



BSI Standards Publication

Performance of high-voltage direct current (HVDC) systems with line-commutated converters

Part 1: Steady-state conditions

National foreword

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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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FOREWORD

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

- a) the changes have been made to the description of multi 12-pulse groups per pole, especially for a large scale ultra high-voltage direct current (UHVDC) converter arrangement;
- b) the different arrangements of d.c. smoothing reactors have been included;

c) the figures depicting two 12-pulse groups per pole arrangement have been added.

This publication 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 the base publication and its amendments will remain unchanged until the stability date indicated on the IEC web site under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

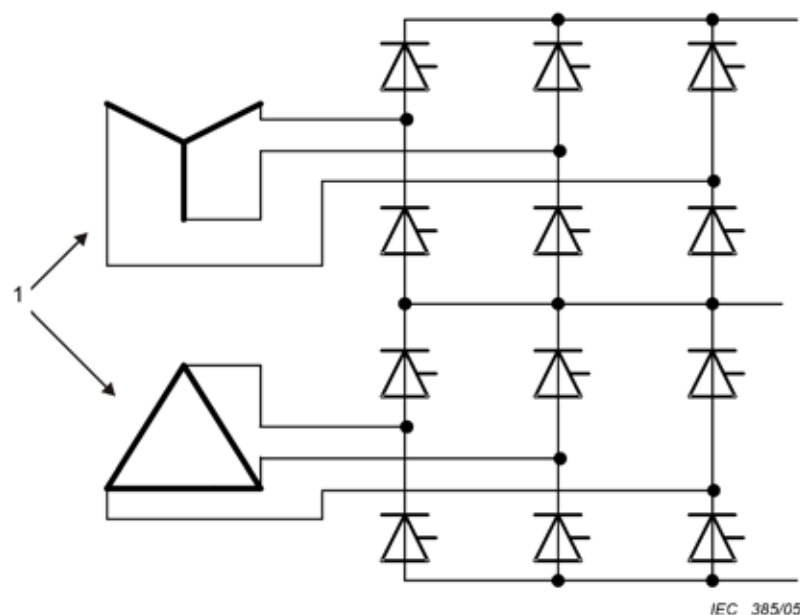
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

Performance of high-voltage direct current (HVDC) systems with line-commutated converters —

Part 1: Steady-state conditions

1 Scope

This part of the 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 report.



Key

1 Transformer valve windings

Figure 1 — Twelve-pulse converter unit

Only line-commutated converters are covered in this report, which includes capacitor commutated converter circuit configurations. General requirements for 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 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 report. Also excluded from this report are detailed seismic

performance requirements. In addition, because there are many variations between different possible HVDC systems, this report does not consider these in detail; consequently, it should 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.

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 given to coordination of each part with the overall HVDC system performance objectives and the interface of each with the system should be clearly defined. Typical of such parts, listed in the appropriate order of relative ease for separate treatment and interface definition, are:

- a) d.c. line, electrode line and earth electrode;
- b) telecommunication system;
- c) converter building, foundations and other civil engineering work;
- d) reactive power supply including a.c. shunt capacitor banks, shunt reactors, synchronous and static reactive power (VAR) compensators;
- e) a.c. switchgear;
- f) d.c. switchgear;
- g) auxiliary systems;
- h) a.c. filters;
- i) d.c. filters;
- j) d.c. 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 be inadvisable.

A complete steady-state performance specification for a 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 10](#)) are included only because of their influence on the HVDC system performance.

For the purpose of this report, 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 a.c. switching substations in this report, a.c. filters and reactive power sources are included, although they may be connected to an a.c. bus separate from the HVDC substation, as discussed in [Clause 16](#).

2 Normative references

The following referenced documents are indispensable for the application 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 convertors — General requirements and line commutated convertors — Part 1-1: Specifications of basic requirements*

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

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

IEC 60633, *Terminology for high-voltage direct current (HVDC) transmission*

3 Types of HVDC systems

3.1 General

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

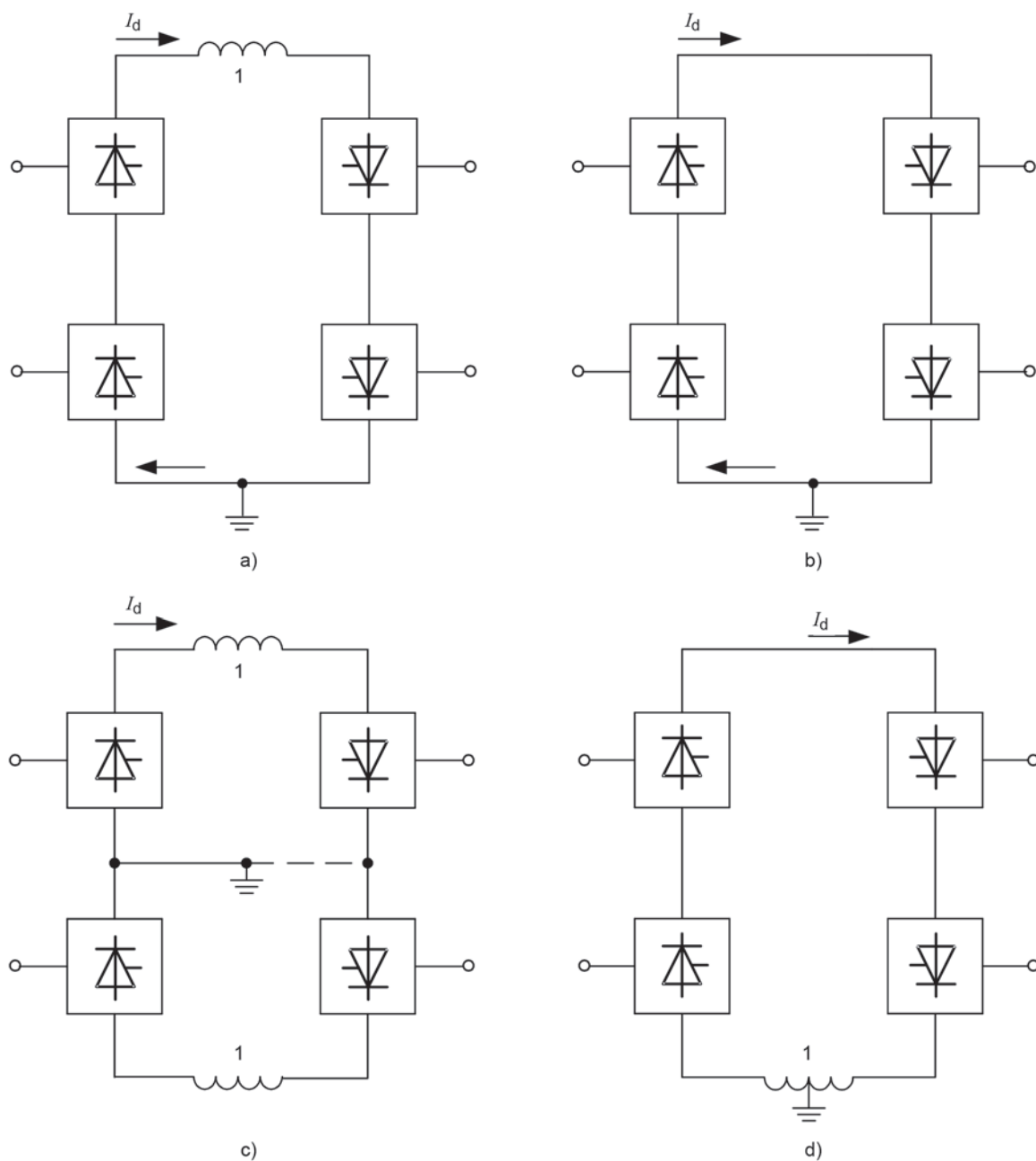
- a) general information on the location of the HVDC substations and the purpose of the project;
- b) type of system needed, including a simple one-line diagram;
- c) number of 12-pulse converter units;
- d) pertinent information derived from the discussion in this section.

