

TECHNICAL REPORT



Performance of high-voltage direct current (HVDC) systems with line-commutated converters – Part 1: Steady-state conditions



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TECHNICAL REPORT



Performance of high-voltage direct current (HVDC) systems with line-commutated converters – Part 1: Steady-state conditions

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CONTENTS

FOREWORD	8
INTRODUCTION	2
1 Scope	11
2 Normative references	12
3 Terms and definitions	12
4 Types of HVDC systems	12
4.1 General	12
4.2 HVDC back-to-back system	13
4.3 Monopolar HVDC system with earth return HVDC system	13
4.4 Monopolar HVDC system with metallic return HVDC system	17
4.5 Bipolar earth return HVDC system	18
4.6 Bipolar HVDC system with metallic return HVDC system	21
4.7 Two 12-pulse groups per pole	22
4.8 Converter transformer arrangements	25
4.9 DC switching considerations	26
4.10 Series-capacitor-compensated HVDC systems	29
4.11 LCC/VSC hybrid bipolar system	33
5 Environment information	34
6 Rated power, current and voltage	37
6.1 Rated power	37
6.1.1 General	37
6.1.2 Rated power of an HVDC system with transmission line	37
6.1.3 Rated power of an HVDC back-to-back system	37
6.1.4 Direction of power flow	37
6.2 Rated current	37
6.3 Rated voltage	38
7 Overload and equipment capability	38
7.1 Overload	38
7.2 Equipment capability	39
7.2.1 General	39
7.2.2 Converter valve capability	39
7.2.3 Capability of oil-cooled transformers and reactors	39
7.2.4 AC harmonic filter and reactive power compensation equipment capability	40
7.2.5 Switchgear and buswork capability	40
8 Minimum power transfer and no-load stand-by state	40
8.1 General	40
8.2 Minimum current	40
8.3 Reduced direct voltage operation	40
8.4 No-load stand-by state	41
8.4.1 General	41
8.4.2 Converter transformers – No-load stand-by	41
8.4.3 Converter valves – No-load stand-by	41
8.4.4 AC filters and reactive compensation – No-load stand-by	41
8.4.5 DC reactors and DC filters – No-load stand-by	42

8.4.6	Auxiliary power system – No-load stand-by.....	42
8.4.7	Control and protection – No-load stand-by.....	42
9	AC system.....	42
9.1	General.....	42
9.2	AC voltage.....	42
9.2.1	Rated AC voltage.....	42
9.2.2	Steady-state voltage range.....	42
9.2.3	Negative sequence voltage.....	43
9.3	Frequency.....	43
9.3.1	Rated frequency.....	43
9.3.2	Steady-state frequency range.....	43
9.3.3	Short-term frequency variation.....	43
9.3.4	Frequency variation during emergency.....	44
9.4	System impedance at fundamental frequency.....	44
9.5	System impedance at harmonic frequencies.....	44
9.6	Positive and zero-sequence surge impedance.....	44
9.7	Other sources of harmonics.....	44
9.8	Subsynchronous torsional interaction (SSTI).....	44
10	Reactive power.....	45
10.1	General.....	45
10.2	Conventional HVDC systems.....	45
10.3	Series capacitor compensated HVDC schemes.....	47
10.4	Converter reactive power consumption.....	47
10.5	Reactive power balance with the AC system.....	47
10.6	Reactive power supply.....	47
10.7	Maximum size of switchable VAR banks.....	48
11	HVDC transmission line, earth electrode line and earth electrode.....	48
11.1	General.....	48
11.2	Overhead line(s).....	48
11.2.1	General.....	48
11.2.2	Electrical parameters.....	48
11.3	Cable line(s).....	49
11.3.1	General.....	49
11.3.2	Electrical parameters.....	49
11.4	Earth electrode line.....	50
11.5	Earth electrode.....	50
12	Reliability.....	50
12.1	General.....	50
12.2	Outage.....	50
12.2.1	General.....	50
12.2.2	Scheduled outage.....	50
12.2.3	Forced outage.....	50
12.3	Capacity.....	51
12.3.1	General.....	51
12.3.2	Maximum continuous capacity P_m	51
12.3.3	Outage capacity P_o	51
12.3.4	Outage derating factor (ODF).....	51
12.4	Outage duration terms.....	51

12.4.1	Actual outage duration (AOD)	51
12.4.2	Equivalent outage duration (EOD)	51
12.4.3	Period hours (PH)	51
12.4.4	Actual outage hours (AOH)	52
12.4.5	Equivalent outage hours (EOH)	52
12.5	Energy unavailability (EU)	52
12.5.1	General	52
12.5.2	Forced energy unavailability (FEU)	53
12.5.3	Scheduled energy unavailability (SEU)	53
12.6	Energy availability (EA)	53
12.7	Maximum permitted number of forced outages	53
12.8	Statistical probability of outages	53
12.8.1	Component faults	53
12.8.2	External faults	53
13	HVDC control	54
13.1	Control objectives	54
13.2	Control structure	54
13.2.1	General	54
13.2.2	Converter unit firing control	54
13.2.3	Pole control	55
13.2.4	HVDC substation control	58
13.2.5	Master control	60
13.3	Control order settings	60
13.4	Current limits	60
13.5	Control circuit redundancy	61
13.6	Protection system	61
13.7	Measurements	61
14	Telecommunication	62
14.1	Types of telecommunication links	62
14.2	Telephone	62
14.3	Power line carrier (PLC)	62
14.4	Microwave	63
14.5	Radio link	63
14.6	Optical fibre telecommunication	63
14.7	Classification of data to be transmitted	63
14.8	Fast response telecommunication	64
14.9	Reliability	64
15	Auxiliary power supplies	65
15.1	General	65
15.2	Reliability and load classification	65
15.3	AC auxiliary supplies	66
15.4	Batteries and uninterruptible power supplies (UPS)	66
15.5	Emergency supply	67
16	Audible noise	67
16.1	General	67
16.2	Public nuisance	67
16.2.1	General	67
16.2.2	Valves and valve coolers	68

16.2.3	Converter transformers	68
16.2.4	DC reactors	68
16.2.5	AC filter reactors	68
16.3	Noise in working areas	68
17	Harmonic interference – AC	69
17.1	AC side harmonic generation	69
17.2	Filters	69
17.3	Interference disturbance criteria	72
17.4	Levels for interference	73
17.5	Filter performance	74
18	Harmonic interference – DC	74
18.1	DC side interference	74
18.1.1	Harmonic currents in HVDC transmission line	74
18.1.2	Characteristic and non-characteristic harmonics	74
18.1.3	Groups of harmonics	75
18.1.4	Calculation of harmonic currents	75
18.1.5	Calculation of induced voltages	75
18.1.6	Personnel safety	75
18.1.7	DC filters	75
18.2	DC filter performance	76
18.2.1	Requirements for voice communication circuits	76
18.2.2	Levels of interference	76
18.2.3	Safety	76
18.3	Specification requirements	77
18.3.1	Economic level of filtering	77
18.3.2	General criteria	78
18.3.3	Factors to be taken into account for calculations	78
18.3.4	Calculation of currents	79
19	Power line carrier interference (PLC)	80
19.1	General	80
19.2	Performance specification	81
20	Radio frequency interference	82
20.1	General	84
20.2	RFI from HVDC systems	84
20.2.1	RFI sources	84
20.2.2	RFI propagation	85
20.2.3	RFI characteristics	85
20.3	RFI performance specification	86
20.3.1	RFI risk assessment	86
20.3.2	Specification RFI limit and its verification	86
20.3.3	Design aspects	87
21	Power losses	82
21.1	General	87
21.2	Main contributing sources	88
21.2.1	General	88
21.2.2	AC filters and reactive power compensation	88
21.2.3	Converter bridges	88
21.2.4	Converter transformer	88

21.2.5	DC reactor	88
21.2.6	DC filter	88
21.2.7	Auxiliary equipment	89
21.2.8	Other components	89
22	Provision for extensions to the HVDC systems	89
22.1	General.....	89
22.2	Specification for extensions	89
Annex A (informative) Factors affecting reliability and availability of converter stations		92
A.1	Design and documentation.....	92
A.1.1	General	92
A.1.2	General design principles	92
A.1.3	More detailed design principles	93
A.1.4	Software design principles.....	93
A.1.5	RAM records.....	94
A.2	Operation.....	94
A.2.1	Training	94
A.2.2	Maintenance programs affecting reliability	95
A.2.3	Spare parts.....	96
Bibliography.....		99

Figure 1	– Twelve-pulse converter unit	11
Figure 2	– Examples of back-to-back HVDC systems	14
Figure 3	– Monopolar HVDC system with earth return	15
Figure 4	– Two 12-pulse units in series.....	16
Figure 5	– Two 12-pulse units in parallel.....	17
Figure 6	– Monopolar HVDC system with metallic return system	18
Figure 7	– Bipolar system	19
Figure 8	– Metallic return operation of the unfaulted pole in a bipolar system.....	20
Figure 9	– Bipolar metallic return HVDC system with metallic return	22
Figure 10	– Bipolar system with two 12-pulse units in series per pole	24
Figure 11	– Bipolar system with two 12-pulse units in parallel per pole	25
Figure 12	– DC switching of line conductors	27
Figure 13	– DC switching of converter poles	28
Figure 14	– DC switching – Overhead line to cable	29
Figure 15	– DC switching – Two bipolar converters and lines	30
Figure 16	– DC switching – Intermediate.....	31
Figure 17	– Capacitor commutated converter configurations	32
Figure 18	– LCC/VSC hybrid bipolar system	34
Figure 19	– Variations of reactive power Q with active power P of an HVDC converter	46
Figure 20	– Control hierarchy for HVDC/UHVDC system.....	57
Figure 21	– Converter voltage-current characteristic	59
Figure 22	– Examples of AC filter connections for a bipole HVDC system	70
Figure 23	– Circuit diagrams for different filter types	71
Figure 24	– RY COM noise interference meter results averaged – Typical plot of converter noise interference levels on the DC line corrected and normalized to 3 kHz bandwidth – 0 dBm = 0,775 V	82

Figure 25 – Recommended measurement procedure with definition of measuring point	87
Figure 26 – Extension methods for HVDC systems	91
Table 1 – Information supplied for HVDC substation	35
Table 2 – Performance parameters for voice communication circuits: Subscribers and trunk circuits	77

INTERNATIONAL ELECTROTECHNICAL COMMISSION

**PERFORMANCE OF HIGH-VOLTAGE DIRECT CURRENT
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IEC TR 60919-1, which is a technical report, has been prepared by subcommittee 22F: Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment.

This fourth edition cancels and replaces the third edition, published in 2010, Amendment 1:2013 and Amendment 2:2017. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) Figure 8 and Figure 20 have been updated, a new Figure 18 "LCC/VSC hybrid bipolar system" has been added;
- b) the HVDC system control objectives have been supplemented;
- c) additional explanations regarding the HVDC system control structure have been given;
- d) a new subclause 13.6 on HVDC system protection has been added.

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

Draft TR	Report on voting
22F/535/DTR	22F/549A/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.

A list of all parts of the IEC 60919 series, published under the general title *Performance of high-voltage direct current (HVDC) systems with line-commutated converters*, can be found on the IEC website.

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.

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INTRODUCTION

The difference between system performance specifications and equipment design specifications for individual components of a system is realized. Frequently, performance specifications are prepared as a single package for the two HVDC substations in a particular system. Alternatively, some parts of the HVDC system can be separately specified and purchased. In such cases, due consideration ~~should be~~ is given to coordination of each part with the overall HVDC system performance objectives and to ensuring that the interface of each with the system ~~should be~~ is clearly defined. Typical of such parts, listed in the appropriate order of relative ease for separate treatment and interface definition, are:

- a) DC line, electrode line and earth electrode;
- b) telecommunication system;
- c) converter building, foundations and other civil engineering work;
- d) reactive power supply including AC shunt capacitor banks, shunt reactors, synchronous and static reactive power (var) compensators;
- e) AC switchgear;
- f) DC switchgear;
- g) auxiliary systems;
- h) AC filters;
- i) DC filters;
- j) DC reactors;
- k) converter transformers;
- l) surge arresters;
- m) series commutation capacitors;
- n) valves and their ancillaries;
- o) control and protection systems.

NOTE The last four items are the most difficult to separate, and, in fact, separation of these four ~~may~~ can be inadvisable.

Clause 4 to Clause 22 of this document set out a complete steady-state performance specification for an HVDC system ~~should consider Clauses 3 to 21 of this report.~~

~~Terms and definitions for high voltage direct current (HVDC) transmission used in this report are given in IEC 60633.~~

Since the equipment items are usually separately specified and purchased, the HVDC transmission line, earth electrode line and earth electrode (see Clause 11) are included only because of their influence on the HVDC system performance.

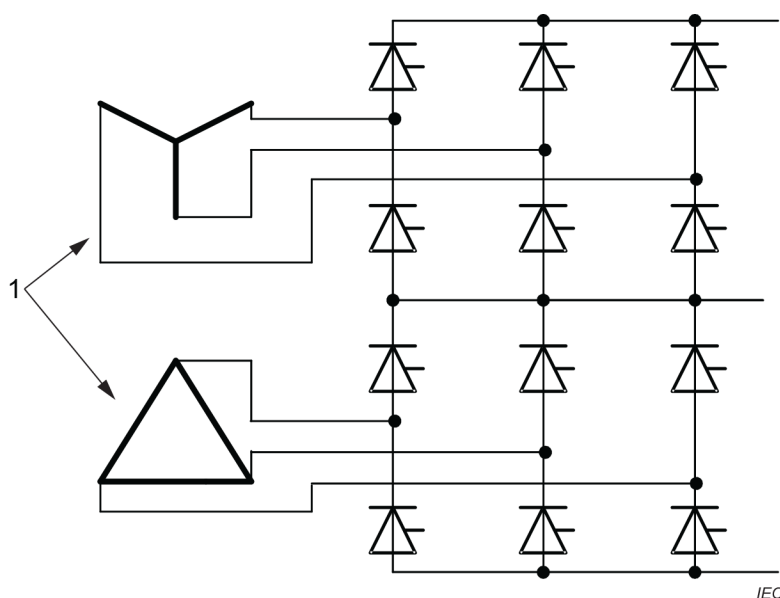
For the purpose of this document, an HVDC substation is assumed to consist of one or more converter units installed in a single location together with buildings, reactors, filters, reactive power supply, control, monitoring, protective, measuring and auxiliary equipment. While there is no discussion of AC switching substations in this document, AC filters and reactive power sources are included, although they ~~may~~ can be connected to an AC bus separate from the HVDC substation, as discussed in Clause 17.

