under low SCR condition. For multi-infeed systems, those converters which will impact the study result should be represented in the studies.

AC/DC interaction is normally studied by digital simulation. In the planning stage a simplified HVDC model may be used when the detailed model is unavailable. This simplified model should have enough precision and the study result should cover all the possible situations in practice. The stable operation and performance of the power grid will be demonstrated and proved by detailed modelling with the actual control in the detailed design. The IEC TR 60919 series provides guidance on specifying the requirements.

Besides the normal power flow and stability study, some special studies may be needed such as a sub-synchronous resonance study, frequency control study, low frequency oscillation damping control study and other such studies. In most cases, mitigation of these resonances or oscillations can be achieved by HVDC control. ^{A1} *Text deleted.* ^{A1} Therefore, in the planning stage, some scanning studies may be conducted to check the necessity for further study and solution formulation in the detailed design.

5.2.5 Insulation coordination

Insulation coordination is closely related to the safety and cost of HVDC projects. Thus, it is necessary to predict the insulation level for a HVDC system even in the planning stage. The detail design will formulate the final arrester protection scheme and verify that the predicted insulation level can be achieved by simulations such as

- fundamental frequency overvoltage,
- overvoltage caused by resonance,
- temporary overvoltage, and
- transient overvoltage.

5.2.6 AC/DC harmonic filtering

The converter will produce harmonics on both the AC and the DC sides during operation. These harmonics vary in different operation modes, including different configurations, control modes and transmission powers, etc. AC side harmonics should be mitigated to levels agreed with the connected utilities. DC side harmonics should also be mitigated to levels agreed with the affected telecommunication companies.

The complete filtering solution and component specifications will be provided by AC/DC harmonic filtering study and design. For further information, refer to IEC TR 60919-1 and the IEC TR 62001 series.

5.2.7 Environmental considerations

The HVDC system can impact the environment and vice versa. Audible noise, electromagnetic field, earth current (in some operation configurations) and radio interference are major environmental impacts from the HVDC system. Pollution, earthquake, temperature, etc. are major impacts from the environment. Surveys on environmental effects should be conducted before the system design.

5.3 System studies and simulations

In order to evaluate and determine the system characteristics, applicable quantitative specification and system performances, various kinds of system study and simulation are required during the system design.

A summary of studies and simulations is listed in Table 1.

Table 1 – Studies and simulations in HVDC system design

No.	Study/Simulation	Input	Output
1	Main Circuit Parameter calculation	Capacity and topology of HVDC system, Basic control strategy, DC transmission line and cable parameters, Electrode and electrode line parameters (as applicable), Normal voltage and its steady-state range of AC bus	Steady state characteristics and ratings
2	Reactive Power Compensation	Main circuit parameter calculation, AC network condition	Total amount of compensation, Permissible reactive units and their capacity
3	AC system equivalent	AC network data	Equivalents for relevant simulations such as AC/DC transient/dynamic simulation and fundamental overvoltage study, etc.
4	Temporary overvoltage and ferro-resonance	Main circuit parameters, Reactive power compensation, HVDC equipment characteristics, Control & Protection characteristics, AC network data or equivalent	Overvoltage and depression strategy
5	DC Resonance Study	Main circuit parameters, Reactive power compensation, AC/DC parallel line interaction, HVDC equipment characteristics, Control & Protection characteristics, AC network data or equivalent	Evidence to determine: size of smoothing reactors, size of DC filters, equipment ratings
6	Insulation Coordination	Main circuit parameters, Reactive power compensation, AC/DC harmonic filtering, HVDC equipment characteristics, Control & Protection characteristics AC system equivalent	Arrester protection scheme, LIPL/LI WV and SIPL/SI WV
7	AC system harmonic impedance scan	AC network data	AC system harmonic impedance
8	AC/DC Harmonic Filtering	AC system harmonic impedance, Main circuit parameters, Reactive power compensation, HVDC equipment characteristics, Control & Protection characteristics	AC/DC filter scheme, Component ratings
9	Dynamic performance simulation and verification	AC system equivalent, Main circuit parameters, Reactive power compensation, Control & Protection characteristics	Control & Protection characteristics
10	Power flow and stability study	AC network data, Main circuit parameters, Reactive power compensation, Control & Protection characteristics	Power flow and stability, Required additional control function, such as frequency control, damping control, etc.

