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TECHNICAL REPORT

colour inside

Guideline for planning of HVDC systems – Part 1: HVDC systems with line-commutated converters

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GUIDELINE FOR PLANNING OF HVDC SYSTEMS –

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FOREWORD

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IEC TR 63179-1, 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:

Draft TR	Report on voting
115/216/DTR	115/230/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- withdrawn,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
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GUIDELINE FOR PLANNING OF HVDC SYSTEMS –

Part 1: HVDC systems with line-commutated converters

1 Scope

This document provides guidelines for the selection of a high-voltage directive current (HVDC) system with line-commutated converters (LCC), hereafter referred to as HVDC system, for the purposes of HVDC system planning. It covers the guidelines on the requirements for integrating HVDC systems in AC power networks, selection of rated voltage and power, overloads, circuit configuration, expandability, comparison of technical, economic, regulatory, political, social and environmental factors, etc. This document is applicable for planning an HVDC system.

This guideline is not exhaustive and it is possible that there will be other specific aspects, particular to a specific HVDC project, which will also need to be considered.

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 General

The HVDC system development and integration cycle may be described in terms of six phases, as shown in Figure 1.

The main task of HVDC system planning is to develop and select an HVDC scheme based on the conclusions of power network development planning where the network requirements are defined. HVDC system planning uses as a minimum the total transmission capacity and range of connection points previously determined by power network development planning, taking into account current and future conditions of the power system, environment, and other contributing factors.

There is a certain degree of repetition and iteration between HVDC system planning and system design (refer to Figure 1). For the purpose of project feasibility study and scheme comparison, some investigation would be carried out during the system planning phase, the detailed studies and final design would be accomplished during the system design phase.

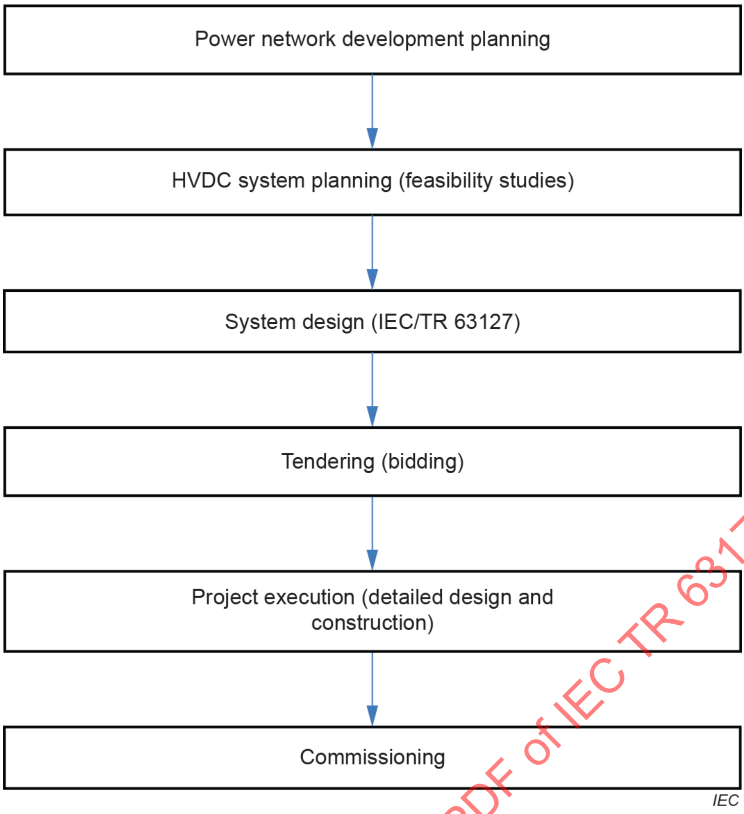

Figure 1 – Phases during integration of a new HVDC system into the power network

The work contents and procedure for planning of an HVDC system are as follows:

a) compare HVDC and AC solutions at high level according to the specific requirements (see Clause 5);

b) when HVDC is the only technically feasible solution, or the use of an HVDC scheme has overwhelming advantages, a number of alternative HVDC solutions could be investigated (see Clause 6). When both HVDC and AC alternatives are technically feasible and neither of them has overwhelming advantages, further analysis is required to confirm the preferred solution;

c) verify the security of supply and stability of each alternative (see Clause 7);

d) compare the economic efficiency of alternative solutions (see Clause 8);

e) present the recommended solution (see Clause 9).

The above steps in the planning of an HVDC system are shown in Figure 2.