PERFORMANCE OF HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS WITH LINE-COMMUTATED CONVERTERS –

Part 1: Steady-state conditions

1 Scope

This part of IEC 60919 provides general guidance on the steady-state performance requirements of high-voltage direct current (HVDC) systems. It concerns the steady-state performance of two-terminal HVDC systems utilizing 12-pulse converter units comprised of three-phase bridge (double-way) connections (see Figure 1), but it does not cover multi-terminal HVDC transmission systems. Both terminals are assumed to use thyristor valves as the main semiconductor valves and to have power flow capability in both directions. Diode valves are not considered in this document.



Key

1 Transformer valve windings

Figure 1 – Twelve-pulse converter unit

Only line-commutated converters are covered in this document, which includes capacitor commutated converter circuit configurations. General ~~requirements for~~ aspects of semiconductor line-commutated converters are given in IEC 60146-1-1, IEC TR 60146-1-2 and IEC 60146-1-3. Voltage-sourced converters are not considered.

~~This technical report, which covers steady-state performance, is followed by additional documents on dynamic performance and transient performance. All three aspects should be considered when preparing two-terminal HVDC system specifications.~~

The ~~difference~~ distinction is made between system performance specifications and equipment design specifications for individual components of a system ~~should be realized~~. Equipment specifications and testing requirements are not defined in this document. Also excluded from this document are detailed seismic performance requirements. In addition, because there are many variations between different possible HVDC systems, this document does not consider these in detail; consequently, it ~~should~~ is not ~~be~~ used directly as a specification for a

particular project, but rather to provide the basis for an appropriate specification tailored to fit actual system requirements.

This document, which covers steady-state performance, is followed by the additional documents of IEC TR 60919-2 on faults and switching as well as IEC TR 60919-3 on dynamic conditions. All three aspects are considered when preparing two-terminal HVDC system specifications.

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 60146-1-1, Semiconductor converters — General requirements and line commutated converters — Part 1-1: Specifications of basic requirements~~

~~IEC/TR 60146-1-2, Semiconductor converters — General requirements and line commutated converters — Part 1-2: Application guide~~

~~IEC 60146-1-3, Semiconductor converters — General requirements and line commutated converters — Part 1-3: Transformers and reactors~~

IEC 60633, ~~Terminology for~~ High-voltage direct current (HVDC) transmission – Vocabulary

CIGRÉ Technical Brochure (TB) No. 391:2009, *Guide for measurement of radio frequency interference from HV and MV substations. Disturbance propagation, characteristics of disturbance sources, measurement techniques, conversion methodologies and limits*

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 Types of HVDC systems

4.1 General

This part of the specification should include the following basic data:

- general information on the location of the HVDC substations and the purpose of the project;
- type of system needed, including a simple one-line diagram;
- number of 12-pulse converter units;
- pertinent information derived from the discussion in Clause 4.

Generally, in studies of projects of the types discussed in this document, economic considerations should take into account the capital costs, the cost of losses, cost of outages and other expected annual expenses.

In terms of the type of system, the ~~relatively new development of~~ "capacitor-commutated converter (CCC)" and "controlled series capacitor converter (CSCC)" technology may be suitable alternatives to a conventional HVDC scheme. These are described in 4.10.

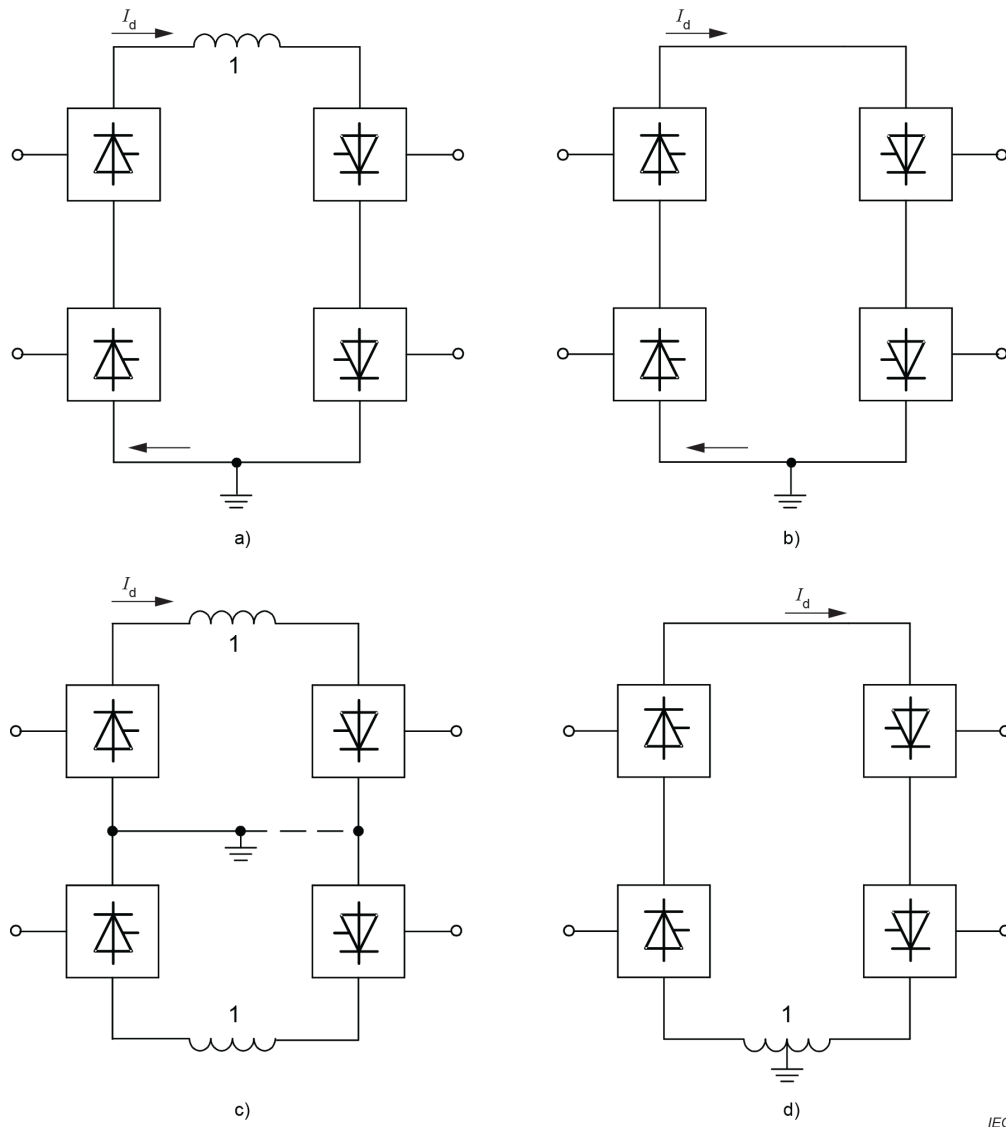
4.2 HVDC back-to-back system

In this arrangement there is no DC transmission line and both converters are located at one site. The valves for both converters may be located in one valve hall, or even in one integrated structure or separately as outdoor valves. Similarly, many other items for the two converters, such as the control system, cooling equipment, auxiliary system, etc., may be located in one area or even integrated in layout into configurations common to the two converters. Circuit configurations may vary. Examples are given in Figure 2. The performance and economics of these configurations differ and ~~must~~ **should** be evaluated. DC filters are not needed.

The voltage and current ratings for a given power rating should 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 reason. Economics dictate that each converter will usually be a 12-pulse converter unit, however it is not mandatory. Where operating criteria require that the loss of one converter unit will not cause loss of full power capability, large HVDC substations could be comprised of two or more back-to-back systems. For this, some of the equipment of the back-to-back systems can, for economic reasons, be located in the same area or even physically integrated, but events which could cause a failure of equipment required by all back-to-back systems need to be carefully considered and preventive measures taken where appropriate.

4.3 Monopolar HVDC system with earth return ~~HVDC system~~

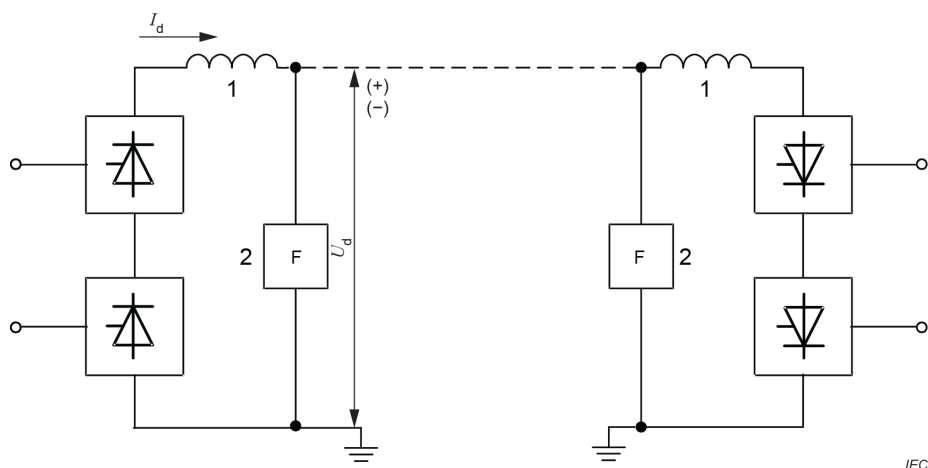
Cost considerations often lead to the adoption of a monopolar HVDC system with earth return ~~system~~ (Figure 3), particularly for cable transmission which may be expensive.



Key

1 DC reactor

Figure 2 – Examples of back-to-back HVDC systems

**Key**

- 1 DC reactor
- 2 DC filters

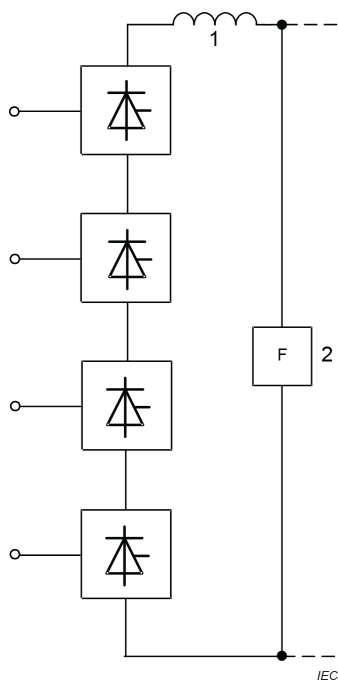
Figure 3 – Monopolar HVDC system with earth return

The monopolar earth return configuration might also be the first stage in the development of a bipolar scheme. Monopolar arrangements may include one or more 12-pulse units in series or in parallel at the ends of the HVDC transmission (Figure 4 and Figure 5). More than one 12-pulse unit ~~might~~ can be used for the following purposes:

- a) to ensure partial transmission capacity during converter unit outages;
- b) to complete the project in stages;
- c) because of the physical limitations of transformer transport.

This arrangement requires one or more DC reactors at each end of the HVDC overhead line or cable; these are usually located on the high-voltage side. ~~However, the d.c. reactors may be divided into two parts and located on the high-voltage side and the earth side respectively if the resulting performance is acceptable, especially for a large scale ultra high voltage direct current (UHVDC) converter arrangement.~~

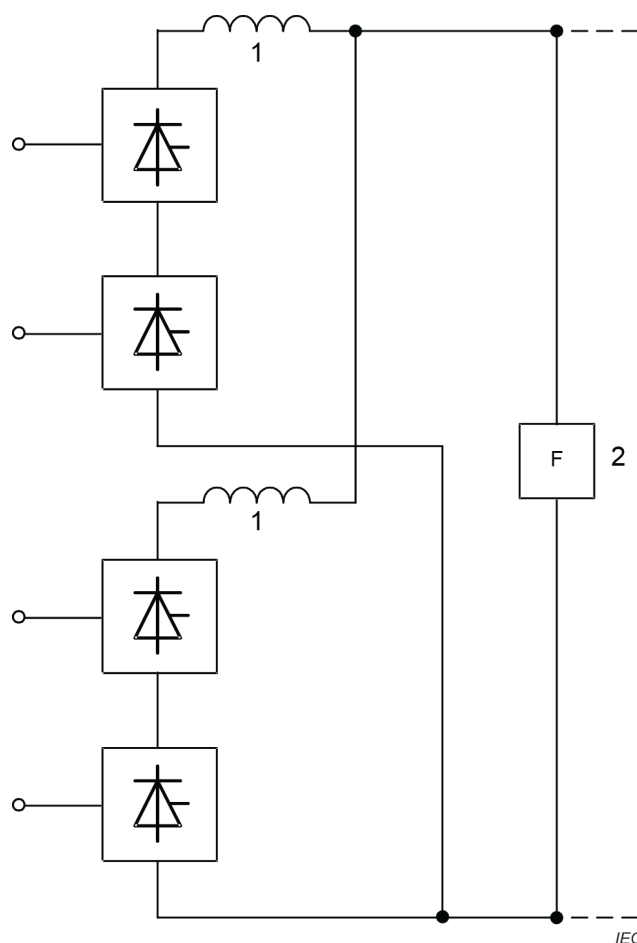
If the line is overhead, DC filters are likely to be needed at each end (see Clause 18). It also requires an earth electrode line and a continuously operable earth electrode at the two ends of the transmission which involves consideration of issues such as corrosion, magnetic field effects, etc.



Key

- 1 DC reactor
- 2 DC filter

Figure 4 – Two 12-pulse units in series

**Key**

- 1 DC reactor
- 2 DC filter

Figure 5 – Two 12-pulse units in parallel**4.4 Monopolar HVDC system with metallic return-HVDC system**

The configuration as illustrated in Figure 6 will generally be used for the following purposes:

- a) as the first stage in the construction of a bipolar system and if long-term flow of earth current is not desirable during the interim period, or
- b) if the transmission line length is short enough to make it uneconomic and undesirable to build earth electrode lines and earth electrodes, or
- c) if the earth resistivity is high enough to impose an unacceptable economic penalty, or
- d) if long-term flow of earth current is unacceptable because of environmental and safety requirements.