No.	Study/Simulation	Input	Output
11	Subsynchronous Torsional Interaction between HVDC & Generator	Main circuit parameters, Reactive power compensation, Control & Protection characteristics, AC network data, Detailed generator characteristics	Confirmation of subsynchronous oscillation (SSO), Subsynchronous damping control (SSDC) specifications ^a
12	AC/DC parallel line interaction study, if applicable	AC and DC line parameters, Main circuit parameters, DC harmonic filtering	Induced fundamental frequency voltage and current on the DC side and influence on the converter transformers
13	Transient current	Main circuit parameters, Reactive power compensation	Transient current ratings
14	AC Breaker /DC Switch study	Main circuit parameters, Reactive power compensation, AC/DC harmonic filtering, HVDC equipment characteristics, Control & Protection characteristics, AC system equivalent	Ratings of breaker
15	Availability & Reliability study	Main circuit arrangement, reactive power compensation and connection scheme, Control & Protection characteristics, auxiliary system, etc. and design target of force outage, rate and schedule outage	Control & protection redundancy requirement, Mandatory spare
^a SSDC specifications can be designed later if some input is not clear.			

6 Determination of design conditions and requirements

6.1 Environmental conditions and requirements

The meteorological data, such as ambient temperature, atmospheric pressure, humidity, wind direction and velocity, rainfall and snow, and solar radiation intensity, are always needed for HVDC system design. The above data and their intended utilizations are listed in detail in IEC TR 60919-1.

Seismic requirements should be specified for the design of converter station buildings including valve halls as well as for equipment design.

The deposition of contamination particles over insulator surfaces could be more severe under DC voltage than under AC voltage. The pollution condition is ordinarily specified in equivalent salt deposit density (ESDD, mg/cm²) for the creepage design of HVDC equipment. ESDD will differ according to meteorological conditions, contamination content, type of insulators and other such factors. It is crucial to adopt a reasonable ESDD for an optimized design. Increasingly composite insulators are used in converter stations where the ESDD is very high, for example higher than 0,1 mg/cm². Another alternative in a heavy pollution area is to use an indoor DC switchyard especially for ultrahigh-voltage direct current (UHVDC) projects. For more information the designer can refer to IEC TR 60919-2 and CIGRE TB 518.

Altitude correction is needed for the external insulation design of converter station equipment when the station is located at higher than 1 000 m above sea level. Guidance for altitude correction is given in IEC 60060-1, IEC 60071-1 and IEC 60071-5.

The effect of an HVDC system on the environment or surroundings will also influence the scheme of HVDC links, which includes earth current, audible noise, radio interference, etc.

In some countries and states, earth current is strictly limited or prohibited because of risk of interference with underground installations. Thus, the choice of HVDC system configurations and operation modes will be limited.

Audible noise is one of the main concerns in many countries. Audible noise reduction measures might be required for converter transformers, smoothing reactors, AC filters and other noise sources. Further details are given in IEC 61973.

In the case of radio interference and telecommunication interference, RI/PLC filters and DC filter are often designed and installed. An AC filter could diminish the interference to the telephone systems.

6.2 DC transmission line (cable) and earth electrode

6.2.1 Parameters of DC overhead transmission line

The data required for modelling the HVDC transmission line include the following:

- a) conductor type;
- b) conductor structure, including the respective numbers and diameters (mm) of aluminium and steel strands in pole conductors;
- c) cross section (mm²) of conductor, including respective cross sections of aluminium and steel strands;
- d) outer diameter (mm) of conductor;
- e) DC resistance of conductor per kilometre at 20 °C (Ω/km);
- f) length of transmission line;
- g) number of conductor bundles per pole and spacing between bundles;
- h) attaching height, horizontal distance and sag of conductors and ground wire on tower.

Owing to the uncertainties of the right of way at system design stage, transmission power and temperature, among others, the total DC resistance of the transmission line can be various. The variation in DC resistance caused by temperature can be calculated for aluminium conductors using Formula (1). For other conductor materials, the resistance calculation can refer to specific specifications.

$$\Delta R = 0,0041 \times R_{20} \times (T - 20\text{ °C}) \quad (1)$$

where

T is the conductor temperature in °C;

R_{20} is the conductor resistance at 20 °C.

Different DC resistances are used in the calculation of main circuit parameters of the HVDC system to define the worst-case scenario. It should be noted that different causes may alter the DC resistance in different directions. For example, the minimum DC resistance at low power and at maximum power may differ substantially for a long HVDC line. The reasonable DC resistance shall be applied in the efficient design.

To carry out the DC filter design and the DC system resonance study, detailed DC line parameters as listed above are required, including shielding wire configuration. For a long-distance DC transmission project, the geographical conditions vary along the line corridor resulting in different towers and earth parameters. It can be difficult to model all the cases one by one. A practical way is to summarize the proportion of each geographical condition along the whole line, such as plains, hills and mountains, and then to calculate the average parameters.