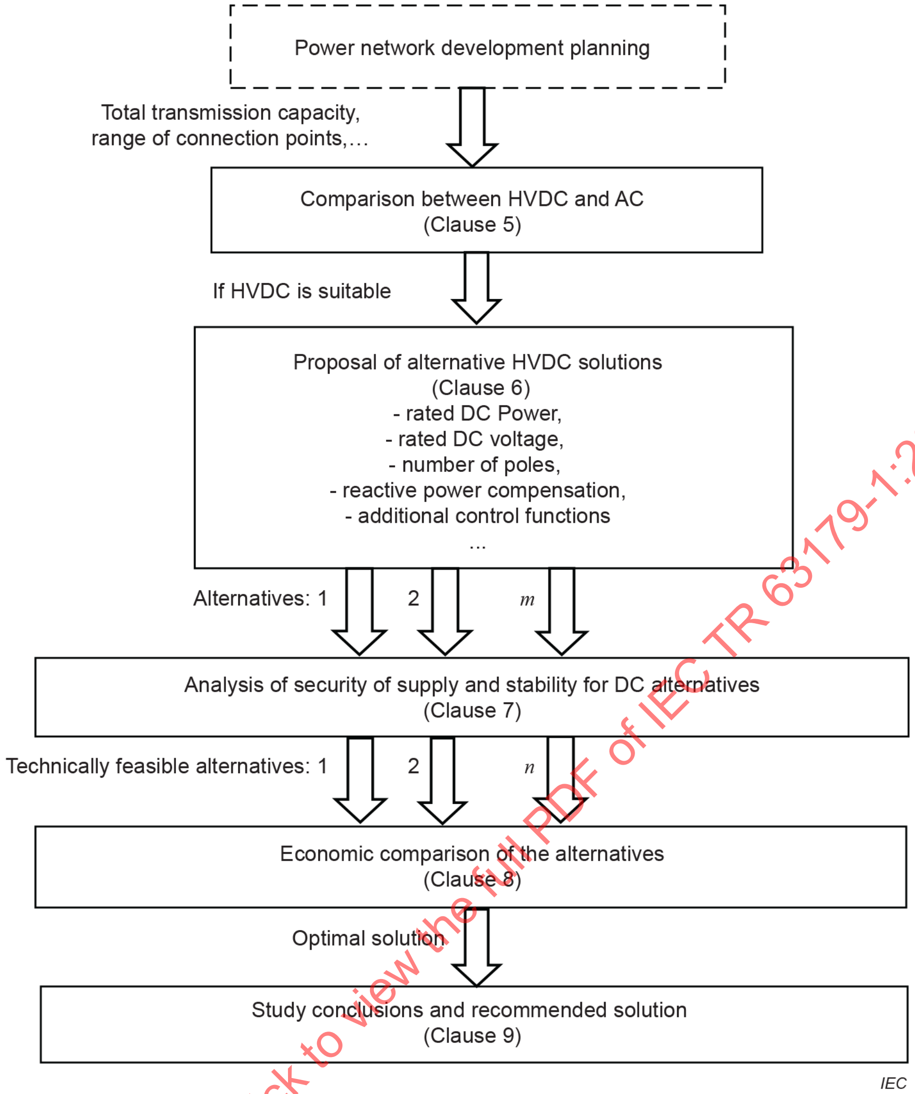

Figure 2 – Procedure for planning an HVDC system

5 Comparison between HVDC and AC alternatives

5.1 Consideration of overall network planning

5.1.1 Overall network planning

When a new line between two areas is planned, the solutions should consider all aspects of transmission planning, including the current and future power demand, line corridor conditions, operation and maintenance, energy dispatch and overall cost.

5.1.2 Connection topologies for HVDC systems

When an HVDC system is to be added to AC power networks, there are two typical connection topologies:

a) HVDC interconnection between two asynchronous AC power networks;

b) embedded HVDC system. An embedded HVDC system is an HVDC link between two parts of the same AC synchronous transmission system.

In addition, a multi-terminal HVDC link could also be considered both in a) and b) above.

5.2 Comparison of transmission capacity

The power transfer between two networks through an AC overhead transmission line is approximately given by the following expression:

$$P = \frac{V_S V_R}{X_{SR}} \sin \theta_{SR}$$

where

V_S and V_R are the voltages at the sending and receiving ends, respectively;

X_{SR} is the series reactance between the two ends;

θ_{SR} is the load angle (phase difference between the two voltages).

To ensure that synchronism between the two networks is maintained following major disturbances, the load angle is kept low during steady state operation. As a result, the power transfer capability of the AC line is reduced compared to its thermal capability. This problem does not exist with an HVDC system, as the two networks are decoupled and the power can be independently controlled by the HVDC system.

For high-voltage AC cable transmission over certain distances, the charging current becomes a major contributor to the thermal loading of the cable, due to its large shunt capacitance. This therefore limits the useful load that the AC transmission circuit can carry. With DC transmission, no charging current problems occur and therefore the useful load is also generally only limited by the thermal capability of the cable.

5.3 Comparison of operation requirements

5.3.1 Comparison of system fault and stability

Faults causing significant voltage variation or power swings do not transmit across an HVDC link. They may emerge on the other end of an HVDC link simply as a reduction in power, without causing severe disturbance on the other end of the HVDC link.

Contrary to AC transmission, HVDC does not significantly increase the short-circuit currents in both sending and receiving ends of AC power networks.

An HVDC link does not suffer from the power angle stability problems which frequently occur with long AC transmission lines. Also, an AC transmission line is sensitive to disturbances of the power balance in AC power networks, and the power flow within connecting AC lines is not easy to be controlled, whereas the controllability of an HVDC system can be used to support the stability of the connected AC networks by power runback or runup. Furthermore, an HVDC link can provide additional benefits, such as possible overload and reduced voltage operation. However, for a short time during a transient, an AC line may be able to transmit more power than a DC link, even beyond its steady state thermal capacity, while the transient overload allowed by the converter stations is usually smaller.

5.3.2 Comparison of voltage regulation and reactive power compensation

An AC transmission line imposes a load-dependent reactive power demand which may impact the active current rating, and may require reactive power compensation at the terminals, and at points along the line, to ensure the desired voltage level and adequate active power transfer capability. While series or shunt compensation can assist transmission through overhead lines, a technical limit is encountered in the case of transmission through insulated cables. Even at relatively short distances, the reactive power consumes the greater part of the current carrying capacity of the cable. Such solutions are possible, but inconvenient.

HVDC systems do not need this type of compensation and therefore do not present the same technical limitations in long transmission distance, with no requirement for special compensation along the line/cable.