Generally, in studies of projects of the types discussed in this report, 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 [3.10](#).

3.2 HVDC back-to-back system

In this arrangement there is no d.c. 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 be evaluated. D.C. filters are not needed.



IEC 386/05

Key

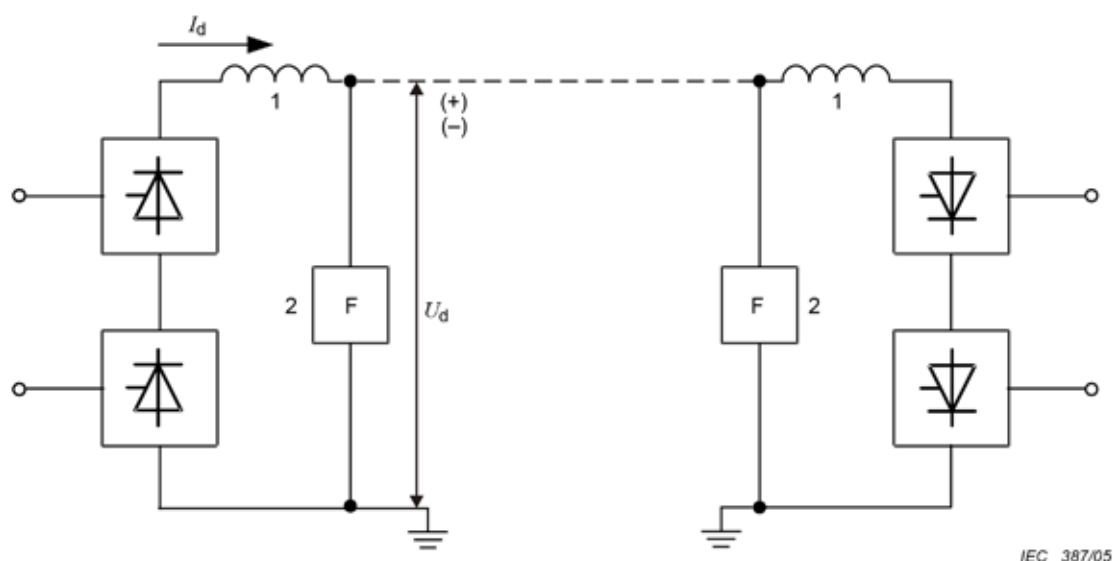
1 DC reactor

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

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 of 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.

3.3 **A₂** Monopolar HVDC system with earth return **A₂**

Cost considerations often lead to the adoption of a **A₂** monopolar HVDC system with earth return **A₂** (Figure 3), particularly for cable transmission which may be expensive.



Key

- 1 DC reactor
- 2 DC filters

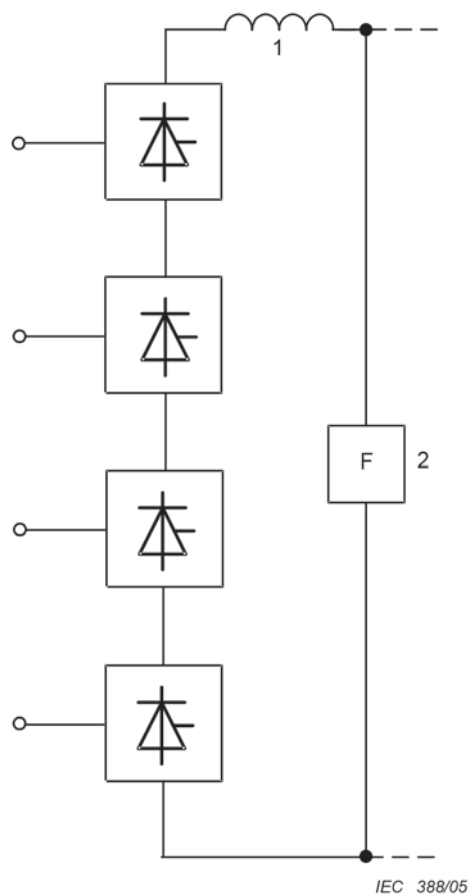
Figure 3 — **A₂ Monopolar HVDC system with earth return **A₂****

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 (Figures 4 and 5). More than one 12-pulse unit might 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 d.c. 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.