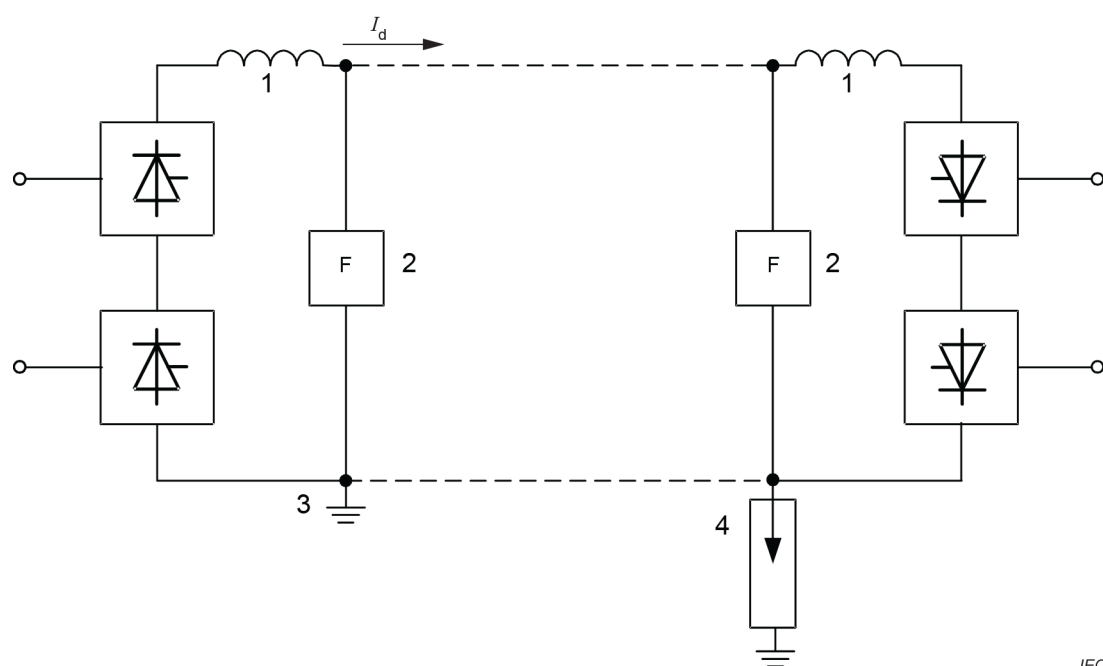
This configuration utilizes one high-voltage and one low-voltage conductor. The neutral is connected at one of the two HVDC substations to its station earth or, alternatively, to the associated earth electrode. The other HVDC substation neutral is connected to its station earth through a capacitor or an arrester or both.

DC reactors are needed at both ends of the high-voltage conductor. However, the DC reactor may be located on the earth side if the resulting performance is acceptable. However, the DC reactors may be divided into two parts and located on the high-voltage side and the earth side respectively if the resulting performance is acceptable, especially for a large scale ultra-high-

voltage direct-current (UHVDC) converter arrangement. DC filters may be needed if the HVDC transmission line is overhead.

If this configuration is the first stage of a bipolar system, its neutral conductor could be insulated for the high voltage at this stage of development.

For a metallic return scheme, DC fault current will flow into the AC system and come back through neutral point of transformers installed in the converter station. This current may lead to the malfunction of protective relays installed in nearby stations, caused by the saturation of cores due to DC current. To prevent such malfunctions, insertion of neutral grounding resistor (small resistance) to transformers in the converter station will be effective.



Key

- 1 DC reactor
- 2 DC filter
- 3 Station earth
- 4 Arrester

Figure 6 – Monopolar HVDC system with metallic return-system

4.5 Bipolar earth return HVDC system

This is the most commonly used arrangement when a DC transmission line connects two HVDC substations and electrodes for earth return operation are provided (Figure 7 (a)). It is effectively equivalent to a double-circuit AC transmission. It reduces harmonic interference from the DC line as compared with monopolar operation and it keeps earth current flow down to a low value. When combined, two monopolar earth return schemes can give a bipolar scheme.

For power flow in one direction, one pole has positive polarity to earth and the other pole has negative polarity to earth. For power flow in the other direction, the two poles reverse their polarities. When both poles are in operation, the unbalance current flowing in the earth path can be kept at a very low value.

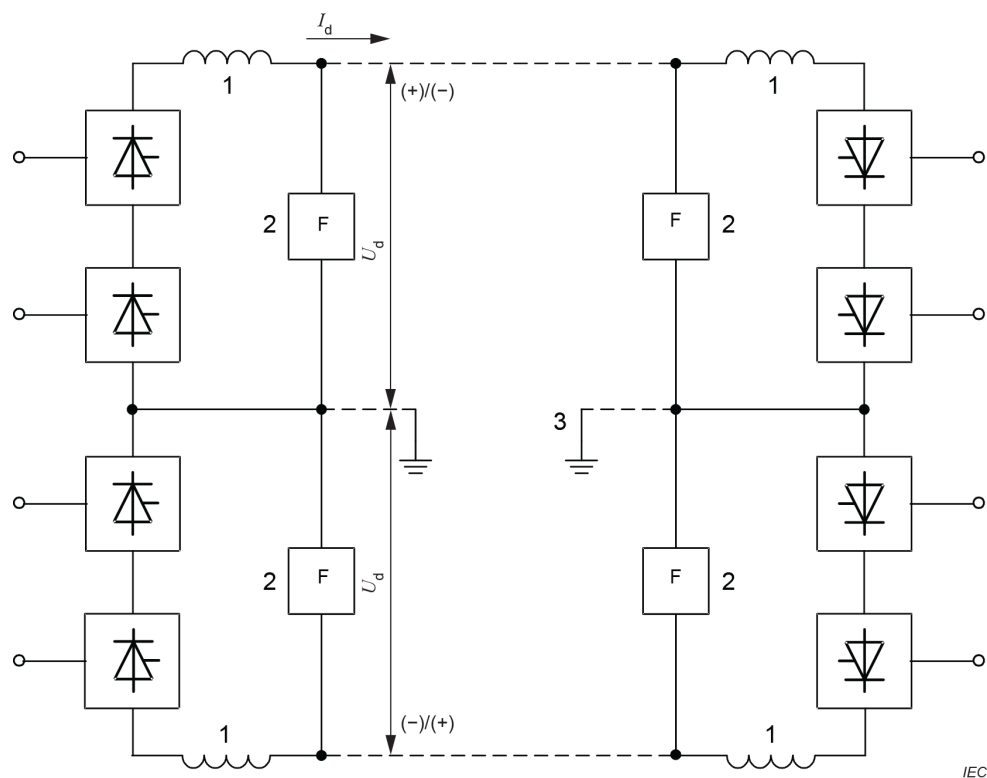


Figure 7 a) – Bipolar HVDC system with earth return

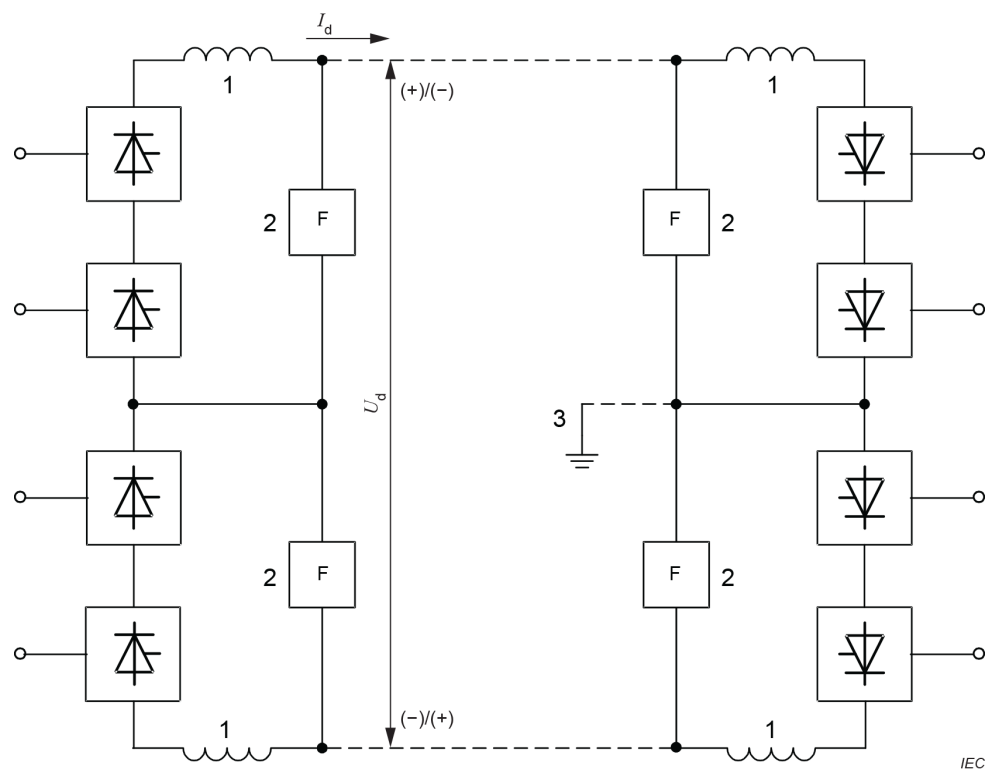


Figure 7 b) – Rigid bipolar HVDC system

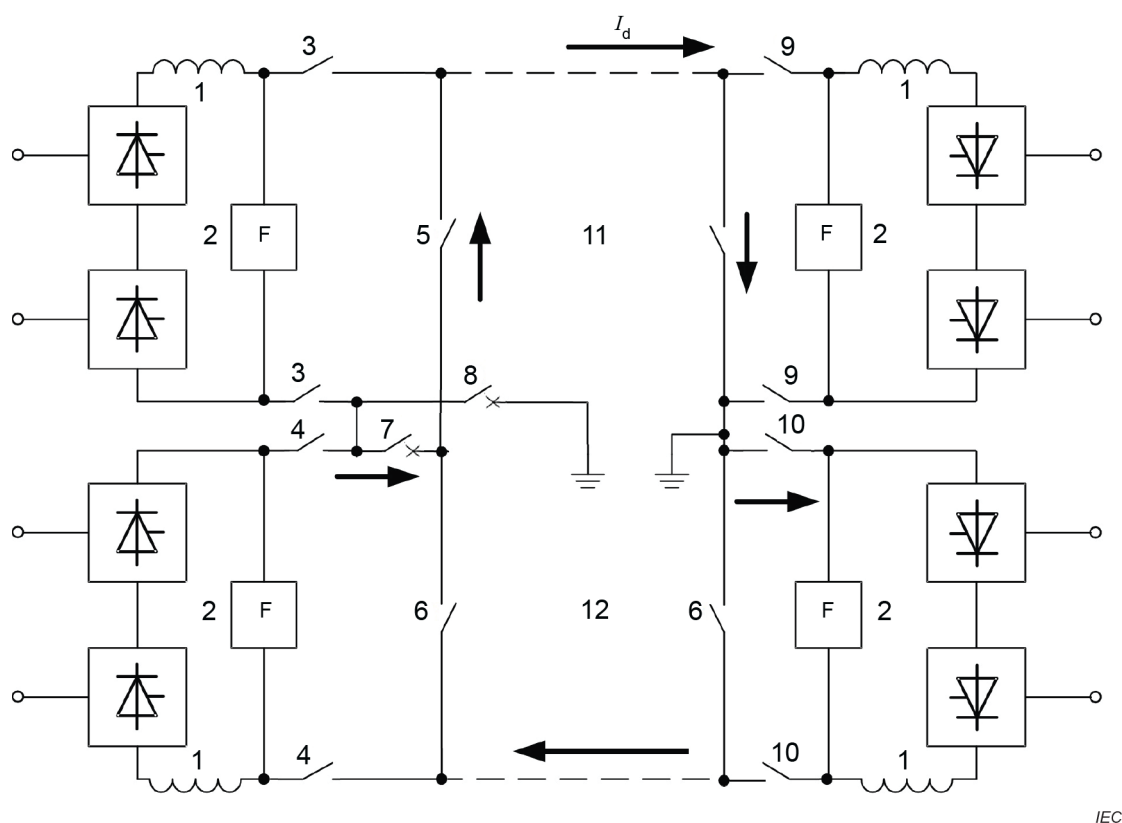
Key

- 1 DC reactor
- 2 DC filter
- 3 Earth electrodes

Figure 7 – Bipolar system

This configuration offers a number of emergency operating modes. Consequently, the requirements in the following list a) to f) should be considered in the specifications.

- a) During an outage of one HVDC transmission line pole 11 in Figure 8 (rectifier DC switches 3 and inverter DC switches 9 have been switched off), the converter equipment of the other pole 12 should be capable of continuous operation with earth return (rectifier DC switches 4, inverter DC switches 10, earth return transfer switch (ERTS) 7 and metallic return transfer breaker (MRTB) 8 have been switched on).
- b) 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 should be capable of operation in the monopolar metallic return mode (Figure 8). To switch into this emergency operating mode the conductor of the out-of-service pole 11 is first connected in parallel with the earth path by switching on pole-to-neutral switches 5 and then the earth path is interrupted to transfer the current to the metallic path (through the conductor of the out-of-service pole) by switching off MRTB 8. Load transfer without interruption requires a metallic return transfer breaker (MRTB) at one terminal of the DC transmission. If a short interruption of power flow is permitted, MRTB would not be necessary. The neutral equipment at the MRTB end of the HVDC transmission system should be insulated from earth for a somewhat higher voltage than at the other end of the system. Figure 8, with DC switches 3 and 4 (named as ERTS and MRTB), is usually valid for a rectifier station. The MRTB is not necessary for the inverter station.



Key

1	DC reactor	7	Earth return transfer switch (ERTS)
2	DC filter	8	Metallic return transfer breaker (MRTB)
3,4	Rectifier DC switches	9,10	Inverter DC switches
5,6	Pole-to-neutral switches	11, 12	HVDC power transmission poles

Figure 8 – Metallic return operation of the unfaulted pole in a bipolar system

- c) During maintenance of the earth electrode(s) or the earth electrode line(s), operation of the bipolar system should be possible 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 very low value. The unbalance current

should be kept low to avoid saturation effects in the converter transformers from the flow of part of the unbalance current through the transformer neutrals. In this arrangement when one transmission line of substation pole is lost, both poles should be blocked automatically.

- d) In bipolar operation with both earth electrodes connected, the two poles of the HVDC system should be capable of operation with substantially different currents in each pole. This may be necessary if loss of cooling or some other unusual condition prevents the operation of one pole with full current.
- e) If continuation of operation is required in the case of poor weather conditions or where the line insulation has been partially damaged, the converters should be designed for continuous operation at reduced voltage, so that either pole can be operated at reduced voltage (see 8.3).
- f) In the event of the loss of one transmission line pole, the two substation poles can also be connected in parallel by using appropriate switches for polarity reversal in at least one station pole enabling both poles to operate in the monopolar earth return mode. This, however, requires that the DC terminals of each 12-pulse group be insulated for the full pole voltage and the line and the earth electrode shall be thermally capable of carrying a current higher than the normal current.