5.4 Comparison of cost

The listed items below should be evaluated and compared from a monetary point of view:

a) station costs;
b) line costs;
c) cost due to the adaptation of the existing network;
d) capitalised cost of converter station and DC line losses during the life of the project;
e) operational costs;
f) maintenance costs;
g) decommissioning costs;
h) land acquisition and rights of way.

NOTE The above list is not exhaustive.

For bulk power transfer over long distances, an HVDC transmission project has a lower cost, whereas an AC transmission project has a lower cost at short distance to transmit the same power. There exists a "breakeven distance" at which HVDC and AC transmission projects have the same cost.

The comparison is shown in Figure 3. Many factors contribute to the cost of AC and DC transmission, including ratings, locations, terrain, losses, etc., therefore the determination of the actual breakeven distance for a particular transmission system should be carried out on a case-by-case basis. The breakeven distance of overhead line is typically around 600 km to 800 km. For transmission by submarine cable the breakeven distance is around 40 km to 120 km. It may not be practical to consider AC cables longer than 40 km without some forms of additional compensation measures, but HVDC links using cables over hundreds of kilometres are feasible.

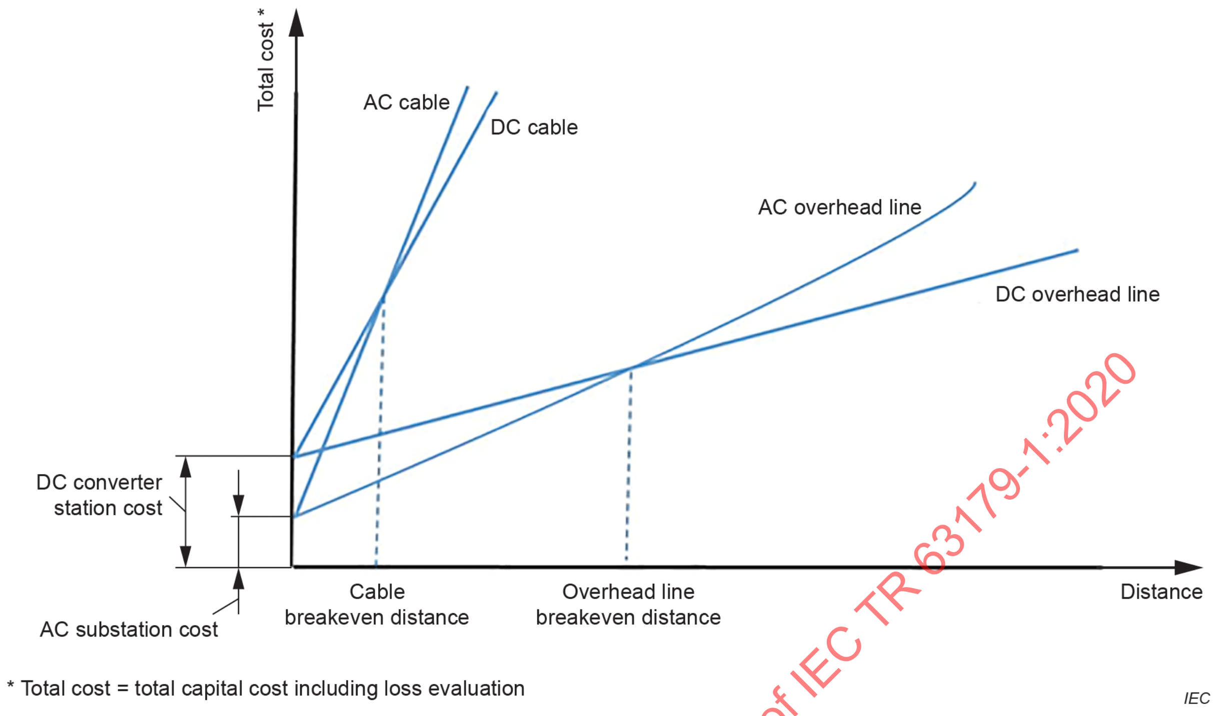

Figure 3 – Cost versus distance

5.5 Comparison of other aspects

In order to determine the most appropriate power transmission solution, a study and comparison should be done for AC and HVDC alternatives.

The items listed below may be evaluated and compared from a strategic point of view:

a) political environment;
b) social impact;
c) environmental considerations;
d) transmission capacity and integration in the future power networks;
e) human resources for maintenance management and maintenance work;
f) regulatory and statutory requirements.

NOTE The above list is not exhaustive.

6 HVDC solutions

6.1 Main circuit topologies

6.1.1 General

There are two main types of HVDC system, namely transmission (two-terminal, also referred to as point-to-point, or multi-terminal, where the different terminals are some distance away from each other) and back-to-back systems (where the two terminals are in the same location without an HVDC transmission line or cable).

For HVDC transmission systems, there are two categories, namely monopole and bipole.

For a back-to-back HVDC system, the monopolar configuration is normally used. There may be more than one monopolar back-to-back converter unit in the same location.

For the main circuit topologies and their features, refer to IEC 60919-1.

6.1.2 Monopolar HVDC transmission system

6.1.2.1 Monopolar HVDC transmission system with earth return

This is the simplest HVDC transmission system topology. It is one of the most cost-effective solutions. This topology is generally used as the first stage in construction of a (future) bipolar system. However, it presents the following disadvantages:

a) a pole outage means that 100 % of power transfer capability is lost;

b) it requires an electrode line and a continuously operable earth electrode at the two ends of the transmission which involves consideration of issues such as corrosion, magnetic field effects, etc., and with possible impacts on the environment and on transformers close to the electrodes.

NOTE Details about electrodes are available in IEC/TS 62344.