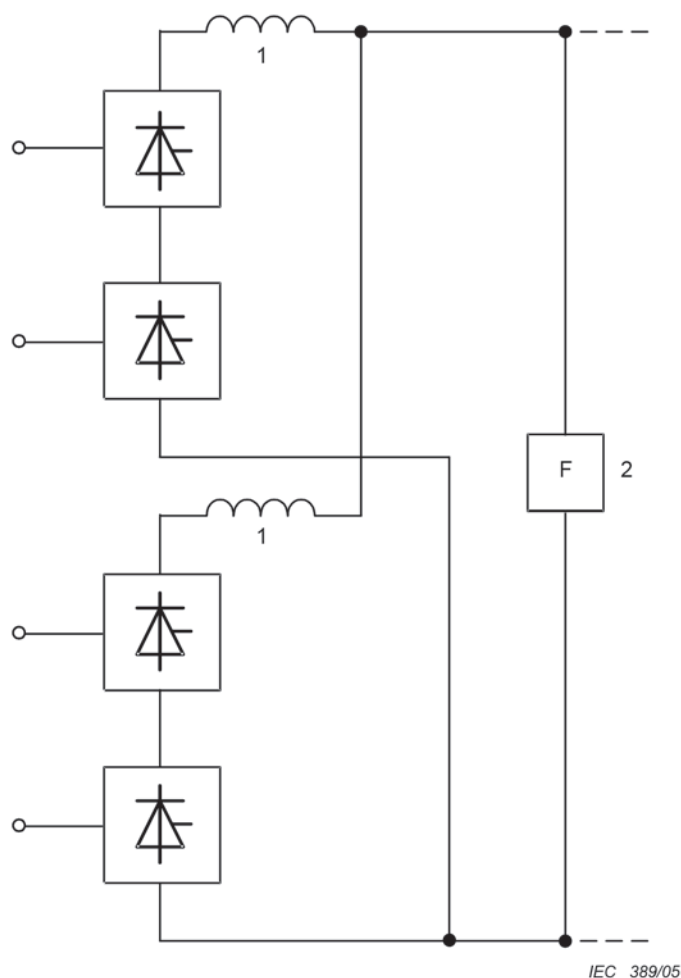
If the line is overhead, d.c. filters are likely to be needed at each end (see Clause 17). It also requires an earth electrode line and a continuously operable earth electrode at the two ends of the transmission which involves consideration of issues such as corrosion, magnetic field effects, etc.



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

3.4 A₂ Monopolar HVDC system with metallic return A₂

The configuration as illustrated in [Figure 6](#) will generally be used for the following purposes:

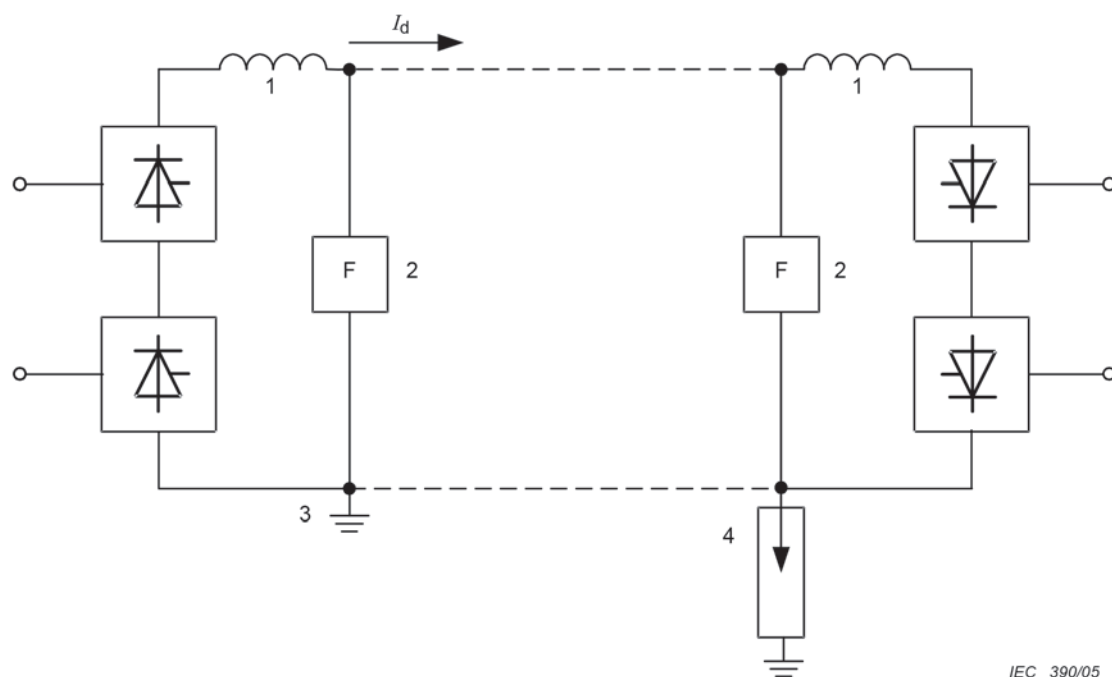
- a) as the first stage in the construction of a bipolar system and if long-term flow of earth current is not desirable during the interim period, or
- b) if the transmission line length is short enough to make it uneconomic and undesirable to build earth electrode lines and earth electrodes, or
- c) 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 d.c. reactor may be located on the earth side if the resulting performance is acceptable. 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.

[A2] For metallic return scheme, DC fault current will flow into 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 converter station will be effective. **[A2]**



Key

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

Figure 6 — **[A2] Monopolar HVDC system with metallic return **[A2]****

3.5 Bipolar earth return HVDC system

This is the most commonly used arrangement when a d.c. transmission line connects two HVDC substations and electrodes for earth return operation are provided (**[A2]** [Figure 7\(a\)](#) **[A2]**). It is effectively equivalent to a double-circuit a.c. transmission. It reduces harmonic interference from the d.c. 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