One or more DC reactors is needed at each end of the system in each pole, these are usually located on the high-voltage side. However, the DC reactors may be divided into two parts and located on the high-voltage side and the earth side respectively if the resulting performance is acceptable, especially for a large scale ultra-high-voltage direct-current (UHVDC) converter arrangement. If the HVDC system includes an overhead line, DC filters would most likely be needed. One 12-pulse unit per pole is most commonly used; however, large capacity systems or staged expansion may require 12-pulse units in series or in parallel (Figure 4 and Figure 5).

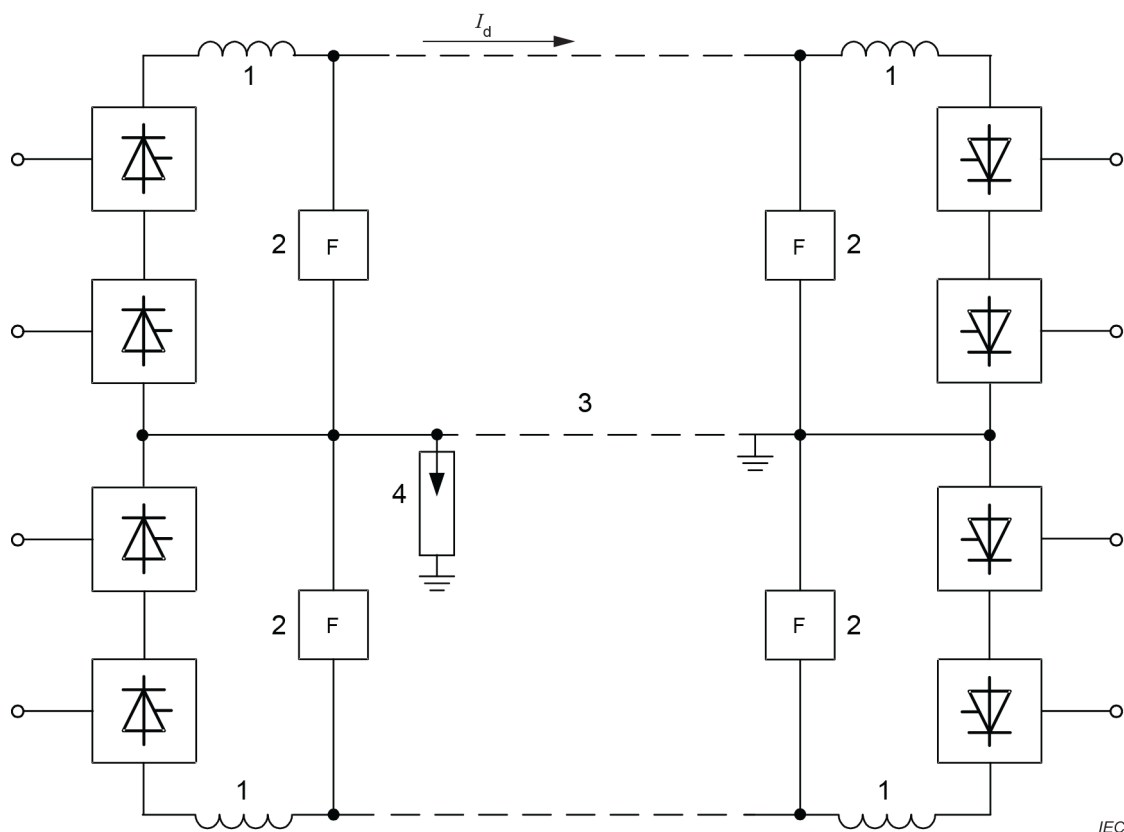
Most HVDC systems utilise ground return or a dedicated metallic return conductor for the DC current path. However, when balanced bipolar operation can always be ensured, these facilities can be eliminated. This scheme is called "rigid bipole HVDC system" configuration, as shown in Figure 7 b). With this scheme, operation modes are limited but installation cost can be reduced.

4.6 Bipolar HVDC system with metallic return ~~HVDC system~~

If earth currents are not tolerable (as mentioned in 4.4, item d)) or if the distance between the HVDC system terminals is short, or if an earth electrode is not feasible because of high earth resistivity, then the transmission line may be constructed with a third conductor to give a bipolar HVDC system with metallic return ~~HVDC system~~ (Figure 9). The third conductor carries unbalance currents during bipolar operation. It also serves as the return path when one transmission line pole is out of service. This third conductor requires only reduced voltage insulation and, in this case, may also serve as a shield wire if the line is overhead. However, if it is fully insulated, it can serve as a spare conductor. In this case, a separate shield wire is required.

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

With this design, the system can still be operated in the bipolar mode if one conductor becomes unavailable and the third conductor is fully insulated. Then, the neutrals at both terminals should be connected to their local station earths, and care should be taken to hold the unbalanced current flow to very low values. Loss of one pole will require blocking of the other pole until the necessary switching has taken place for operation of the remaining sound portions of the HVDC transmission system.



Key

- 1 DC reactor
- 2 DC filter
- 3 Metallic neutral
- 4 Arrester

Figure 9 – Bipolar-metallic-return HVDC system with metallic return

If one ~~substation~~ pole becomes unavailable, the system can be operated in monopolar metallic return mode by utilizing the other substation pole. This configuration is also called "metallic return mode" (MRM).

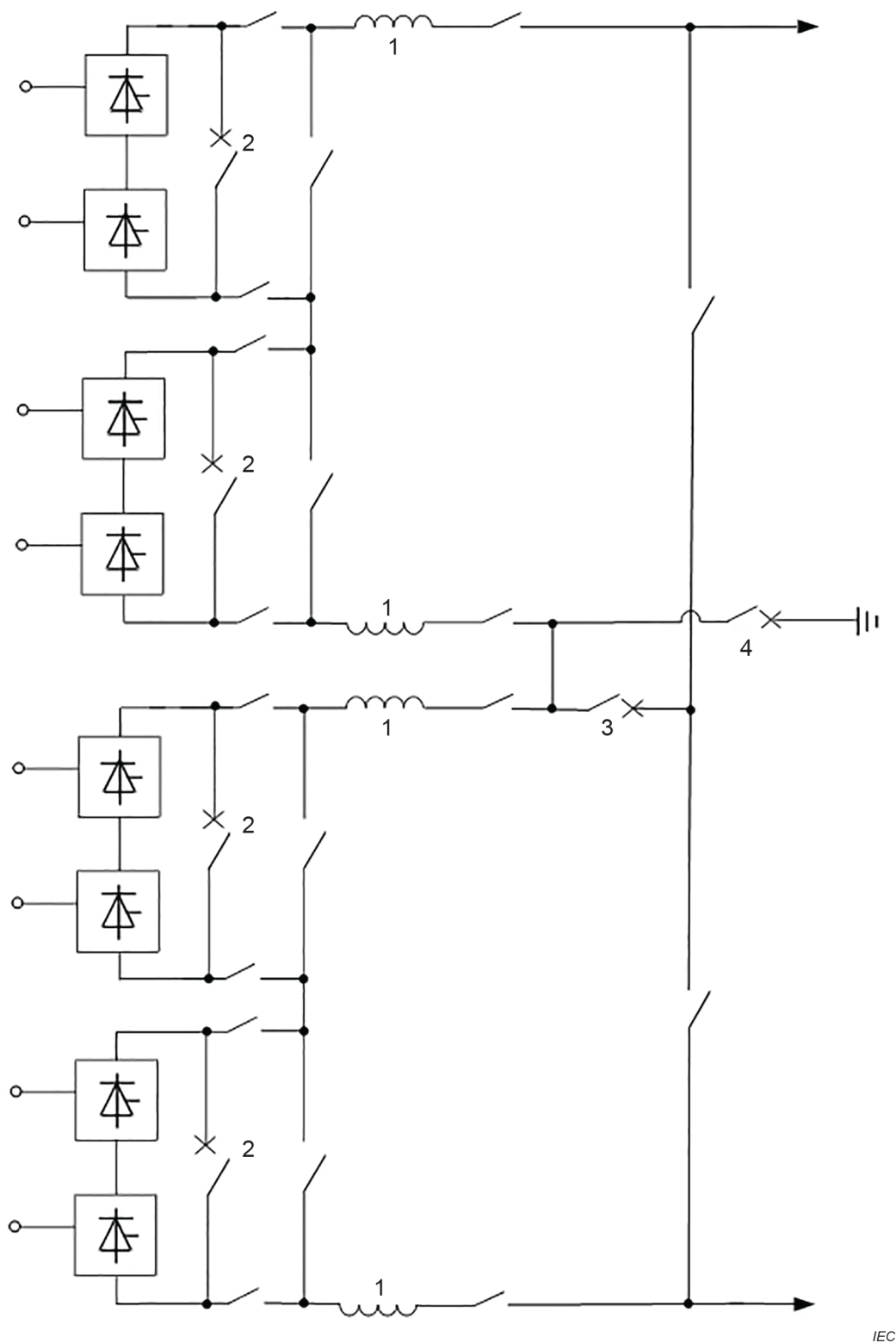
For a metallic return scheme, DC fault current will flow into the AC system and partly come back through neutral point of transformers installed in the converter station. This current may lead to the malfunction of protective relays installed in nearby stations, because of saturation due to DC current. To prevent such malfunctions, insertion of neutral grounding resistor (small resistance) to transformers in converter station will be effective.

4.7 Two 12-pulse groups per pole

For a high-power ultra-high-voltage direct-current (UHVDC) converter arrangement, two 12-pulse units per pole may be a better solution to achieve required rating, because the dimension and weight of converter equipment (especially converter transformer) would become too large if only one 12-pulse unit per pole were used.

Two 12-pulse converters can be connected in series (Figure 10) or in parallel (Figure 11), and the selection of converter arrangement depends on the specific requirements of the project. On the other hand, if a project requires reduced voltage operation, for instance, due to occasional salt contamination, then the series option ~~should~~ may be ~~selected~~ preferred.

~~Basically series/parallel option has no difference regarding loss of~~ The series and parallel options are equivalent in terms of loss of transmitting power when a forced or scheduled outage of a 12-pulse converter occurs. ~~In both cases,~~ only 25 % of the capacity will be lost, assuming ~~all converters have the same power rating~~ ~~converters are employed~~. If sufficient overload capability is available, full power or almost full power can be restored. For the series option, the two poles can still operate with balanced current (without earth current) after a forced or scheduled outage of a 12-pulse converter occurs. However, note that a by-pass switch is required for each 12-pulse converter in series connected option. For the parallel option, the two poles can still operate with unbalanced current when a forced or scheduled outage of a 12-pulse converter occurs, while there is large current flowing through earth.

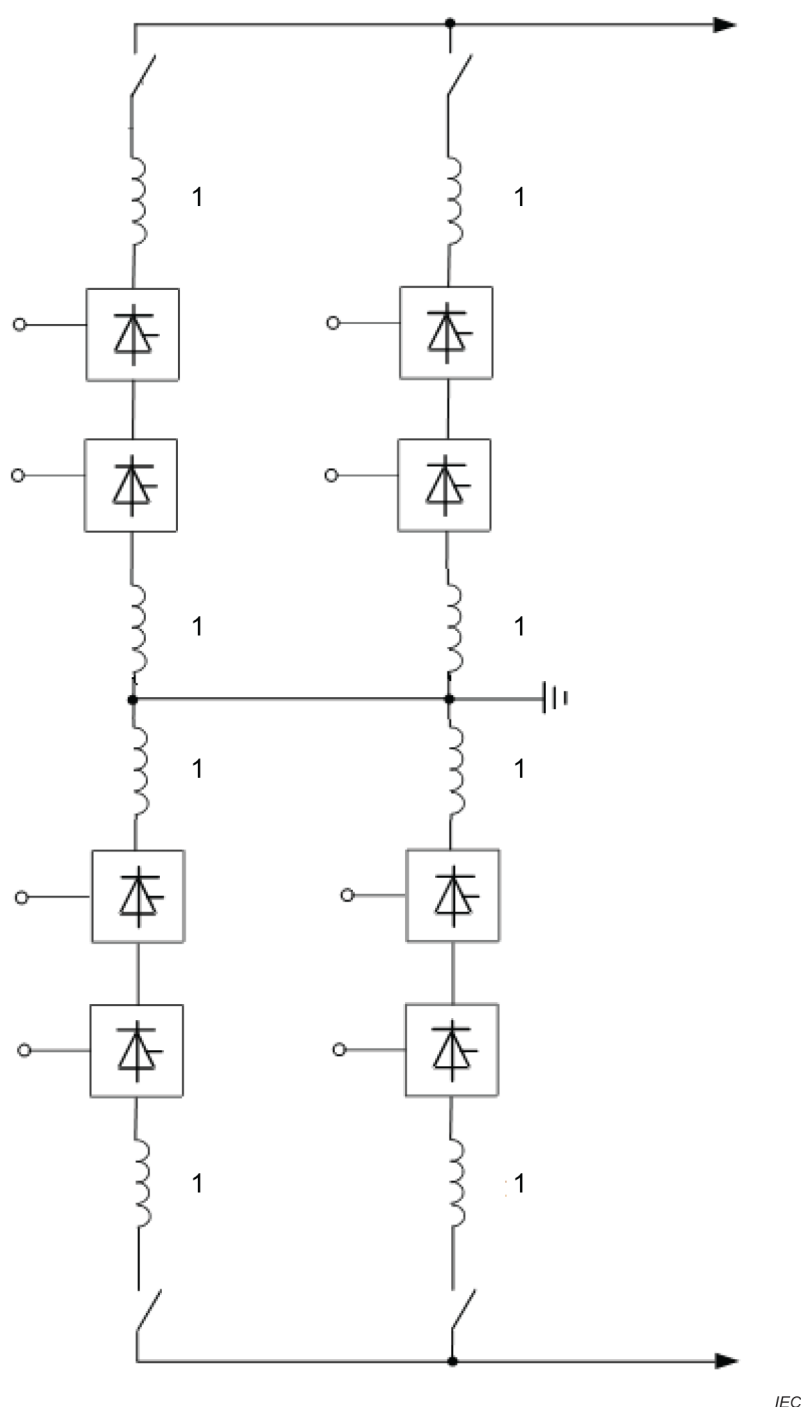


Key

- 1 DC reactor
- 2 By-pass switch
- 3 Earth return transfer switch (ERTS)
- 4 Metallic return transfer breaker (MRTB)

Figure 10 – Bipolar system with two 12-pulse units in series per pole

The cost of the two 12-pulse group per-pole arrangement, compared to one 12-pulse group per pole for the same total rating, would be expected to be greater, and the control system will become more complicated.