6.1.2.2 Monopolar HVDC transmission systems with dedicated metallic return

This topology will generally be used:

a) as the first stage in construction of a bipolar system and if long term flow of earth current is not desirable during the interim period; or

b) if the HVDC transmission line length is short, where electrode lines and earth electrodes are not economical; or

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

d) if the environmental impact due to earth/sea return, such as dryness of land, sea temperature rise, emission of dissolved gases, etc., is not acceptable.

6.1.3 Bipolar HVDC transmission system

Bipolar HVDC transmission topology is the most commonly used topology when an HVDC transmission line connects two HVDC converter stations. The bipolar HVDC system with earth return may be designed such that when one pole converter is out of service, the healthy pole may use the faulty pole's high-voltage line as a metallic return.

The advantages of the bipolar topology compared to monopolar are as follows:

a) lower losses for a given transmitted power;

b) a pole outage means only 50 % of the total power transfer capability of the HVDC link is lost. Owing to this, a bipole HVDC link is compared to a double circuit AC line;

c) overload capability may be incorporated into the rating of each pole, such that when one pole is out of service the healthy pole may pick up some of the faulted pole power, leading to some contingency power capability above 50 %, although this is scheme-specific;

d) lower earth current flow.

The disadvantages of this topology (compared to monopolar) include the following:

e) higher converter station costs;

f) more converter station equipment and therefore more land usage.

6.1.4 Rigid bipolar HVDC system

In this topology, there is not neutral connection between both converter stations. Since only two (pole) conductors exist, no unbalance current between both poles is possible. In case of interruption of power transfer of one converter pole, the current of the other pole also has to be interrupted (at least for a limited time to allow reconfiguration of the DC circuit).

The advantages of the rigid bipolar topology compared to the conventional bipolar topology described in 6.1.3 are as follows:

a) no environmental impact due to earth current;

b) lower cost;

c) either return conductor or electrode station is not required.

The disadvantages of the rigid bipolar topology compared to the conventional bipolar topology described in 6.1.3 are as follows:

d) lower availability because the outage on one of the two pole conductors will lead to a bipole (100 %) power loss and any failure of main equipment excluding pole conductors will result in at least a short total power interruption to re-configure the DC circuit;

e) impossibility to have a scheduled outage of an individual pole including the associated pole conductor without an outage of the complete bipole, and maybe of possibility to have a scheduled outage of an individual pole excluding the associated pole conductor but at least with a short total power interruption to re-configure the DC circuit.

6.2 Main equipment

6.2.1 General

Typically, an HVDC converter station includes mainly the following primary equipment:

a) converter (comprising one or more converter bridges, one or more converter transformers, converter control equipment, essential protective and switching devices and auxiliaries, if any, used for conversion, according to IEC 60633);

b) AC filtering equipment and reactive power compensation equipment;

c) DC smoothing reactor;

d) DC filtering equipment;

e) surge arresters;

f) AC switchgear and measuring equipment;

g) DC switchgear and measuring equipment;

h) wall bushings.

Converter and AC filtering equipment may be considered in some detail during the planning stage, since these items have the most significant impact on cost, land requirements, etc. For detailed descriptions of this equipment, refer to IEC 60919-1.

6.2.2 Converter

Most modern HVDC transmission schemes utilize twelve-pulse converters. Meanwhile, there is also another kind of configuration which uses two or more twelve-pulse converters per pole connected in series or in parallel. Compared with using a single twelve-pulse converter, the main advantage of the two twelve-pulse configuration is that for any single outage, only 50 % of the pole power capability is lost, instead of 100 %. Its main disadvantage is that the cost and land requirements are higher. One of the reasons for using multiple converters per pole is that a single twelve-pulse converter may not be feasible due to the capability limitations of manufacturing or transportation for items such as converter transformers.

The following factors should be considered to determine the optimum HVDC converter configuration:

a) the maximum capacity of a single twelve-pulse converter in terms of ability to manufacture;

b) the limits of transportation of converter transformers from factory to site;

c) reliability of the AC power network connected to the HVDC link;

d) reliability of the HVDC system;

e) flexibility of operation, especially during maintenance and fault conditions;
f) construction in phases;
g) cost-effectiveness of the project.

NOTE This list is not exhaustive and there can be additional applicable factors.

There are four basic types of converter transformer:

1) three-phase, three-winding transformer;
2) three-phase, two-winding transformer;
3) single-phase, three-winding transformer;
4) single-phase, two-winding transformer.

The choice of transformer type is based on the following factors:

– HVDC power transmission rating;
– voltage requirements on both AC and DC sides;
– transformer manufacture capacity;
– transportation constraints;
– replacement work requirements;
– cost effectiveness;
– available land for station layout;
– spare transformer / reliability and availability philosophy.

NOTE This list is not exhaustive and can contain other factors.

6.2.3 AC filtering equipment

The AC filters have two primary purposes:

a) to filter the AC harmonics generated by the HVDC converter; and
b) to provide reactive power needed by the HVDC converter.

The type/size of the filters can be calculated based on the system requirements (i.e. AC filter performance, AC network equivalent impedance, maximum AC filter switching voltages, etc.). These performance requirements have a significant effect on the AC filter designs and consequently also on the station footprint/layout and cost.

6.3 Key DC rating parameters

6.3.1 Rated DC power

Rated DC power refers to the power transmitted continuously by an HVDC link under the specified environmental conditions without the redundant cooling equipment in service. The rated power is generally defined at the rectifier DC terminals, but can also be defined at the inverter DC terminals, or at either of the two converter AC terminals. The rated power of an HVDC link is decided based on many aspects. Below are three of the key considerations:

a) power levels required to be transmitted in the link, considering the minimum and maximum power levels needed according to short and long-term power network planning;
b) overall transmission network considerations, including capacity in the connection points;
c) technological-economic factors to reach a cost-optimised power level.