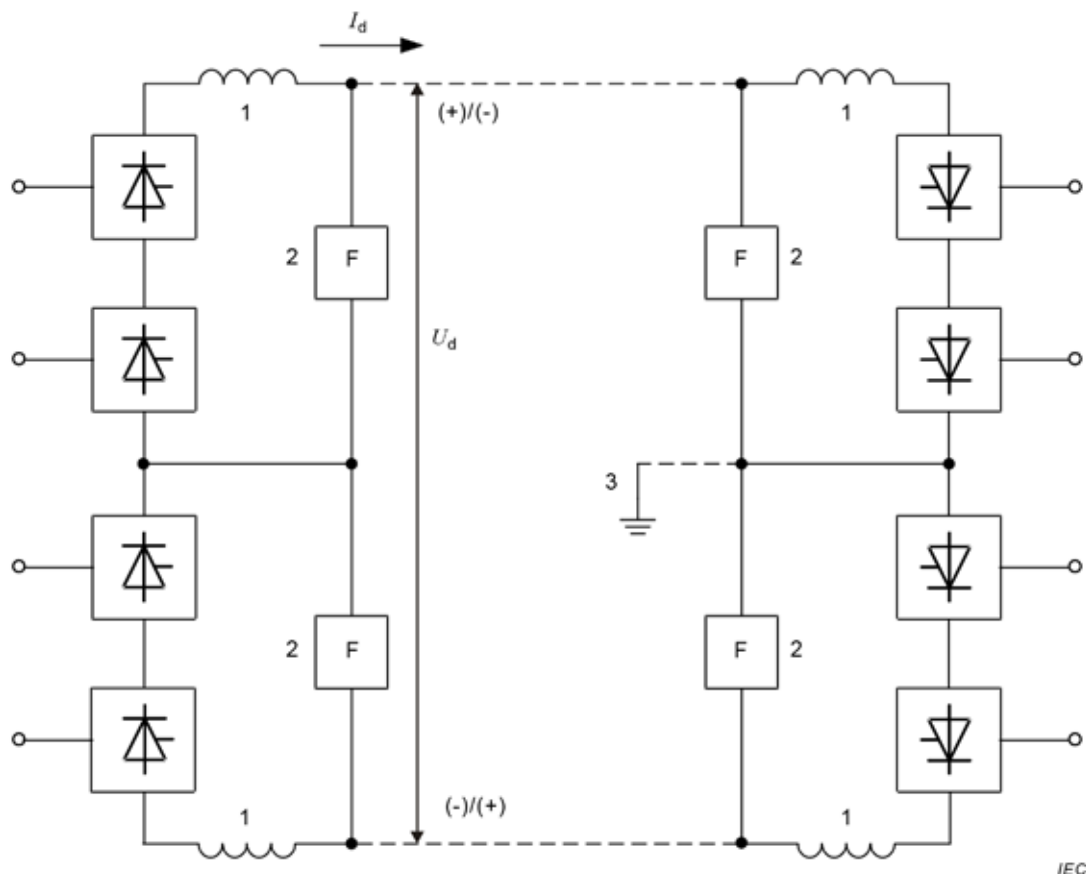


Figure 7(b) — Rigid bipolar HVDC system

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 following requirements should be considered in the specifications.

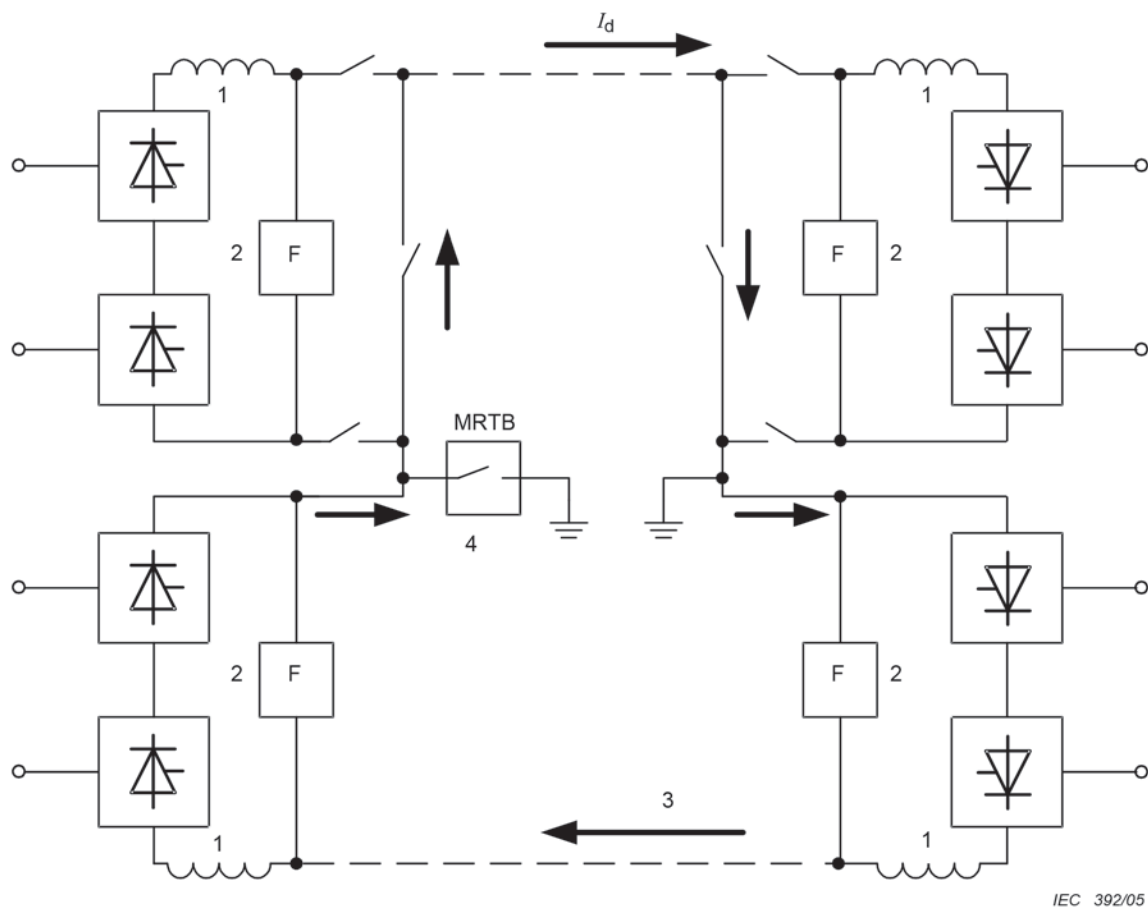
- a) During an outage of one HVDC transmission line pole, the converter equipment of the other pole should be capable of continuous operation with earth return.
- b) If long-term flow of earth current is undesirable and if the defective line pole still retains some low-voltage insulating capability, 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 is first connected in parallel with the earth path and then the earth path is interrupted to transfer the current to the metallic path (through the conductor of the out-of-service pole). Load transfer without interruption requires a metallic return transfer breaker (MRTB) at one terminal of the d.c. 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.
- 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 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 [7.3](#)).
- 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 d.c. 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 d.c. reactors is needed at each end of the system in each pole, 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 HVDC system includes an overhead line, d.c. 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 ([Figures 4](#) and [5](#)).