Key

1 DC reactor

Figure 11 – Bipolar system with two 12-pulse units in parallel per pole

4.8 Converter transformer arrangements

Each 12-pulse converter requires two three-phase transformer valve windings, one star-connected and the other delta-connected. These are provided by ~~either~~ one of the following:

- a) one three-phase transformer with two valve windings, or
- b) two three-phase transformers, one connected star-star and the other star-delta, or
- c) three single-phase transformers each with two valve windings, one for star connection and the other for delta connection, or
- d) six single-phase transformers, connected in two three-phase banks, one connected star-star and the other star-delta.

Depending on the HVDC system availability requirements, spare transformers may be needed at one or both ends. If one three-phase transformer with two valve windings is used, only one spare unit would be required. Since the star- and delta-connected three-phase transformers would be of different designs, spares considerations would indicate one spare of each design. Only one spare would be required for the single-phase, double-valve winding transformers since all three would be identical. The last of the above options would suggest two spare transformers, one each for the star- and the delta-valve winding single-phase transformers.

If spare transformers are not employed, alternatives b) and d) above allow for six-pulse operation at half-power in case of a transformer outage, if the HVDC system is designed for this mode of operation and the AC and DC harmonic conditions ~~would be~~ are acceptable. Six-pulse operation is not possible with alternatives a) and c).

It is not always needed to split the DC reactors, especially for parallel connection. The number and arrangement of DC reactors depend on the results of system studies and design.

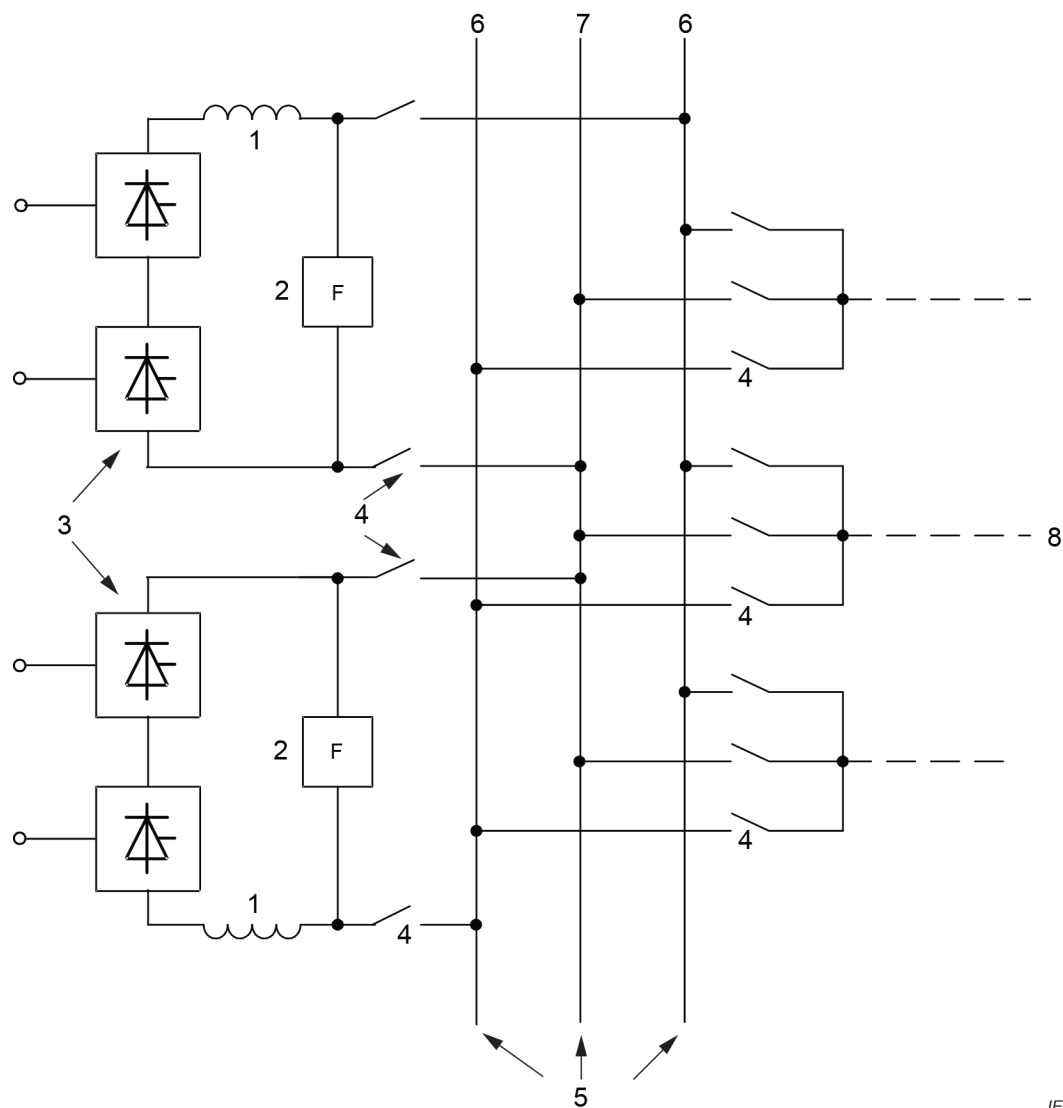
Converter transformers with a tertiary winding for reactive power and AC harmonic filter equipment may also be used.

4.9 DC switching considerations

There are a number of possible DC switching arrangements intended to increase HVDC system availability.

Monopolar metallic return operation of a bipolar system is discussed in 4.5.

For bipolar systems, DC switching may be provided (Figure 12) so as to allow the use of any conductor for connection to any substation pole or to neutral. 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, then 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 would preclude connection of the two substation poles in parallel.



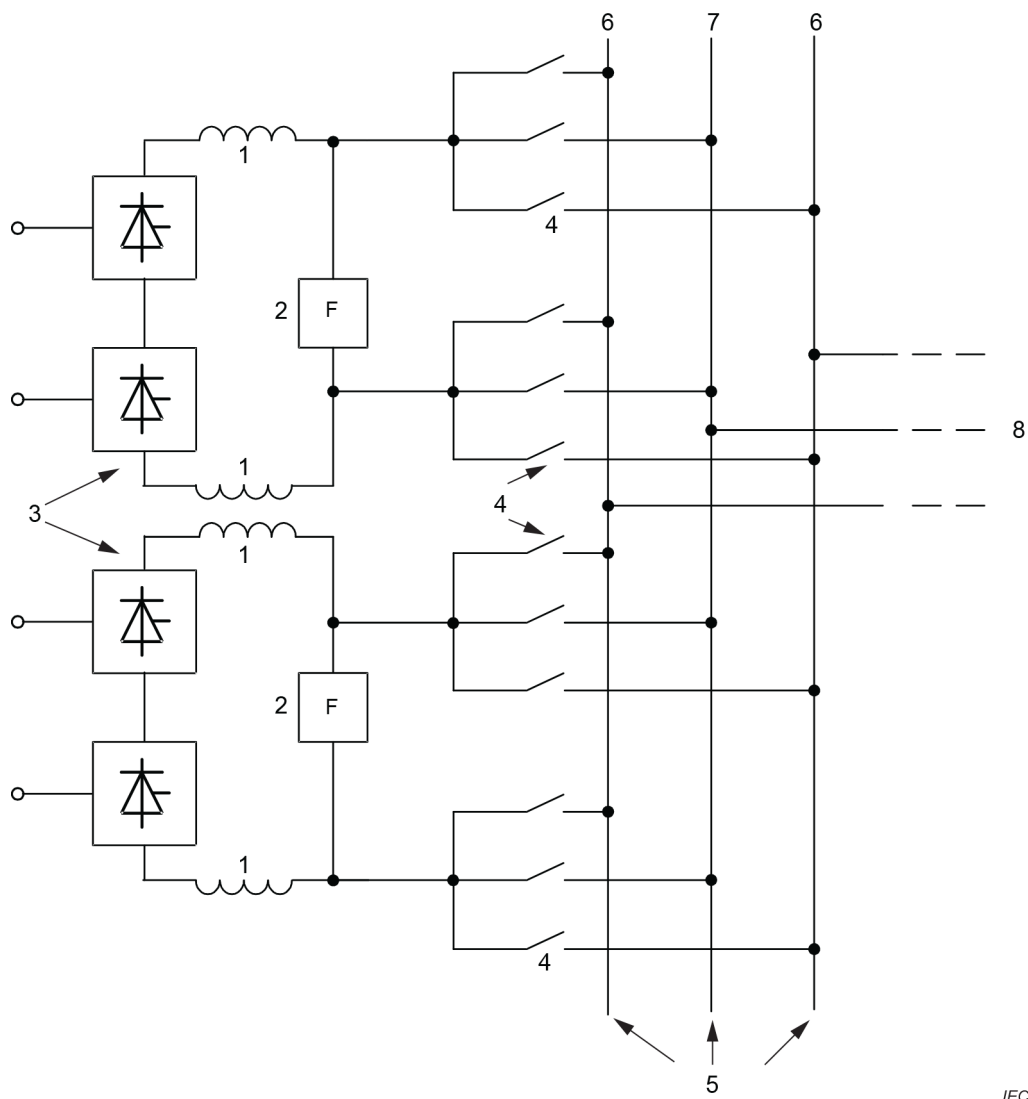
IEC

Key

1	DC reactor	5	DC bus
2	DC filter	6	Pole
3	Two-converter poles	7	Neutral
4	DC switches	8	DC line/cable

Figure 12 – DC switching of line conductors

However, if flexibility of connecting the two substation poles in parallel is needed, then provision for polarity reversal of at least one substation pole could be made and the neutral end of that substation pole will also have to be insulated for full line voltage. A possible switching arrangement is shown in Figure 13.



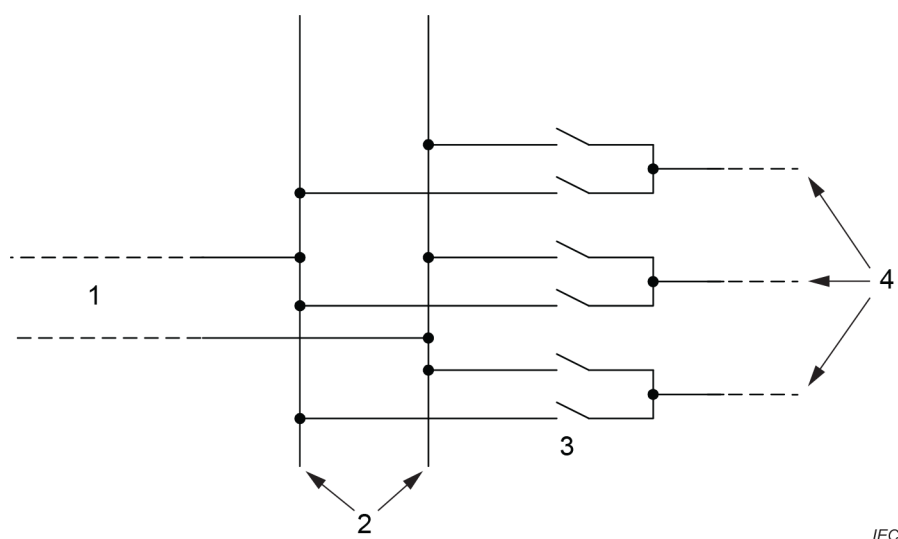
IEC

Key

1	DC reactor	5	DC bus
2	DC filter	6	Pole
3	Two-converter poles	7	Neutral
4	DC switches	8	DC line/cable

Figure 13 – DC switching of converter poles

If an HVDC transmission system includes both overhead line and cable sections, a DC switching arrangement such as in Figure 14 may be used at the junction of the overhead and cable sections.

**Key**

- 1 Bipolar overhead line
- 2 DC bus
- 3 DC switches
- 4 DC cables (two poles, one spare)

Figure 14 – DC switching – Overhead line to cable

For more than one bipolar line, paralleling of converter poles may be considered, in order to allow restoration of transmission capability (Figure 15) for transmission line outages.

For long bipolar lines in parallel, intermediate switching such as in Figure 16 may be provided.

4.10 Series-capacitor-compensated HVDC systems

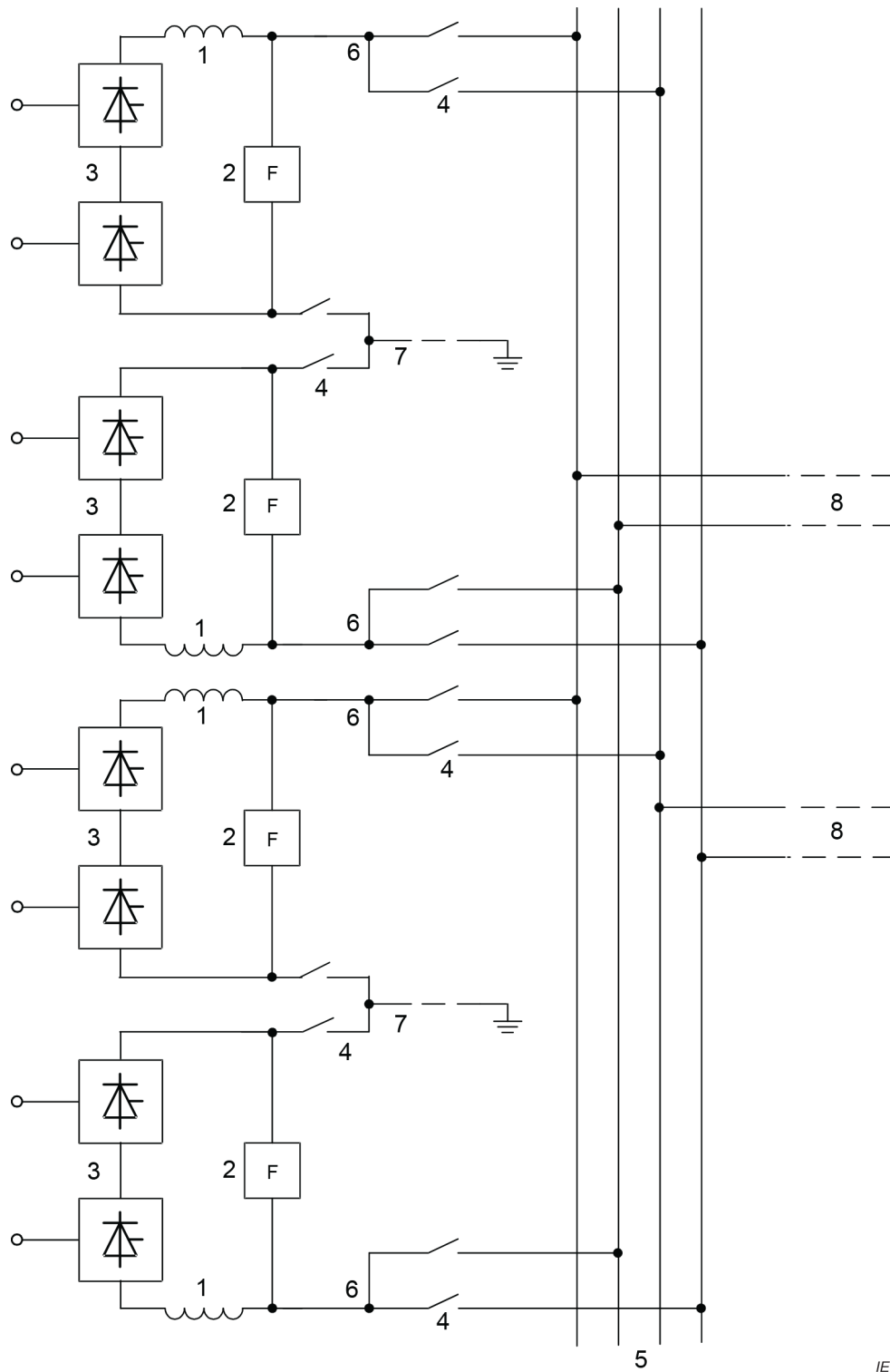
Although the conventional line-commutated converter (LCC) technology has reached maturity, such converters still have two weaknesses:

- a) a large amount of reactive power consumption, roughly 50 % of its active power;
- b) susceptibility to AC side disturbance, commonly observed as commutation failures.