The maximum continuous and short-term overload capacities should be defined carefully, as these may impact the redundant cooling requirements for the thyristor valves and converter transformers, and the ratings of main circuit equipment, including thyristor valves, the overhead line or cable conductor, etc. The overload capability of the HVDC transmission system should be determined according to the stability and reliability requirements of the power system.

The minimum power should be defined as this could have an impact on the rating of converter equipment and on other power circuit equipment such as a smoothing reactor due to discontinuous current. In the case of a very weak AC network, the value of minimum power should be low enough to keep the network stable when the HVDC system starts.

Further, power direction should also be defined. It could be fully bidirectional (symmetrical ratings), only unidirectional, or bidirectional with a reduced power rating in the direction opposite to the "normal" direction. Specifying a scheme for fully bidirectional power transmission when this is not actually required could add extra cost.

6.3.2 Rated DC voltage

The rated DC voltage is the continuous DC voltage at which the rated power is to be transmitted. For an HVDC system, the rated DC voltage is generally defined at the rectifier terminals, but may also be defined at the inverter terminals or at a point along the DC transmission line based on the needs of a specific project.

For an HVDC transmission system, the rated voltage is selected through analysis considering many aspects including total investment and operation cost including cost of capitalized losses. Below are three of the key considerations:

a) the transmission rated power;

b) the manufacturing capability of equipment;

c) technological-economic factors to reach a cost-optimum power level.

Table 1 lists typical rated voltage ranges under various transmission powers and distances.

Table 1 – Typical overhead bipolar HVDC project for power transmission

	Up to 200 km	Up to 500 km	Up to 1 000 km	Up to 1 500 km	Up to 2 000 km	2 000 km or more
Up to 500 MW	250 kV	400 kV	----------------	----------------	----------------	----------------
Up to 1 000 MW	350 kV	400 kV	500 kV	----------------	----------------	----------------
Up to 3 000 MW	----------------	500 kV, 600 kV	500 kV, 600 kV	600 kV, 800 kV	600 kV, 800 kV	800 kV
Up to 4 000 MW	----------------	600 kV	600 kV, 800 kV	800 kV	800 kV	800 kV
Up to 6 000 MW	----------------	800 kV	800 kV	800 kV	800 kV	800 kV
6 000 MW or more	----------------	800 kV	800 kV	800 kV	800 kV or more	800 kV or more

As the cost depends a lot on the terrain and country, Table 1 can be considered as a reference, and project-specific calculations should be made.

Extreme environmental conditions which may adversely affect the insulation capability of the HVDC link should be considered during the planning stage. Depending on the frequency of occurrence of these conditions, it may be necessary to temporarily impose a lower operating limit on the HVDC voltage during the operation of an HVDC system, for example during metallic return operation. Under these circumstances, the required voltage during reduced voltage operation should be stated, together with the transmitted power requirements, as it may not be possible to achieve full rated power at this reduced DC voltage.

For a back-to-back system, the rated voltage is generally the rated power divided by the rated current. The rated voltage is determined through the maximum utilization of current capability of converter valves/thyristors, as converter station space and converter cost saving are major concerns, and thus normally this is not finalized in the planning phase.

6.3.3 Rated DC current

For an HVDC transmission system, the rated current is the rated power divided by the rated DC voltage.

Rated current is a key factor in the design of all main circuit equipment in the HVDC system, as the current must pass through all of these individual components, which requires an assessment of the physical weight and dimensions, cooling, mounting, and cost. This also applies to the overhead line or cable conductors. For these reasons the selection of both the rated DC current and DC voltage should take all factors into account to achieve a fully cost-optimized solution for a given power rating.

For a back-to-back system, the rated DC current should be selected based on the current carrying capability of the converter equipment. A higher rated DC current is preferred such that rated DC voltage can be lower, thus leading to lower converter equipment costs. However, this must be subject to other factors such as converter loss evaluation, overload requirements, etc. This is generally decided in the detailed design phase.

6.4 Line conductor

An HVDC transmission line conductor may be an overhead line, a cable or a combination of both. When an overhead line is impractical or not feasible, an HVDC cable (underground or submarine) might be the preferred or the only alternative.

Depending on the distance between the two converter stations, the HVDC transmission line may be one of the major components for an HVDC transmission system in terms of overall cost and power losses. The selection of line conductor should therefore be an integral part of the optimization at the planning stage, when considering the overall cost, rated power and voltage for the HVDC transmission system.

For overhead lines, the critical considerations for the conductor design are the corona effects (radio interference, losses and audible noise), as well as the power losses. The corona effects are generally reduced by increasing the equivalent radius of the conductor (also referred to as geometric mean radius), and by increasing the number and/or the cross-sectional area of the sub-conductors in a bundle. The power losses may be reduced by increasing the overall cross-sectional area of the conductor. Both the number and the cross-sectional area of the sub-conductors in a bundle will have major implications on the cost of the HVDC transmission line. Usually, the cross-sectional area of conductors should be selected based on the rated current and the determined economic current density, and then checked in terms of corona effects and other constraints. In conditions of high elevation and high voltage, the corona effects may be significant, requiring particular consideration.