[A2] Most of the HVDC system utilises electrode line or metallic return conductor (cable) for d.c. current return path. However, as far as the balanced bipolar operation is always assured, 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. **[A2]**



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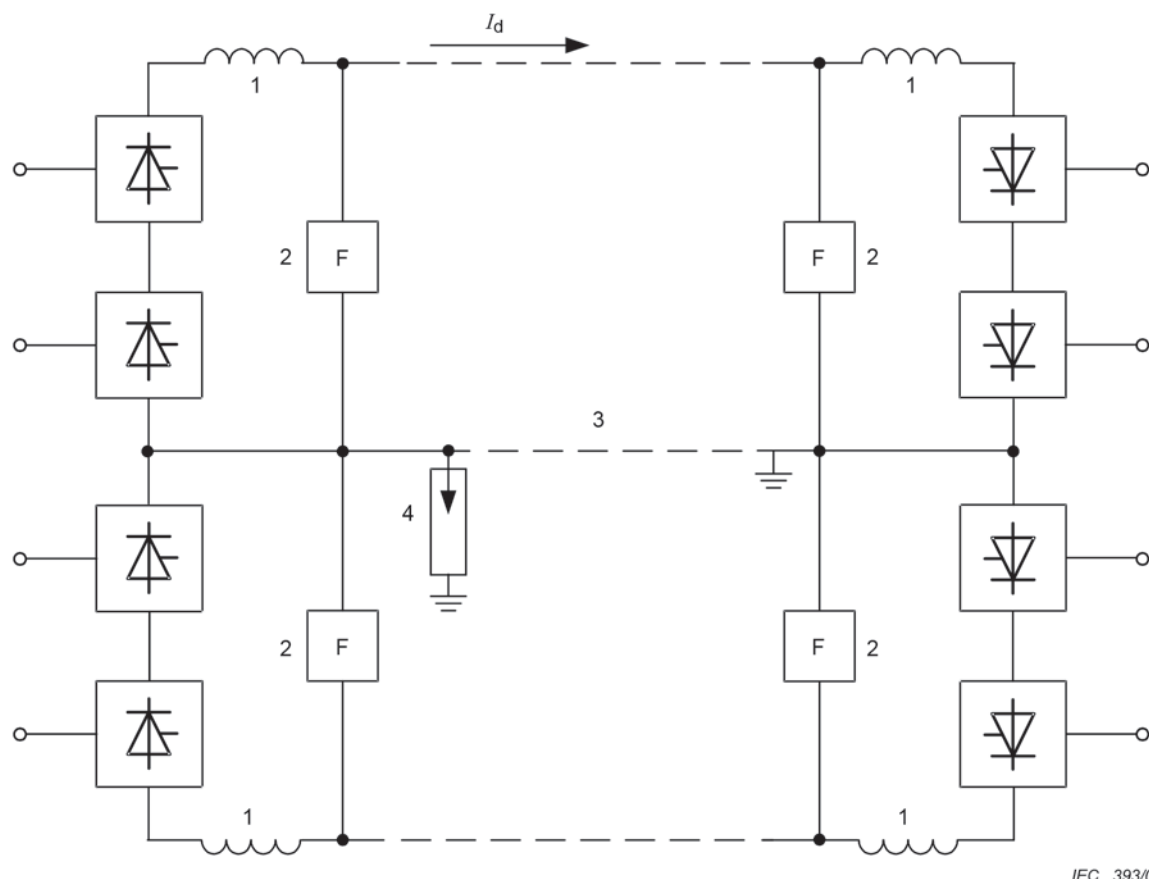
Key

- 1 DC reactor
- 2 DC filter
- 3 Operating pole
- 4 MRTB Metallic return transfer breaker

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

3.6 $\boxed{A_2}$ Bipolar HVDC system with metallic return $\boxed{A_2}$

If earth currents are not tolerable (as mentioned in 3.4, 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 $\boxed{A_2}$ bipolar HVDC system with metallic return $\boxed{A_2}$ (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.



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Key

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

Figure 9 — A_2 Bipolar HVDC system with metallic return A_2

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.

If one substation pole becomes unavailable, the system can be operated in monopolar metallic return mode by utilizing the other substation pole. A_2 This configuration is also called a "dedicated metallic return" (DMR). A_2

A_2 For metallic return scheme, d.c. fault current will flow into a.c. 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, because of saturation due to d.c. current. To prevent such malfunctions, insertion of neutral grounding resistor (small resistance) to transformers in converter station will be effective. A_2

3.7 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 series option [\[A2\]](#) may be preferred [\[A2\]](#).

Basically series/parallel option has no difference regarding loss of power when a forced or scheduled outage of a 12-pulse converter occurs, only 25 % of the capacity will be lost, assuming the same power rating converters are employed. If sufficient overload capability is available, full power or almost full power can be restored. For 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 bypass switch is required for each 12-pulse converter in series connected option. For 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.

The cost of 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 control system will become more complicated.

[\[A2\]](#) For a large bipole capacity, two 12-pulse groups in series per pole may be considered. This means that when a forced or scheduled outage of a 12-pulse converter occurs, only 25 % of the capacity will be lost and the two poles can still operate with a balanced current (without earth current) for two 12-pulse groups in series connection, or operate with an unbalanced current (with earth /metallic return current) for two 12-pulse groups in parallel connection. If sufficient overload capability is available, full power or almost full power can be restored. The other advantages of this configuration are that two 12-pulse scheme can provide soft start and stop sequence and flexible utilization of the HVDC system with various combinations of converter groups.