To overcome these weaknesses, further developments have been made using series-capacitor compensation.

Practically, there are two types of series-capacitor compensated HVDC schemes.

- Capacitor-commutated converter (CCC), in which series capacitors are included between the converter transformer and the valves.
- Controlled series capacitor converter (CSCC) is also suggested. In this scheme, the basic topology of the converter is the same as the conventional topology; however, series capacitors are inserted between the AC filter bus and the AC network. Occurrence of ferroresonance with the CSCC option is eliminated by controlling the amount of series compensation.

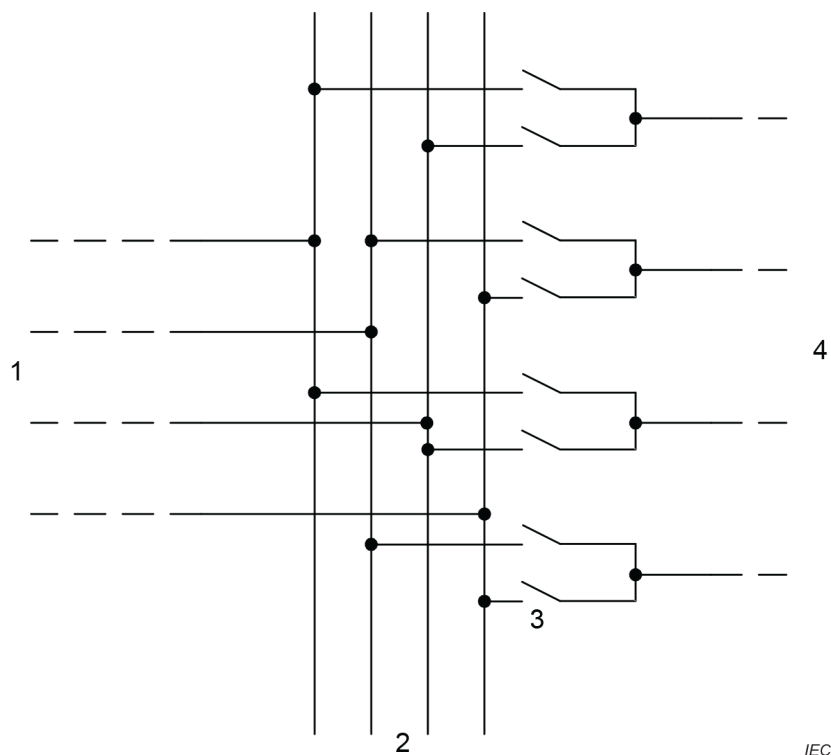


IEC

Key

- | | | | |
|---|---------------------|---|---------------|
| 1 | DC reactor | 5 | DC bus |
| 2 | DC filter | 6 | Pole |
| 3 | Two-converter poles | 7 | Neutral |
| 4 | DC switches | 8 | DC line/cable |

Figure 15 – DC switching – Two bipolar converters and lines

**Key**

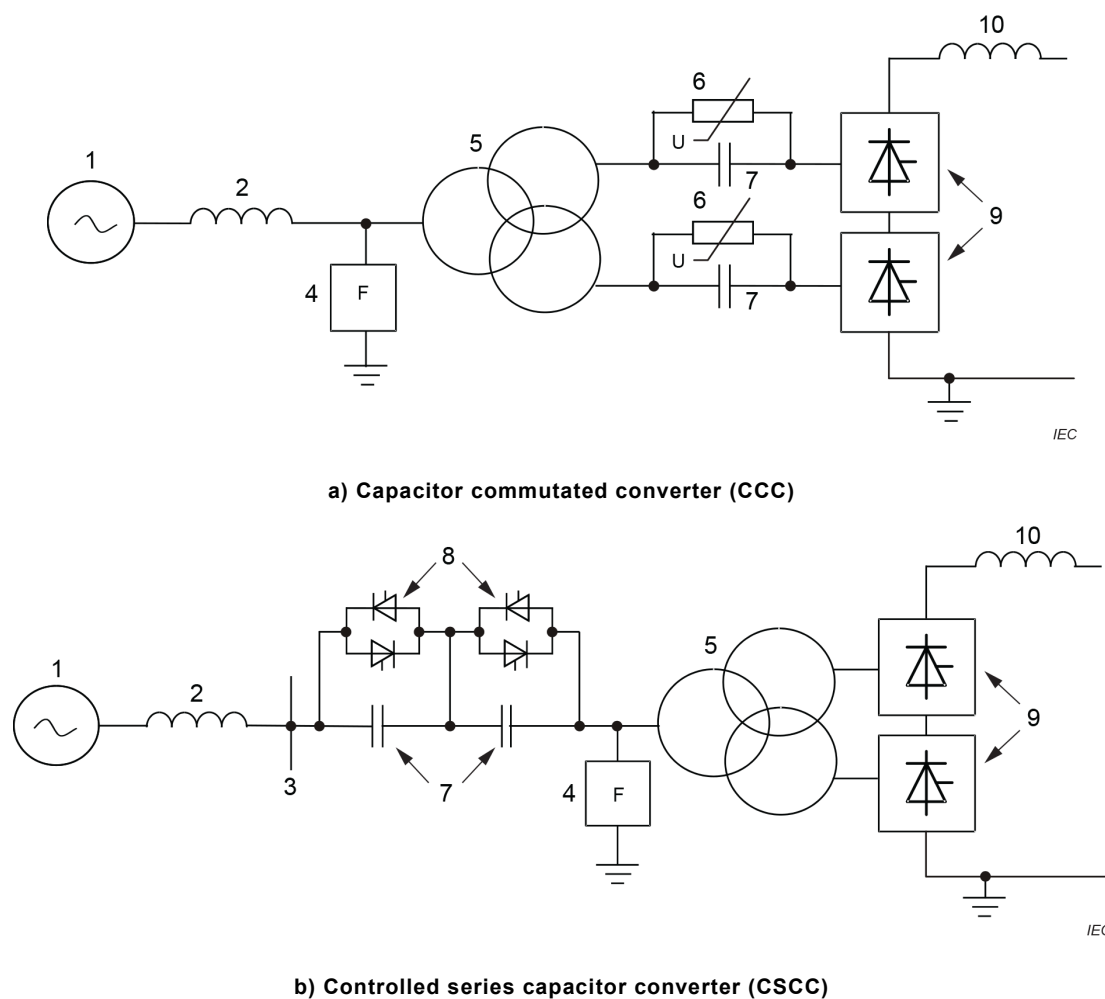
- 1 Two bipolar lines
- 2 DC bus
- 3 DC switches
- 4 Two bipolar lines

Figure 16 – DC switching – Intermediate

The CCC circuit shown schematically in Figure 17 a) is based on a topology in which series capacitors are included between the converter transformer and the valves. The CSCC circuit has the series capacitors inserted at the connection of the filter bus to the AC system as shown in Figure 17 b). This provides similar performance to the CCC, with the additional advantage of controllability of the reactive power exchange with the AC network.

Both alternatives offer improved immunity from commutation failure, lower load rejection overvoltages and increased stability margins in power control mode, over the conventional HVDC scheme. They are, therefore, suitable candidates for use at the inverter end in long cable systems or in back-to-back ties connected to weak AC systems. The performance of the two alternatives is very similar for steady state as well as transient operation.

The maximum valve voltages and also the AC current harmonics for the CSCC configuration are lower than for the CCC configuration. On the other hand, the CCC in rectifier operation exhibits a smaller valve short-circuit current. The previously identified problem with ferroresonance in the CSCC is eliminated through the application of controlled series capacitors.



Key

1	AC system e.m.f.	6	Overvoltage limiter
2	AC system impedance	7	Capacitor
3	AC system bus	8	Thyristors
4	AC filters	9	Converters
5	Converter transformer	10	DC reactor

Figure 17 – Capacitor commutated converter configurations

The advantages of using CCC in comparison with conventional converter may be summarized as follows:

- significantly less reactive power consumption, which, in combination with sharply tuned filter branches, eliminates the need for switching filter and shunt capacitor banks during power ramps;
- immunity to commutation failure during AC side disturbance, which is beneficial with long lines or cables feeding weak AC networks;
- stable operation in lower short-circuit capacity systems;
- lower overall installation cost in some cases, due to elimination of switchable filter and shunt capacitor banks or synchronous compensators, in applications associated with weak AC network connections;
- robustness in situations of converter-arm short-circuit fault due to lower fault current;
- less variation of reactive power during disturbances, which results in improved power quality and reduced load rejection.

The disadvantages are:

- increased harmonic current;
- slightly increased converter losses;
- requirement for detailed study of transient stresses on equipment;
- reduced inherent overload capability, due to the capacitor connected in series with the converter;
- requirement for shielding against lightning and radio interference between the valve winding, the capacitor and the valve;
- slightly increased valve voltage stress.

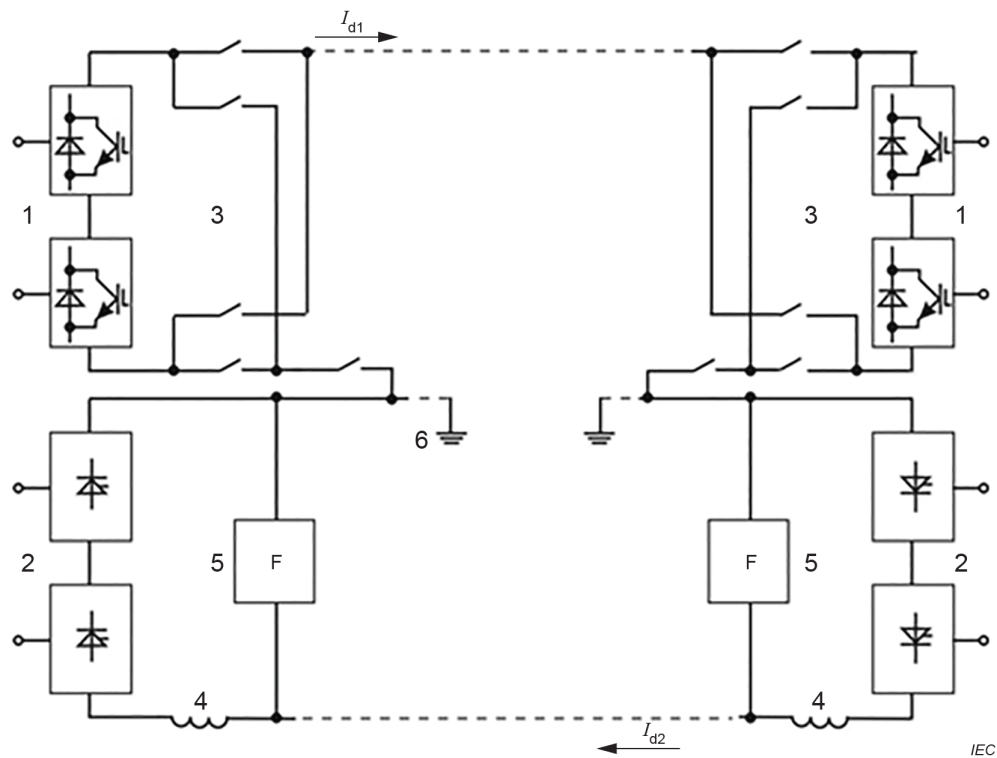
When CCC or CSCC is being considered as an HVDC topology for a particular project, it should be emphasized that the selection of optimal system rating is different from conventional HVDC. Therefore, in order to make a selection between conventional HVDC schemes and these alternatives, a detailed analysis is required with respect to economics and technical performance, taking into account losses, installation costs, etc.

4.11 LCC/VSC hybrid bipolar system

In case one pole of the LCC is combined with a VSC pole, a hybrid bipolar system of LCC and VSC will be formed. For an LCC/VSC hybrid bipolar system, special consideration should be taken because power reversal of the VSC system requires current reversal, whereas LCC changes voltage polarity. The combined operation of both systems will lead to excessive current on electrode line or return line for one of the power directions. In order to prevent this problem, switches for polarity reversal should be installed on the VSC converter, as depicted in Figure 18.

The other possibility of LCC/VSC hybrid system is the case that consists of LCC for one terminal and VSC for the other terminal. This configuration can be applied to the DC system that transmits power to a weak AC system.

Adopted VSC for hybrid systems should be in asymmetrical monopole configuration.



Key

- | | | | |
|---|---------------------------------|---|-----------------|
| 1 | voltage-sourced converter (VSC) | 4 | DC reactor |
| 2 | line-commutated converter (LCC) | 5 | DC filter |
| 3 | polarity reversal switches | 6 | earth electrode |

Figure 18 – LCC/VSC hybrid bipolar system

5 Environment information

The location and the information listed in Table 1 should be supplied for each HVDC substation.