For an HVDC link using insulated cables, either underground or submarine, the following factors may be taken into consideration:

a) insulation coordination with the converter station design;

b) load carrying requirements, including overload;

c) DC voltage;

d) HVDC link topology;

e) depth of water in submarine transmission;

f) installation costs (trenching, horizontal direct drilling, etc.);

g) protection requirements, for example, rock dumping, cable burial depth, etc.;

h) transition between land cables and submarine transmission cables;
i) transition between cables and overhead lines (if necessary);
j) landing point of submarine cables;
k) environmental issues, for example, the temperature rise of the seabed or land;
l) power reversal requirements.

NOTE This list is not exhaustive and can contain other factors.

The earth electrode line will require particular attention, as there are several different aspects to the duty which it performs. Its length is usually insignificant compared to the distance between the two converter stations, as it is generally determined by the nearest suitable site (to achieve the best separation from a converter station and the best soil conductivity in all climatic conditions), typically at 20 km to 100 km distance from the converter station. Its voltage classification may be viewed as "medium voltage" in terms of insulation levels. Further, the most common duty of the electrode line is to carry a relatively small amount of current during bipole operation, and the utilization time of an electrode at rated current in contingency monopole operation is usually limited. In some projects, monopolar earth return configuration might be used for limited/short time and is then transferred to monopolar metallic return mode. As a consequence, it is generally not considered as a major factor in the techno-economic optimization of the HVDC system design option, although some exceptions have been encountered where the distance to a suitable electrode site may significantly exceed the typical range given above (i.e. at 20 km to 100 km distance from the converter station). Nevertheless, for its current rating, the expected maximum DC current that it could carry under any operating configuration shall be considered.

6.5 Station sites and transmission line routes

6.5.1 Converter station sites

The location of converter station sites is normally decided taking into account a wide range of factors, including:

a) preferred connection points in the AC power network according to the power network development planning;
b) availability of the land selected to build a converter station:
   - proximity to preferred DC line or cable routes;
   - cost of acquisition;
   - constructability;
c) transport of heavy equipment (e.g. converter transformers) to the site;
d) technical and environmental factors such as:
   - air pollution;
   - seismic risk or geothermal activity;
   - landfill sites and contaminated lands;
   - altitude;
   - climate, such as snowfall/wind/temperatures;
   - audible noise (impact on station and adjoining land, e.g. avoid locating on hilltop or close to residential areas);
   - risk of flooding;
   - onshore cable landing point;
   - land cable/line route;
   - electromagnetic fields;
   - visual intrusion;

- topography;
- sub-grade soil and rock conditions to support construction;
- proximity to available auxiliary power supplies.

NOTE This list is not exhaustive and other factors can also be considered.

6.5.2 Electrode station sites

The location of electrode sites is normally decided taking into account the following factors:

a) soil resistivity (both shallow and deep);

b) minimum distance to the converter station (not less than 10 km);

c) accessibility for electrode line construction;

d) technical and environmental factors such as:

- electric and magnetic fields;
- risk of corrosion, for example, perforation of buried pipes and metal structure nearby;
- production of electrolysis by-products from sea anodes;
- power transformer saturation in other areas of the AC network.

NOTE This list is not exhaustive and other factors can also be considered.

Items listed in 6.5.1 for converter station sites may also be applied here.

6.5.3 Overhead line route

When selecting the route of the HVDC transmission line, while trying to minimize the overall length, factors that should be taken into account include, but are not limited to, the following:

a) accessibility (mountains, water, wetlands, etc.);

b) as far as possible, avoidance of farmlands and residential areas;

c) as far as possible, avoidance of crossing over roads, railways, communication/power lines, oil or gas pipelines and other infrastructure; special considerations need to be taken if HVDC lines have to be in parallel or run cross AC lines;

d) avoidance of military facilities, aviation facilities, ecologically sensitive areas, areas which prohibit construction through policy or legal restriction, etc.;

e) avoidance of designated sites of scenic spots, specific wildlife sanctuary and migration routes, areas of scientific interest, etc., to minimize visual intrusion;

f) avoidance of historic and archaeological sites (both direct physical impacts and maximization of distance to reduce settling impacts);

g) minimization of the exposure in terms of the number of towers on prominent ridges and skylines;

h) HVDC transmission systems across international borders will require additional consultation and approval from appropriate national agencies at both ends of the HVDC system.

NOTE This list is not exhaustive and other factors can also be considered.

6.5.4 Submarine cable route

The objective of the submarine route selection is to propose a route, including the selection of landfalls, which meets the overall objectives of HVDC transmission performance and overall project cost. Route selection will be the ideal compromise between technical, economic, and environmental constraints. The following environmental factors should be considered when selecting the route:

a) assessment of marine physical environment (e.g. water depth, water temperature, seabed slope, boulders, seabed geology, the physical characteristics of the landfall), sea current and likelihood of seabed movement;

b) consideration of areas designated for fishing, marine activity and ship anchoring;

c) avoidance of impact on marine biological environment;

d) assessment of mitigation required for existing submerged and buried obstacles, such as unexploded ordnance (UXO) in some locations;

e) avoidance of impact on marine archaeology;

f) assessment of utility crossings and need for crossing agreements;

g) assessment of magnetic fields and compass deviations.

NOTE This list is not exhaustive and other factors can also be considered.

Liaison with the fishing industry and other marine environment stakeholders is recommended. Depending on the route location, it might be required to liaise with any appropriate state agencies for mandatory permits.

If the HVDC transmission system operates across national boarders, then it might be required to establish additional liaisons with national approval agencies at both ends of the HVDC system.

6.5.5 Land cable route

The location and route of land cable should be integral with the converter station site and the landing point of any submarine cable section. In very rare situations, land cable may also be part of an overhead DC line system where environmental issues, visual impact, line corridor economics, approval and other reasons require the undergrounding of part of the DC connection.