DC switches will be necessary to bypass and remove any 12-pulse group from operation. The cost of such an arrangement, compared to one 12-pulse group per pole for the same total rating, would be expected to be higher. [\[A2\]](#)

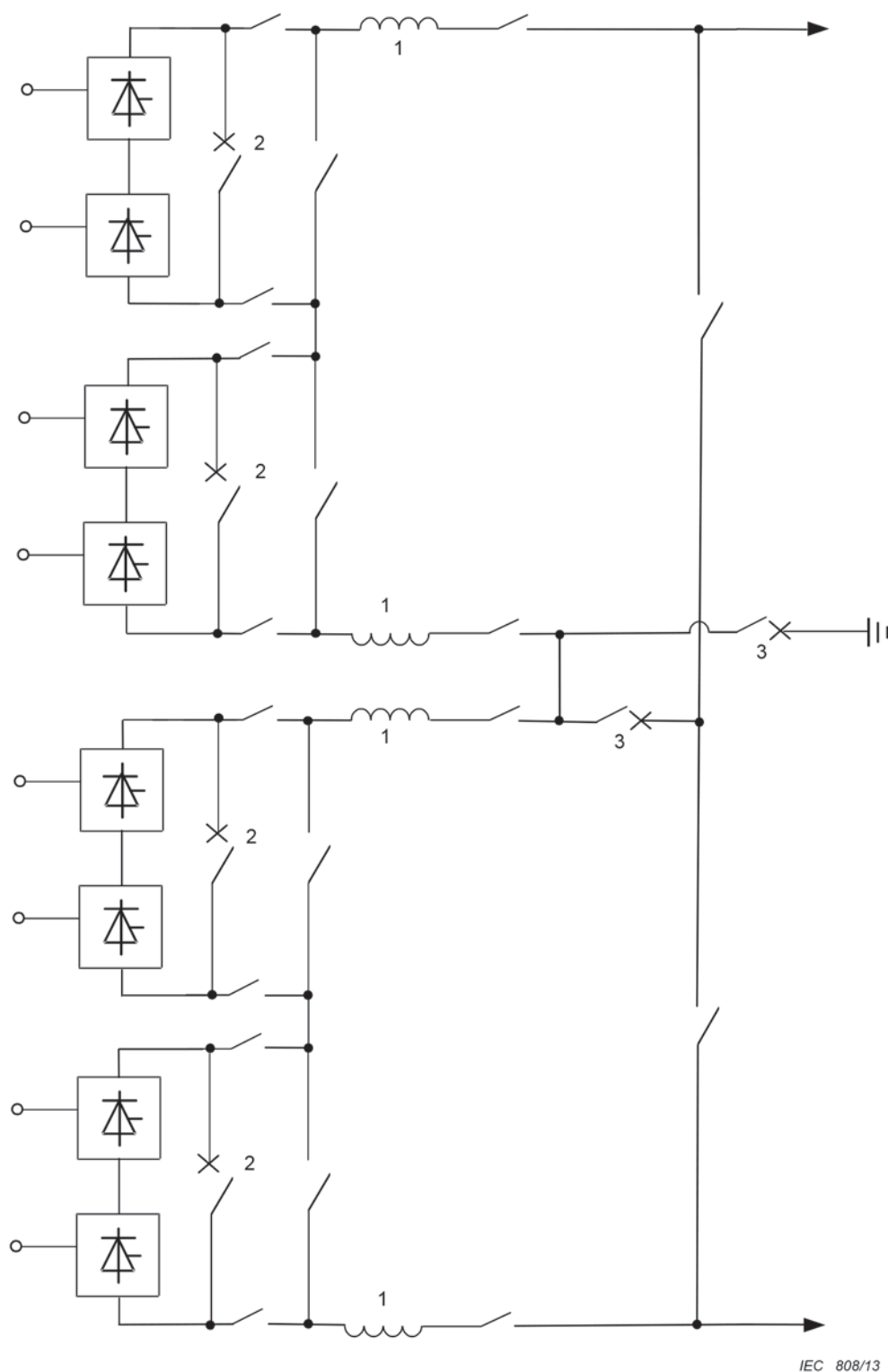
3.8 Converter transformer arrangements

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

- 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 a.c. and d.c. harmonic conditions would be acceptable. Six-pulse operation is not possible with alternatives a) and c).