The soil resistivity varies along the HVDC transmission line and the electrode line corridors, which is typically within several hundred $\Omega\cdot\text{m}$.

6.2.2 Parameters of DC cable

Historically, several types of cables, including polyethylene (PE), ethylene propylene rubber (EPR), paper-insulated oil filled cables and mass-impregnated cables, have been used in submarine HVDC projects. The choice of cable type is determined by the transmission power and length.

Regardless of the type, the following cable electrical parameters are needed as a minimum for an HVDC system design:

- a) inner radius of each conducting layer;
- b) outer radius of each conducting layer;
- c) resistivity of each conducting layer;
- d) relative permeability of each conducting layer;
- e) outer radius of each insulation layer;
- f) relative permittivity of each insulation layer;
- g) relative permeability of each insulation layer.

The IEC 60287 series provides more information.

6.2.3 Parameters of electrode line and ground electrode

When the DC system is allowed to use the ground return operation, the parameters of the ground electrode lines and ground electrodes are an integral part of the DC circuit and therefore are a necessary input for the relevant studies and simulations, such as the main circuit parameter calculation, DC filter design and control and protection system. For specific parameter requirements, refer to 6.2.1 and 6.2.2. IEC TS 62344 provides relevant details about the design of electrode stations. Where several projects share one common electrode, the main circuit arrangement, rated parameters and operation mode of the other projects need to be provided for ground system protection purposes.

6.3 AC system conditions

6.3.1 Operating scenarios of AC/DC system

The operating scenarios of the AC/DC system are defined by the combination of DC transmission powers, generator(s) in service and loads.

The typical operating scenarios of the AC/DC system need to be defined for the project in the system design and study. Some additional scenarios such as emergency operation, commissioning operation or stage operation also need to be considered because they may cause higher stresses on the HVDC equipment if the design of the equipment is based on them. Since these additional scenarios appear just in the early stage of the project or very rarely through the project life, an alternative option for the customer is to design the HVDC system for normal operating conditions and later on verify the design under special scenarios to avoid additional investment. In this case, reduced power or other degradation in performance of the DC system may be acceptable for operation.

6.3.2 AC system modelling

AC system data should generally be provided by the purchaser, which includes all the data necessary for system modelling such as:

- a) lines, transformers, reactive power compensators;
- b) generators and their regulators such as excitation regulator, prime mover, governor, PSS,

- c) unit commitment and load model;
- d) configuration, parameters and control model for power electronics based devices (e.g. HVDC, FACTS, STATCOM, SVC, etc.).

AC system modelling should follow the guidance in CIGRE TB 563.

Some special studies, such as the subsynchronous oscillation study, also need the spring mass parameters of the generators.

The configuration of AC lines at various voltage levels in the vicinity of the DC transmission line is needed while performing interaction studies with parallel AC lines.

6.3.3 Relevant AC system protection

The AC system protection scheme is needed for DC system design, including the fault clearing time for normal and backup protection, and the time sequence for single-phase or three-phase auto-reclosing.

The HVDC system design needs to be properly coordinated with the overvoltage protection of AC components. The DC system normally remains in operation and withstands the overvoltages during AC system faults. The overvoltage caused by the sudden loss of complete or partial DC power due to DC faults needs to be depressed to below the level where the AC component overvoltage protection will not operate, by switching sub-banks or other effective methods. Switching banks can also be adopted if it is allowed by the interrupting capability of bank breakers.

The parameters of nearby AC arresters are needed in the insulation coordination study of the converter station, including rated voltage (kV, RMS value), continuous operating voltage (kV, RMS value), and switching impulse protective level (kV, peak value).

6.3.4 Reactive power supply and absorption

Converter stations balance the reactive power demand mainly by on site self-compensation. However nearby generators or reactive power equipment installed in connected grid can also supply or absorb reactive power and the same should also be considered, as appropriate, to reduce the amount of reactive compensation to be provided in the converter station.

The reactive power flow may vary with AC system conditions, which can be determined through power flow studies. The following information needs to be provided:

- permitted steady-state voltage range under different load levels;
- reactive power demand from other nearby loads;
- number of generators in service;
- maintenance of important AC line(s) to power station;
- power factor of feeding unit;
- minimum active power limit of generator;
- self-excitation limit.

Typically the rated power factor of a generator is 0,85 to 0,9. When calculating the reactive power supply of the AC system, a higher power factor for the generator (0,92 to 0,95) is recommended in a more conservative way.

The HVDC power normally remains unchanged after slight AC network contingencies but can run back under emergency conditions to improve network stability. If HVDC power runs back under AC system contingencies, the reactive power supply can be decided according to the conditions before the contingencies, otherwise the conditions after the contingencies should be adopted.