The most direct route between the submarine cable section landing point and converter station is preferred. The list of factors which shall be taken into account is similar to those previously listed for submarine cables and overhead lines:

a) known environmentally sensitive areas – animal habitats, species of flora and fauna;

b) known archaeological sites;

c) difficult terrain, for example, watercourses ranging from small ditches to medium sized rivers and canals;

d) underground obstructions such as buried utilities;

e) soil thermal resistivity;

f) cable drum size for road transportation;

g) ground temperature at installation depth.

NOTE This list is not exhaustive and other factors can also be applied here.

6.6 Interface requirements between AC network and HVDC

The following interface requirements between AC network and converter station should be specified at the planning and/or specification stages, since they are critical to the subsequent design, costing and execution of the HVDC project:

a) AC voltage variation: The maximum specified voltage determines the voltage rating of the converter equipment directly connected to interconnection bus. The AC voltage range is one of the key factors in the sizing of the on-load tap changer for converter transformers;

b) frequency variation: The AC frequency influences the impedance of converter equipment such as transformers and AC/DC filters. Its variation is therefore critical to the performance and rating of the HVDC transmission system, in particular to the AC and DC harmonic filters;

c) AC network short-circuit levels: The maximum short-circuit level of the network at the point of connection determines the short-circuit current rating of the converter equipment. It may be a key factor in determining the converter transformer impedance, which is necessary to limit the thyristor valve short-circuit current. The minimum short-circuit level is critical to the dynamic performance of the HVDC link, the risk of commutation failure in the inverter station, and the arrester rating of load rejection;

d) reactive power exchange limits: Whether operating as a rectifier or an inverter, an LCC converter absorbs reactive power, which is generally mitigated by using switchable reactive power elements – generally configured as shunt-connected AC filters. Since these elements have finite Mvar ratings, the reactive power exchange with the AC network cannot be maintained to a fixed value, but within a dead-band. The reactive power exchange limits indicate the AC network's capability to absorb or supply reactive power. These limits are critical in determining the size of an individual reactive power element, and hence the quantity. The narrower the allowable range between these limits, the more elements of smaller individual Mvar rating will be required, which will bring the need for extra land and cost to the converter station;

e) AC voltage step change limit on filter switching: As switching of reactive power elements or AC filters will cause a step change in the AC voltage, it is necessary to clarify the maximum limit of such change that can be accommodated by the AC network. The lower this limit is, the smaller the size of individual reactive power elements or filters will be, the more elements will be required which will bring the need for extra land and cost to the converter station;

f) AC network harmonic impedance, existing background harmonics and harmonic performance limits: Whether operating as a rectifier or an inverter, an LCC converter generates harmonics on both AC and DC sides. The AC network harmonic impedance, existing background harmonics and harmonic performance limits are critical to the design of the AC filters, which are used to absorb the harmonics generated by the converter on the AC side;

g) number of AC lines and generators connected to the commutation bus.

6.7 Requirements of HVDC control systems

6.7.1 Requirements for basic control and protection

The following basic requirements may be considered during the planning stage:

a) power control;

b) fault clearing and recovery speed;

c) reduced voltage operation shall be requested if needed;

d) other basic requirements might be added here if necessary for specific HVDC systems.

6.7.2 Supplementary control

The following supplementary control may be considered during the planning stage which may be implemented in an HVDC system during detailed design:

a) reactive power exchange control;

b) frequency control;

c) power modulation;

d) emergency power control including runup/runback;

e) sub-synchronous damping control;

f) other supplementary control might be added here if necessary for specific HVDC systems.

7 Analysis of security of supply and stability for DC alternatives

7.1 Requirements for power network connection criteria

7.1.1 General requirements for AC/DC power network

The grid connection of an HVDC link should meet the requirements of power system stability, short-circuit current, and appropriate distribution of power flow under different operation scenarios (normal operation modes, typical contingency operation modes, and some special operation modes).

For an LCC HVDC system, the AC transmission system should provide adequate voltage and power support, and the basic requirement is the strength of those AC transmission systems. Normally, the strength of an AC transmission system can be reflected in the following two aspects:

a) short-circuit level of the network at the point of connection, which can reflect the voltage support capability;
b) mechanical inertia of the AC transmission system, which can reflect the supporting capability of the power sources in the AC power system. The mechanical inertia of turbine generators in an AC system ensures that the power system does not collapse due to faults, and that the frequency of the power system does not change substantially.

The transmission power through an HVDC system is limited by the strength of the AC transmission system connected to the HVDC system. Once the power transmission capacity of the HVDC system is determined, the power network should be strong enough to provide support to ensure stability of the combined AC/DC power networks.

7.1.2 Short-circuit ratio (SCR) of the AC system connected with single DC system

The AC transmission system strength has a significant impact on the AC/DC transmission system interactions. The short-circuit ratio (SCR) has evolved as a measure to evaluate the relative strength of the AC transmission system with respect to the DC power rating. The SCR is defined as:

$$SCR = \frac{S_{\mathrm{SC}}}{P_{\mathrm{d}}}$$

where

S_{SC} is the short-circuit capacity at converter bus (MVA);

P_{d} is the rated DC transmission power of HVDC system (MW).

From the viewpoint of evaluating the performance of the HVDC transmission system, it is more straightforward to look at the effective short-circuit ratio (ESCR), which includes parameters of AC side equipment associated with the DC link: filters, shunt capacitors, synchronous compensators, etc. The ESCR is defined as:

$$ESCR = \frac{S_{\mathrm{SC}} - Q_{\mathrm{C}}}{P_{\mathrm{d}}}$$

where

Q_{C} is the reactive power installed in filters and shunt capacitors (Mvar).