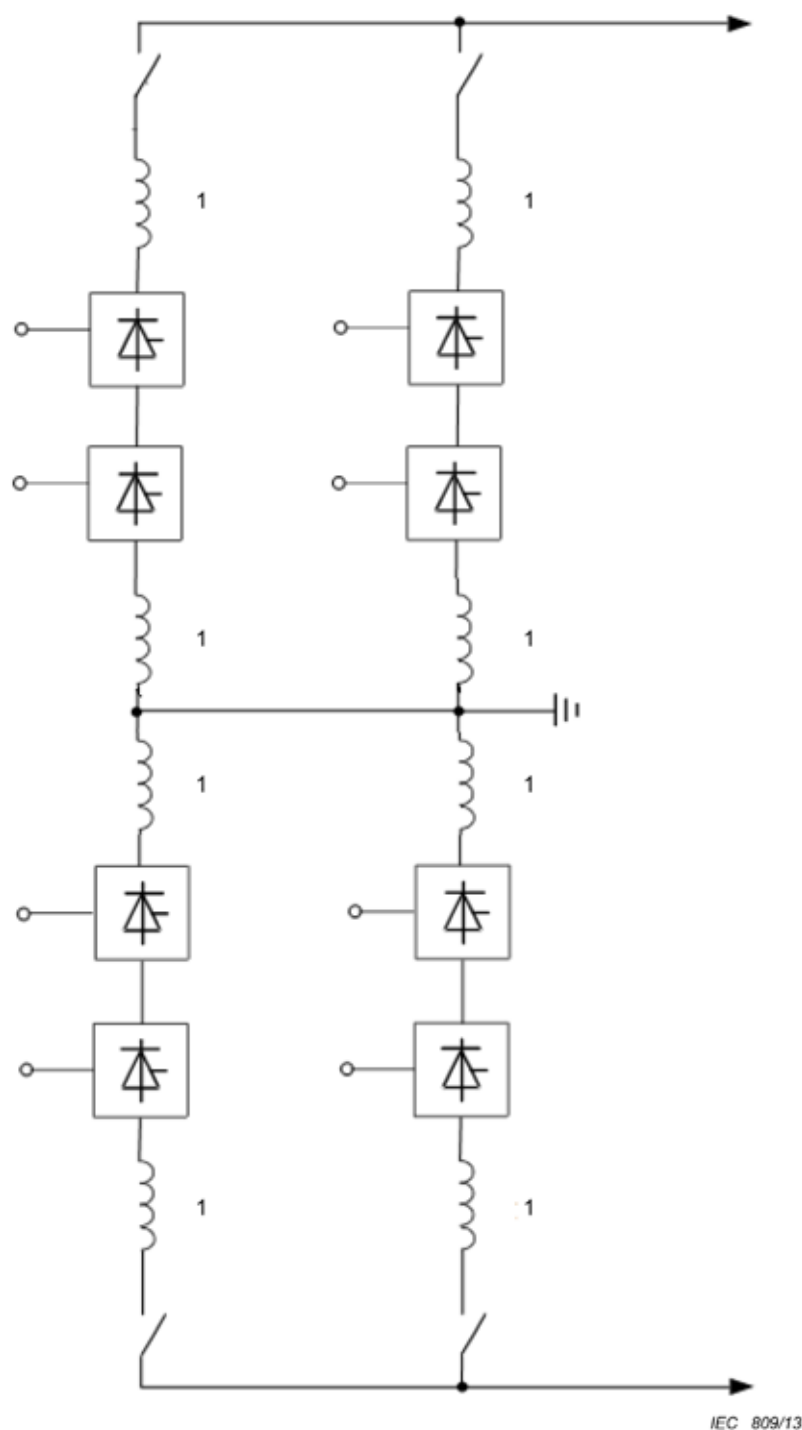


Key

- 1 DC reactor
- 2 By-pass switch
- 3 DC switch

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

^[A2] Figure 10, with d.c. switch 3 (named as: MRTB and GRTS), is usually valid for rectifier station. The d.c. switch 3 is not necessary for the inverter station. ^[A2]



Key

1 DC reactor

^[A1] **Figure 11 — Bipolar system with two 12-pulse units in parallel per pole** ^[A1]

^[A2] It is not always needed to split the d.c. reactors, especially for parallel connection. The number and arrangement of d.c. reactors depend on the results of system studies and design. ^[A2]

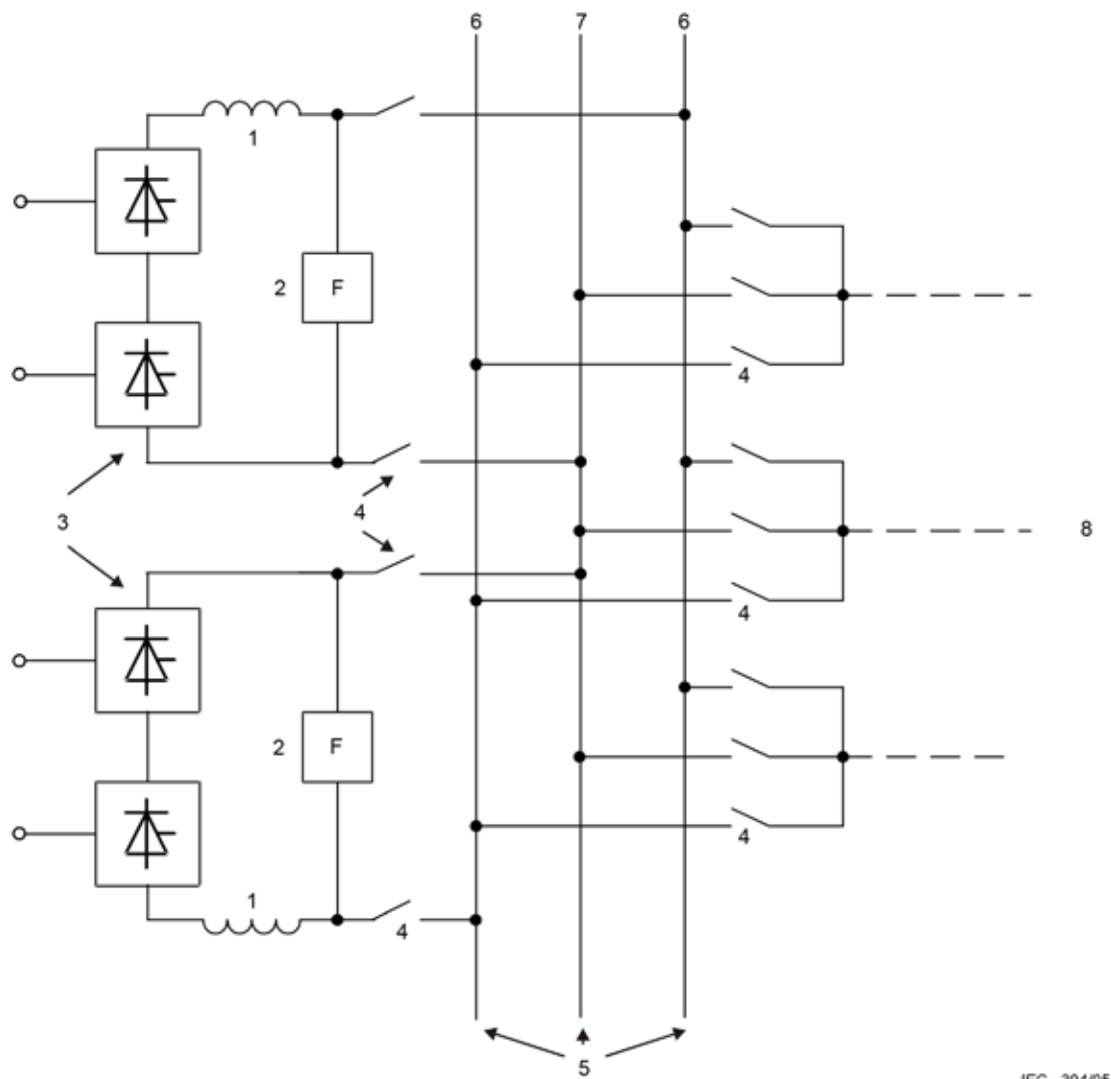
Converter transformers with a tertiary winding for reactive power and a.c. harmonic filter equipment may also be used.