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 requirements. If the user intends to overload the equipment and accept a corresponding loss-of-life expectancy, this should be stated and the necessary 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, may be provided instead
Maximum dry-bulb temperature	°C	°C	Valve cooling, transformer and reactor design, AC and DC filter 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 oil insulated reactor design
Minimum average dry-bulb temperature for a period of 24 h	°C	-	Transformer, reactor and disconnector switch design and building heating needs
Minimum dry-bulb temperature	°C	-	Transformer, reactor and disconnector switch design and building heating needs, AC and DC filter design
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		
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 speed ofm/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			
Annual average	mm		Building and site drainage
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 requirements for insulation and air-cooling system filter design. An estimated equivalent salt deposit density level should be specified for insulator design
Keraunic level at the station and the first 5 km to 10 km of the line	Strokes/km ² /year (substation) Strokes/100 km/year		Station lightning protection design



Parameter	Unit		Examples of use and comments	
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	Cycles			
Cooling water available at the site (if used for secondary cooling)			Secondary cooling water may 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 should be carefully located	
Source of water			Reservoir, well, etc. If preferred, curves showing how these parameters vary over the year on a monthly basis may be provided instead.	
	For low temperature capability	For rated power capability		
	Maximum continuous flow rate	m ³ /s	m ³ /s	Required for cooling system design
	Maximum flow rate for a period of 24 h	m ³ /s	m ³ /s	Required for cooling system design
	Minimum continuous flow rate	m ³ /s	m ³ /s	Required for cooling system design
	Minimum flow rate for a period of 24 h	m ³ /s	m ³ /s	Required for cooling system design
	Maximum water temperature	-	°C	Required for cooling system design
	Minimum water temperature	°C	-	Required for cooling system design
	Maximum allowable dump water temperature to drain	°C	°C	Required for cooling system design
pH level			Design of water treatment plant	
			Parameters apply only in the case where well water is used for evaporative cooling	
Conductivity of water	μ Siemens/m		Design of water treatment plant	
Type of dissolved solids			Design of water treatment plant	
Quantity of dissolved solids	g/m ³		Design of water treatment plant	
Type of undissolved solids			Design of water treatment plant	
Quantity of undissolved solids	g/m ³		Design of water treatment plant	
Maximum earth resistivity at the HVDC substation	Ωm		Station earth design	
– Depth of water table	m		Foundation design	
– Site soil conditions			Bore hole information (for example, rocks) and any special conditions, such as maximum frost depths, foundation design	
– Site accessibility			To determine installation and delivery costs	
– Weight and size limitations for transportation	kg, m		Equipment design – especially transformers and DC reactors	
– Local profile limitations on equipment and buildings			Influence on equipment, bus and building design	
– Environmental considerations			Audible noise limits, aesthetic requirements – architectural treatment, landscaping, etc.	
Any special conditions not listed above, for instance, related regulations, which influence system performance should be given.				

6 Rated power, current and voltage

6.1 Rated power

6.1.1 General

Rated power is the active power which the HVDC system shall be able to transmit continuously, over the range of ambient conditions specified, with all equipment in service, but without the need to utilize redundant components; the HVDC system voltage and frequency as well as the converter firing angle and the extinction angle being in their steady-state range.

Because an HVDC transmission system in general consists of three sections, i.e. the two HVDC substations and the transmission line, each of which produces losses, the point of measurement of rated power should be specified.

6.1.2 Rated power of an HVDC system with transmission line

The rated power of an HVDC transmission system on a per-pole basis is defined as the product of rated direct voltage times rated direct current.

For a given direct current, transmission line losses vary with ambient conditions, which can be non-uniform along the length of the line. Therefore, it is customary to specify rated power at the rectifier DC bus. If the required transmission capability is defined at some other location, i.e. the sending-end AC bus, receiving-end AC bus, or somewhere along the HVDC transmission line, then the rated DC voltage should be defined and the rated direct current should be chosen through design optimization of the HVDC system.

Rated power and voltage at the inverter DC bus are derived values from rectifier quantities, and line losses are usually based on defined conductor parameters and uniform conductor temperature assumptions along the line.

Long distance HVDC systems may be monopolar or bipolar. Rated power should be specified on a per-pole basis stating the number of poles.

6.1.3 Rated power of an HVDC back-to-back system

With system ties in a back-to-back configuration, there is no transmission line. Therefore, the rated DC voltage and current are chosen through design optimization of the HVDC system. Moreover, the rectifier and inverter are solidly connected at the DC side, operating as one unit. Rated power of such a system can, therefore, be defined as the product of rated direct voltage times the rated direct current.

6.1.4 Direction of power flow

If the same power rating is required in each direction, such as with system ties for power exchange, this should be stated.

Where power flow is primarily in one direction, such as with systems fed from remote generation, rated power may be specified only for that direction to minimize the inverter cost. Then a lower inherent transmission capability should be accepted for reversal of power flow.

6.2 Rated current

Rated direct current is the mean value of the direct current that the system should be able to transmit continuously for all ambient conditions specified and without time limitations. The rated current should not be specified for back-to-back systems as detailed in ~~5.1.3 above~~ 4.2, unless there are specific reasons for doing so.

6.3 Rated voltage

The rated voltage is the mean value of the required direct voltage to transmit rated power at rated direct current. It is measured between the high-voltage bus at the line side of the DC reactor and the low-voltage bus at the HVDC substation, excluding the earth electrode line. The rated voltage is defined at nominal AC system voltage and nominal converter firing angle while operating at rated direct current.

For long distance HVDC transmission systems, the rated voltage should be specified at the sending end. If the voltage capability of the transmission line is higher than the rated voltage, then this shall be stated. The rated voltage need not be specified for back-to-back systems as detailed in 6.1.3, unless there are specific reasons for doing so.

7 Overload and equipment capability

7.1 Overload

Overload in an HVDC substation usually refers to direct current flow above its rated value. For this, consideration may be given to acceptable reduction in life expectancy of equipment (for example, due to thermal ageing), use of redundancy, and low ambient temperatures.

Overload may be specified in terms of power. Voltage regulation in the converter including the transformer normally causes a reduction of DC voltage under overload conditions and hence an increase in current somewhat more than an amount proportional to the increase in power. If rated voltage is to be maintained under overload conditions, then the following measures may be adopted, at additional cost.

- a) The converter should be designed for a higher no-load voltage. This results in a higher MVA rating if overload is required over the full range of AC bus voltage.

NOTE This ~~may not~~ cannot be necessary if overload is required only for the upper range of the steady-state AC system voltage.

- b) The voltage rating of the converter valves, which is based on transformer no-load voltage, should be increased.
- c) The on-load tap changer range should be increased if the converter firing angle is to be maintained at its nominal value. Alternatively, the converter may be designed for a higher nominal firing angle at rated power. This will increase reactive power consumption, harmonics and losses, as well as the internal stresses on valve components.

As a consequence, if rated direct voltage is to be maintained under overload conditions, oversizing of equipment will be necessary.

For a more economical design, an overcurrent rating may be specified, without regard for direct voltage regulation. Basic converter equations then permit determination of the maximum current, beyond which further increase would be offset by excessive voltage regulations.

When the converter is operated in overload it will absorb more reactive power. Unless this increased reactive power absorption can be compensated by filters/shunt capacitors, for example, from another pole, then the AC busbar voltage will reduce. When the AC system short-circuit level is low, this effect may limit the achievable overload.

The required duration of HVDC substation overloading is most often determined by AC system needs, especially following contingencies in either the AC or HVDC system.

However, some constraints should be observed for the HVDC substation equipment. Thermal time constants range from 1 s to some hours, as detailed in 7.2. Longer duration overload requirements of high magnitude may, therefore, result in an effectively increased rating of

equipment and thus impose a greater cost or a reduction of life expectancy. These factors should be weighed against system benefits when specifying overload.

EXAMPLE A practical value ~~may~~ can be a 1,2 per unit overload for 1 h which does not result in loss of life expectancy of oil-cooled transformers and reactors but ~~may~~ it is possible that it will have to be designed into thyristor valves. Also depending on the particular design, it is possible that the 1 h overload ~~may~~ will be converted to continuous if cooling redundancy is utilized. Other examples include oscillatory overloads at a frequency of up to 1 Hz for durations of several seconds, for example for power oscillation damping, and 5 s overloads to counteract temporary overvoltage or frequency changes.

The frequency and the time intervals between such overload cycles should be specified.

7.2 Equipment capability

7.2.1 General

This is defined as the ability of the HVDC substation equipment to permit transmission of greater than rated power, without loss of equipment life expectancy. It depends on operating conditions as well as on the design criteria for individual components. Implications resulting from the latter 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 is available for increased capability if the constraints listed in 7.2.4 can be overcome. This margin depends on the design chosen for the particular equipment and would 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 should be specified in terms of wet-bulb and dry-bulb ambient temperatures.

7.2.2 Converter valve capability

The thermal time constant of the thyristor heat sink combination in a thyristor 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 thyristor junction temperature. This should be considered with respect to the specified fault suppression capability of the valve. Consequently, thyristor valve cooling should be designed so that safe operating temperatures are not exceeded even during specified overload operation.

Redundancy is provided as a general practice in the valve cooling circuit. Valves are designed such that the specified rating will be met under the most adverse ambient conditions and loss of thyristor cooling equipment redundancy. If additional capability is needed when redundant cooling is not available, this should be explicitly specified.

On the other hand, with all redundant cooling equipment in service, extra thermal capability is 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 should state the magnitude and duration of overload, frequency of oscillatory overloads for modulation purposes, as well as the cooling equipment status to be assumed at maximum ambient temperatures.

7.2.3 Capability of oil-cooled transformers and reactors

The thermal time constant of the transformer or reactor windings is approximately 15 min and ranges from one to several hours for their oil circuits (if any), depending on the design.

Consequently, for short time overloads in the 5 s range, oil-cooled equipment is not the limiting factor on HVDC substation overloads. For overloads lasting longer than 1 h, it should

be specified whether loss-of-life expectancy is permitted. The expected frequency of occurrence of such overloads should be specified.

7.2.4 AC harmonic filter and reactive power compensation equipment capability

HVDC substation overloads will usually generate increased harmonic currents. These in turn increase harmonic loading, losses in filters and harmonic interference levels. The specifications should state whether the interference performance under rated conditions should be met under overload conditions or to what extent degradation of performance is permitted.

Also, since overload increases the converter reactive power consumption, the specifications should state how this is to be taken into account when designing reactive power compensation equipment. If additional reactive power is drawn from the system under HVDC substation overload conditions, excessive AC bus voltage regulation and a consequent reduction in power flow may take place. For this reason, the expected AC bus voltage under overload conditions should be specified. *Air-cored equipment such as air-cored reactors should be specified especially for their overload capability.*

7.2.5 Switchgear and buswork capability

Switchgear and buswork normally do not impose limits on HVDC substation overloads unless paralleling of converters is planned. However, special attention should be paid to the overload capabilities of current transformers and bushings.

8 Minimum power transfer and no-load stand-by state

8.1 General

With HVDC substations there exists a minimum steady-state direct current limit. This is due to the fact that at some low level the current becomes discontinuous and is the principal criterion for a minimum power limit.

8.2 Minimum current

Since the direct voltage output of an HVDC converter is made of sections of the sinusoidal bus voltage, direct current would not be a smooth or constant quantity by itself. Rather, it is made continuous by the DC reactor connected in series with the converter. Assuming a constant average direct voltage, the direct current would become discontinuous, at low power, depending on the commutating reactance of the converters, the inductance of the DC reactor, the number of valve groups in service, where series connection of groups is used, and converter firing angle, as well as the negative sequence component of the AC system voltages. Discontinuous current should be avoided in steady-state operation, unless the converter equipment is designed for this mode of operation.

Since the DC reactor inductance is usually determined by other criteria and the firing angle can be of any value, a minimum current limited shall be specified. A value of 5 % to 10 % of rated current is commonly used. This minimum direct current can further be reduced by choosing a larger value of DC reactor inductance.

8.3 Reduced direct voltage operation

Under contamination conditions, often in combination with unfavourable weather conditions, operation of an overhead DC transmission line may not be possible at its rated voltage. However, the control system of the HVDC substation offers various means to achieve continuation of power flow at reduced transmission voltages.

One possibility is to move the transformer tap changer to the position resulting in the lowest AC voltage for the valves. In addition, a further decrease of transmission voltage can be achieved through operation at an increased firing angle.

This requirement could mean a special valve design and thus increase valve costs. Furthermore, since operation at large firing angles causes an increased harmonic generation and reactive power consumption, operation at reduced direct voltage then requires a reduction of the direct current if the filtering and compensation equipment is not rated for these conditions.

Other possibilities are to increase the tap changer range, or where the HVDC system is fed from an isolated power station, a reduction of AC bus voltage can also be considered.

Practical values for reduced direct voltage operation are at 70 % to 80 % of rated voltage, perhaps at reduced current. It is reasonable to expect continuous operating capability at approximately rated current at 75 % voltage with use of redundant cooling, provided that somewhat higher harmonic interference level is acceptable; this in turn depends on expected frequency and duration of such operations.

Where two series-connected 12-pulse converter units are used in each pole, one unit ~~might~~ can be switched out, resulting for example in a 50 % voltage reduction when both have the same rating, thus eliminating the necessity to operate at increased converter firing angle or reduced direct current.

To arrive at an economic design of the equipment, the AC voltage levels should be specified for expected direct voltage operations.

8.4 No-load stand-by state

8.4.1 General

In this mode, the HVDC substation is ready for immediate pick-up of load without the need for a lengthy start-up procedure. A definition of the status of various pieces of equipment shall be specified to determine the no-load losses of the HVDC substation, if operation in the no-load stand-by state is planned.

8.4.2 Converter transformers – No-load stand-by

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

8.4.3 Converter valves – No-load stand-by

The converter valves should be in the blocked condition. There will be small losses in the voltage grading circuits if the converter transformers are energized. Primary, secondary and valve hall cooling should be in operation at a sufficient level to permit immediate pick-up of load.

8.4.4 AC filters and reactive compensation – No-load stand-by

The AC filters and reactive compensation may be connected or disconnected depending on reactive power control strategy within the AC system. However, for the sake of no-load loss determinations, they should be considered disconnected.

8.4.5 DC reactors and DC filters – No-load stand-by

The DC reactors and DC filters should be connected. ~~DC reactors,~~ Pumps and coolers for DC reactors (where fitted) should be in operation on a minimum level, as appropriate to the design of the reactors.