For an AC transmission system connected with a single HVDC link, the supporting capability provided by the AC transmission system to the HVDC link can be assessed by SCR and ESCR. Normally, the strength of the AC transmission system can be classified for the inverter side as follows:

- SCR > 3: strong system;
- SCR < 2: very weak system.

If the SCR is less than 3, planning of the HVDC link should be checked through simulation studies. If the SCR is smaller than 2, the system security and stability of the HVDC link should be checked and analysed. If the planned HVDC link cannot meet the requirements of system stability, the HVDC link needs to be redesigned, or the AC power network needs to be strengthened to increase its supporting capability for the HVDC system.

Control strategies of the HVDC can improve its dynamic characteristics and decrease its dependency on the AC transmission system support. Thus, the SCR that assesses the strength of the AC system does not need to strictly obey the limit value for the planned HVDC link. But it is necessary to analyse and evaluate the stability of the planned HVDC link by detailed simulation with appropriate models of HVDC and its control system.

Compared with traditional HVDC converters, the capacitor commutated converters (CCC) and controlled series capacitor converter (CSCC) technology have better performance when applied in a very weak system. In addition to this difference, CCC and CSCC also present a very robust behaviour when encountering commutation failures.

NOTE Details about CCC/CSCC are available in CIGRE Technical Brochure 352.

7.1.3 Short-circuit ratio of the AC system connected with multi-infeed DC system

If multiple HVDC links feed into an AC power network, considering the interaction among different HVDC links, the SCR/ESCR is no longer used to assess the strength of the AC/DC system. Critical to the planning process for a system involving HVDC is the active and reactive power interchanged between the HVDC link and the AC power network. An indicator based on the observed AC voltage change at one inverter AC bus for a small AC voltage change at another inverter bus provides a first level indication of the degree of interaction between two HVDC links. This interaction factor is called the multi-infeed interaction factor (MIIF), and is defined mathematically as:

$$MIIF_{ji} = \frac{\Delta U_j}{\Delta U_i}$$

where

ΔU_j and ΔU_i are the observed voltage changes at bus i for a small induced voltage change at bus j.

Inverter AC busses electrically far apart will have MIIF values approaching zero, while MIIF values approaching unity indicate AC busses that are very close. MIIF > 0,15 indicates the possibility of some degree of interaction. For AC systems with a number of HVDC links, a matrix of MIIF values can be formed. MIIF values can be easily derived by using a transient stability program.

In a multi-infeed system, the short-circuit levels appearing at the respective inverter AC busses cannot be considered as being dedicated to the associated HVDC link, but rather shall be shared amongst HVDC links in proximity. The SCR can be extended to the multi-infeed environment through the following formula:

$$MISCR_i = \frac{S_{aci}}{P_{deqi}} = \frac{S_{aci}}{P_{di} + \sum_{j=1, j \neq i}^{n} MIIF_{ji} \times P_{dj}}$$

where

MISCR is the multi-infeed definition of ESCR;

subscript j refers to all other HVDC links in electrical proximity;

S_{aci} is the short-circuit capacity at converter bus i(MVA);

P_{deqi} is the equivalent DC power at converter bus i (MW);

P_{di} is the rated DC power of the i HVDC system (MW);

P_{dj} is the rated DC power of the j HVDC link (MW).

For an AC power network connected with multi-infeed HVDC links, the supporting capability provided by the AC power network to the HVDC links should be assessed in terms of the multi-infeed short-circuit ratio (MISCR). The robustness of the AC power network to which multi-circuit HVDC links are connected should be defined as follows:

- MISCR > 3: strong system;
- MISCR < 2: very weak system.

When planning a new HVDC link, the MISCR of all the HVDC links feeding into the AC power network should be calculated, including the existing and new HVDC links.

If the MISCR is in the range of 2 to 3, the planning of the HVDC link should be checked through simulation studies. If the MISCR of any HVDC link is smaller than 2, the new HVDC link should be redesigned, the use of CCC or CSCC configuration should be considered, or the AC power network should be strengthened to increase its capability in supporting the HVDC link.

Control strategies of the HVDC can improve the dynamic characteristics and decrease the dependency on the AC power network. Thus, the MISCR that assesses the strength of the AC transmission system does not need to strictly obey the limiting value of the planning scheme. But it is necessary to analyse and evaluate the stability of the planning scheme by detailed simulation with the appropriate models of HVDC and its control systems.

7.1.4 Effective inertia constant of AC/DC power network

The ability of the AC power network to maintain the required voltage and frequency depends on the rotational inertia of the AC power system. For satisfactory performance, the AC power system should have a minimum inertia relative to the capacity of the HVDC link. A measure of the relative rotational inertia is the effective DC inertia constant, named H_{dc} and is defined as:

$$H_{dc} = \frac{T}{P_d}$$

where

T is the total rotational inertia of the AC power system (MW × s);

H_{dc} is the inertia constant of the AC power system (s);

P_d is the rated DC power of the HVDC link (MW).

After the HVDC link is connected to the AC power network, the H_{dc} should be at least 2 s to 3 s, which can meet AC/DC operational requirements. If the H_{dc} is less than 2 s, the stability of the power system needs to be studied through simulation, and reliable control strategies need to be formed to ensure power system stability. For AC power systems with inadequate generation resulting in low inertia, appropriate measures, for example, using synchronous condensers, should be considered in order to increase the inertia and assist in satisfactory operation of the HVDC link.