8.4.6 Auxiliary power system – No-load stand-by

The auxiliary power system should be fully operative and ready to pick-up rated load, for example, all station service transformers energized, battery chargers in operation, ~~etc.~~

8.4.7 Control and protection – No-load stand-by

All control and protection circuits should be operative.

9 AC system

9.1 General

The following information in Clause 9 should be specified for AC systems at both ends for each stage of development as well as for expected future changes. Different values may be specified for performance and rating purposes.

The arrangement of the AC switchgear to which the converter units and filters are to be connected, including AC lines, should be described. This should also be done for the planned operating schemes of the switchyard.

Specific data should be made available for generators in the close vicinity, particularly if the major load for the generators is served through the rectifier. Often all data pertinent to load flow and short-circuit studies are also needed.

9.2 AC voltage

9.2.1 Rated AC voltage

Rated AC voltage is the RMS phase-to-phase fundamental frequency voltage for which the system is designed and to which certain characteristics of the AC equipment are related, such as AC switchgear, AC filters, reactive power compensation equipment, primary windings of converter transformers, etc.

Rated voltage may be used to define the rated power of such AC equipment.

9.2.2 Steady-state voltage range

9.2.2.1 General

The steady-state voltage range is the range over which the HVDC system should be able to transmit rated power and over which all performance requirements are to be met, unless stated otherwise.

Any special performance requirements beyond the limits of the steady-state range should be specified. These may affect the design of main equipment, converter transformers, filters, auxiliary equipment, etc.

9.2.2.2 Short-term voltage range

There may be situations under which the voltage exceeds the normal steady-state operating range but the HVDC system may be required to remain in operation. Under these conditions the HVDC system may be designed to operate in a manner whereby no equipment should be

at risk of damage, but the performance limits of the system may be acceptably degraded (for harmonics, losses, etc.).

The acceptable degraded performance limits should be specified since these will have an effect upon the ratings of equipment.

The HVDC control system may even be specified to assist in the restoration of the voltage to within the normal operating range (through either HVDC control action or addition/removal of filters and reactors) if this is appropriate.

9.2.2.3 Voltage variation during emergency

Dynamic overvoltages could determine ratings and protection strategies.

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

The HVDC control system may even be specified to assist in the restoration of the voltage to within the normal operating range (through either HVDC control action or addition/removal of filters and reactors), if this is appropriate.

9.2.3 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.

Although it is difficult to obtain an actual value for this parameter, the maximum to be used in determination of non-characteristic harmonics of the current on the AC side and the non-characteristic harmonic voltages on the DC side should be specified. These harmonic currents and voltages are respectively used for the design of the AC filter, DC filter and DC reactor (see Clauses ~~46~~, 17, 18, and 21).

9.3 Frequency

9.3.1 Rated frequency

The frequency of an AC system should be specified to give the basis of rating of the AC equipment, converter transformer, etc., as well as converter bridges and control.

The design of the DC filters is also influenced by the AC system frequency.

9.3.2 Steady-state frequency range

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

9.3.3 Short-term frequency variation

Limits and duration of short-term frequency excursions for which system performance is required should be specified. This can be a sensitive parameter for AC and DC filter design. Filtering performance during such variations may be specified.

9.3.4 Frequency variation during emergency

During an emergency the AC system frequency may reach extreme values for limited periods. These values and their expected durations should be specified. In this condition, the equipment should remain in service without damage, but should not be required to meet the performance specified. For excursions beyond the specified operating frequency limits, it may be permissible to automatically disconnect the equipment.

9.4 System impedance at fundamental frequency

For the purpose of analysis of commutation conditions in the converter, the system impedance at fundamental frequency should be stated. Maximum and minimum values of the subtransient impedance at the AC bus, without any filter or compensating equipment, are needed for such analysis.

Subtransient impedance is the positive sequence impedance of the AC system as determined by the subtransient reactance of synchronous machines, leakage reactance of induction machines and positive sequence impedance of connecting lines.

Additionally, a detailed AC system impedance or a suitable equivalent should be specified, in order to optimize the DC control.

9.5 System impedance at harmonic frequencies

System impedance at all harmonic frequencies from the 2nd up to the 50th is needed for AC filter design and performance calculations.

This impedance may be calculated using the parameters of the lines, transformers and generators up to five to eight HVDC substation buses. However, this impedance may change considerably under different load conditions and extension stages of the system. Therefore, it is usually more convenient to use an R - X diagram and to plot the envelope of the locus of the system harmonic impedance under expected system conditions. The values of $R_{\min}$ and $X_{\min}$ should be included in the diagram.

In practice, this diagram may take various forms such as a circular plot, limited by constant R/X ratio or ~~the combination of both~~ a series of polygons defining ranges of harmonic impedance for each frequency. Further guidance can be found in IEC TR 62001 (all parts).

9.6 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.

9.7 Other sources of harmonics

Other sources of harmonics electrically close to the HVDC substation should be identified. Their influence should be taken into account in AC filter and capacitor bank ratings. Generated harmonic currents should be stated for the static reactive power compensators connected to the converter substation bus or to nearby AC substations.

9.8 Subsynchronous torsional interaction (SSTI)

If subsynchronous torsional interaction (SSTI) problems are expected, all related information from the pertinent studies should be provided (see also ~~Clause 9~~ 13.2.4).

10 Reactive power

10.1 General

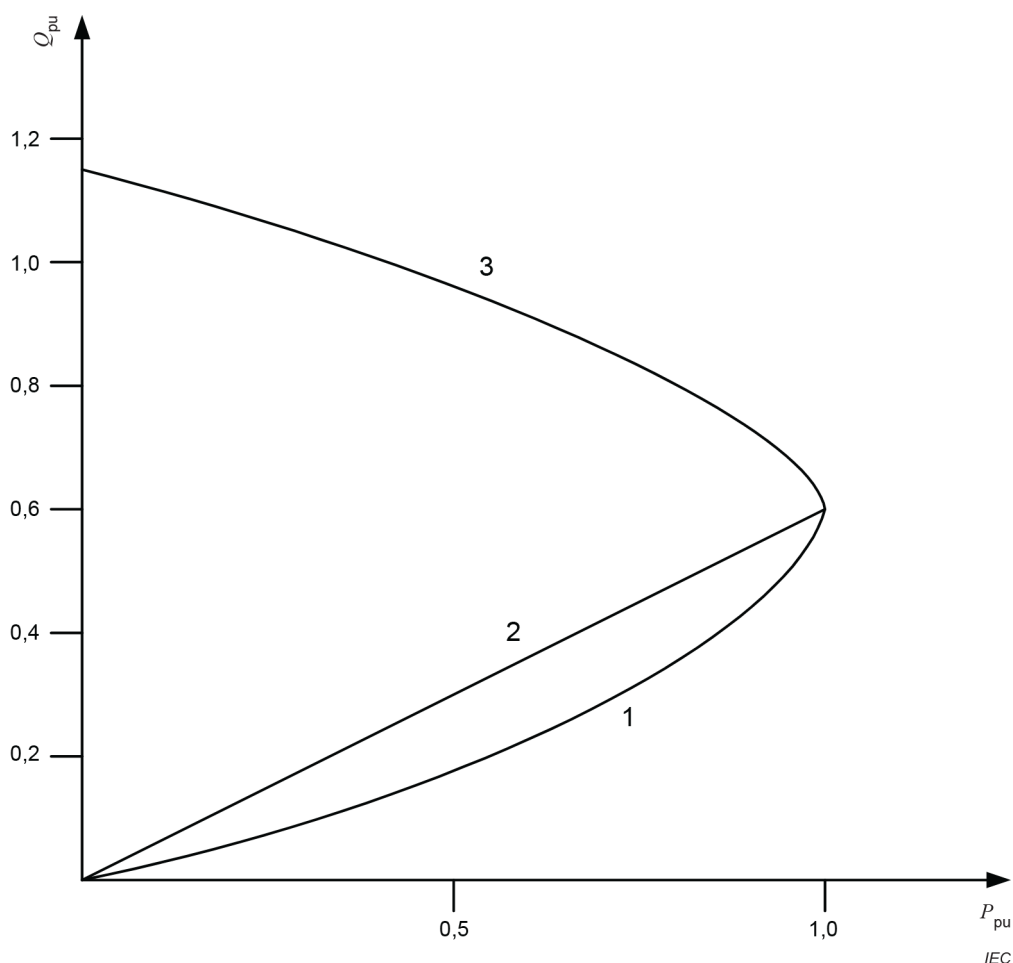
Clause 10 identifies the considerations relevant to reactive power.

10.2 Conventional HVDC systems

Line commutation of converter bridges, as used in conventional HVDC systems, requires a consumption of reactive power in both rectifier and inverter operation. At full load, this consumption represents 50 % to 60 % of rated power for commonly used values of transformer impedance and firing angle or extinction angle.

At partial load reactive power consumption can be varied according to AC system requirements by using an appropriate control strategy. A control strategy which is often adopted is to maintain the delay angle α in the rectifier, or the extinction angle γ in the inverter, within narrow limits by means of the tap changer of the converter transformer. Under this strategy, the variation of reactive power versus real power is shown in Figure 19, curve 1, for constant direct voltage and constant extinction angle γ . As an alternative, a linear variation may be obtained, as shown on Figure 19, curve 2, which involves maintaining constant no-load direct voltage U_{d0} by means of an increase of the delay angle α in the rectifier and extinction angle γ in the inverter, when the load is reduced.

If the direct current is kept constant and partial load is achieved by increasing the delay angle and thus reducing the direct voltage, reactive power consumption is increased at partial load according to curve 3 in Figure 19. Any characteristic between curves 1 and 3 can be implemented to meet specific AC system requirements.



Key

- 1 Constant DC voltage – Constant γ
- 2 Constant DC voltage – Constant U_{d0}
- 3 Constant DC current

Figure 19 – Variations of reactive power Q with active power P of an HVDC converter

Combined changes of the valve firing angle and the load tap changer of the converter transformer may be used to control the reactive power demand of an HVDC substation. However, since this requires an increase of the firing angle, it leads to an increased generation of harmonic currents and voltages and increased losses in the damping circuits of the valves.

Looked at another way, filtering of AC current is obtained through harmonic filters, which also generate reactive power. However, the fundamental frequency reactive power generated by the filters as determined by the AC filtering requirements at full load is generally less than the reactive power consumption of the converter bridges. Therefore, additional capacitor banks are usually provided to meet the total reactive power demand of the converter.

The net reactive power of the converters and filters, taking into account filtering consideration, may be controlled within certain limits, by switching of capacitor banks and also part of the filter banks, if needed.

To define a suitable strategy of reactive power control, the aspects described in 10.4 to 10.7 should be specified.

10.3 Series capacitor compensated HVDC schemes

Reactive power requirements of conventional HVDC schemes are addressed by adding shunt devices such as shunt capacitors and filters.

Conversely, both CCC and CSCC treat this differently, as instead of connecting capacitor banks in parallel to the converter bus, they are inserted between the transformers and valves (CCC) or between the transformers and the AC network (CSCC). By these configurations, the voltage across the series capacitor adds to the commutation voltage resulting in a wide range of trigger delay angle (α) and extinction angle (γ). This brings about less overlap angle (μ) and thus less reactive power consumption. AC filters are required only for harmonic elimination and not for reactive power support. This reduces the MVar rating of the filter to small values. Unlike the conventional case, neither the CCC nor CSCC configuration requires filter-bank switching for variations in the load over the full range of operation.

10.4 Converter reactive power consumption

The reactive power consumption should be determined for the different operating conditions for the rectifier and inverter under partial load, full load and overload conditions. The method of calculation and the parameters used in the calculations should also be specified.

The operating conditions to be considered include: direction of power flow, monopolar earth return, monopolar metallic return, bipolar and reduced direct voltage operation over the specified range of steady-state AC bus voltage.

Also at minimum power transfer with a minimum number of AC filters connected, the ability of the converter valves to operate with increased firing angle/extinction angle can be utilized to minimize the reactive power flow to the AC systems.

10.5 Reactive power balance with the AC system

To determine the reactive power sources to be installed, an overall balance of reactive power has to be known. To determine the appropriate reactive power, balance load flow studies may need to be performed. Apart from the reactive power needs of the converters, consideration should be given to the following:

- 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;
- reactive power available from nearby generators;
- redundancy requirements.

If the rectifier is directly connected to a power station, the following points should also be considered:

- generator capability over the maximum and minimum permissible operating voltage range;
- tap changer range available in the step-up transformer, and the tap to be used for each development stage;
- reactive power requirement of other loads;
- minimum permissible active power for the generators;
- self-excitation limit of the generators;
- minimum number of generators to be connected.

10.6 Reactive power supply

The sources of reactive power supply to meet the set of requirements should include the most economical combination of filters, shunt capacitors, shunt reactors, series capacitors, synchronous and static reactive power compensators that meets the performance criteria. Much of the reactive power should be supplied in the form of filters to meet the harmonic

performance. Under light load conditions, the minimum size of the available filter bank connected ~~may~~ can lead to surplus reactive power and consequently excessive steady-state voltage. This ~~may~~ can require provision of shunt reactors or use of converter capability to consume greater reactive power.

Shunt capacitor banks are the most economical source for the required remaining reactive power. Synchronous and static reactive power compensators should be considered only if there is a dynamic voltage and/or stability problem (see Clause 9). There ~~may~~ can be additional requirements associated with the adjacent AC systems.

10.7 Maximum size of switchable VAR banks

Filters and capacitor banks may be divided into small switchable banks. The size of switchable banks depends on:

- a) voltage control requirements over the whole operating range from no load to full load and overload;
- b) acceptable regulation step per switching operation. It should be noted that the regulating effect from switching reactive power banks can be modulated with the help of converter control;
- c) frequency of switching.

When considering combinations of filters and shunt capacitors with synchronous compensators, the filters and shunt capacitors should be limited in size to avoid self-excitation of the synchronous machines.

11 HVDC transmission line, earth electrode line and earth electrode

11.1 General

Clause 11 identifies those characteristics of the HVDC transmission line, 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 requirements. It does not provide the information that should 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 the earth electrode should be determined in advance.

11.2 Overhead line(s)

11.2.1 General

The total length of the line should be given, including details concerning any overhead and cable sections. Details should 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 is not known, the expected range for this length should be stated.

For bipole and multi-pole lines, information on the spacings between poles and bipoles along the complete route will be needed.

11.2.2 Electrical parameters

The electrical parameters are the following:

- 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.