3.9 DC switching considerations

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

Monopolar metallic return operation of a bipolar system is discussed in 3.5.

For bipolar systems, d.c. 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, d.c. 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.



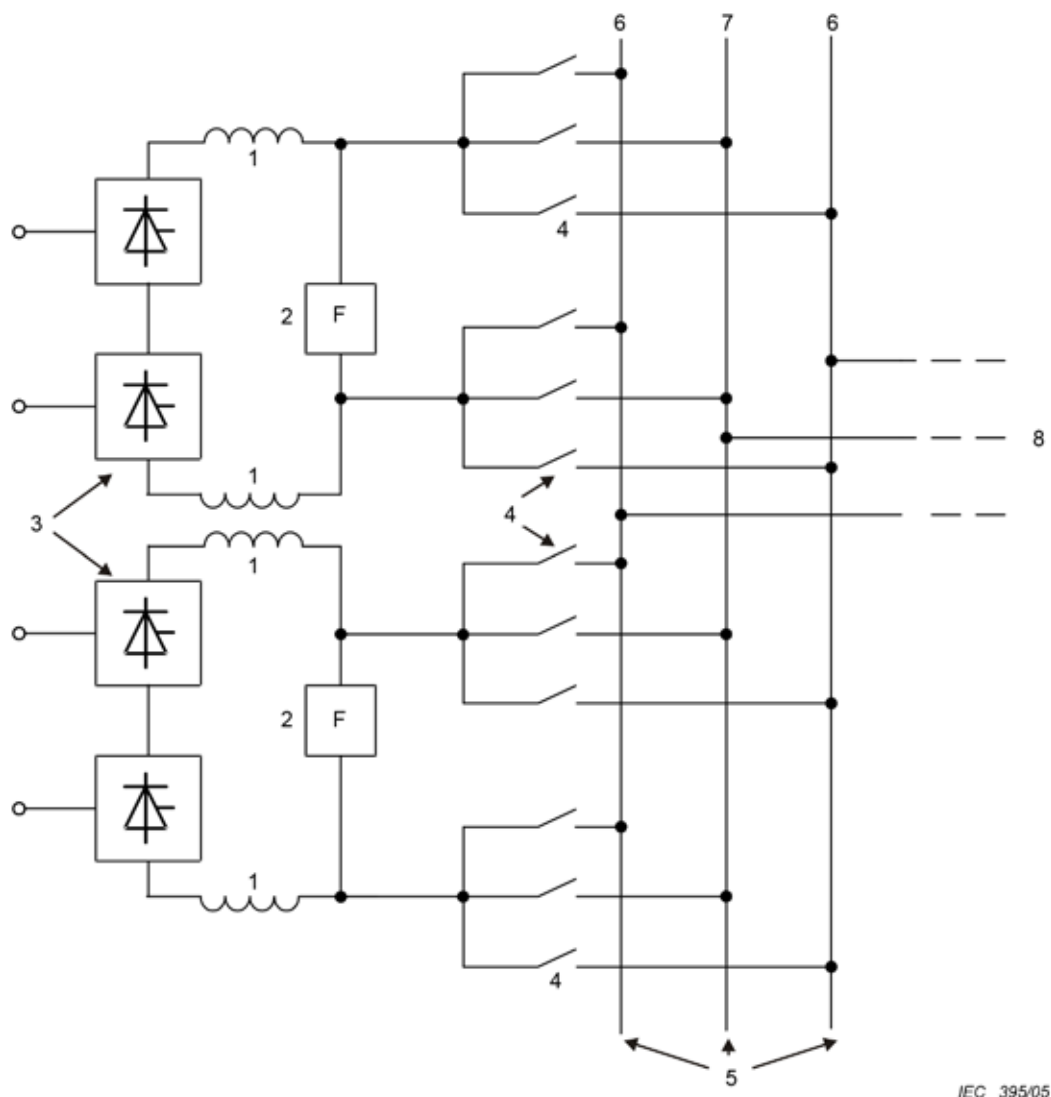
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Key

- | | |
|-----------------------|-----------------|
| 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](#).

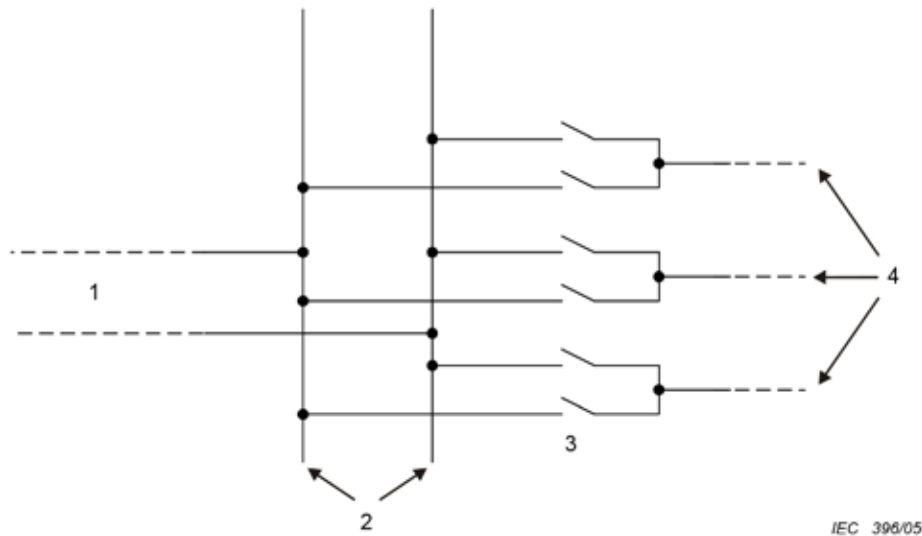


Key

- | | |
|-----------------------|-----------------|
| 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 a HVDC transmission system includes both overhead line and cable sections, a d.c. 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.

3.10 Series capacitor compensated HVDC systems

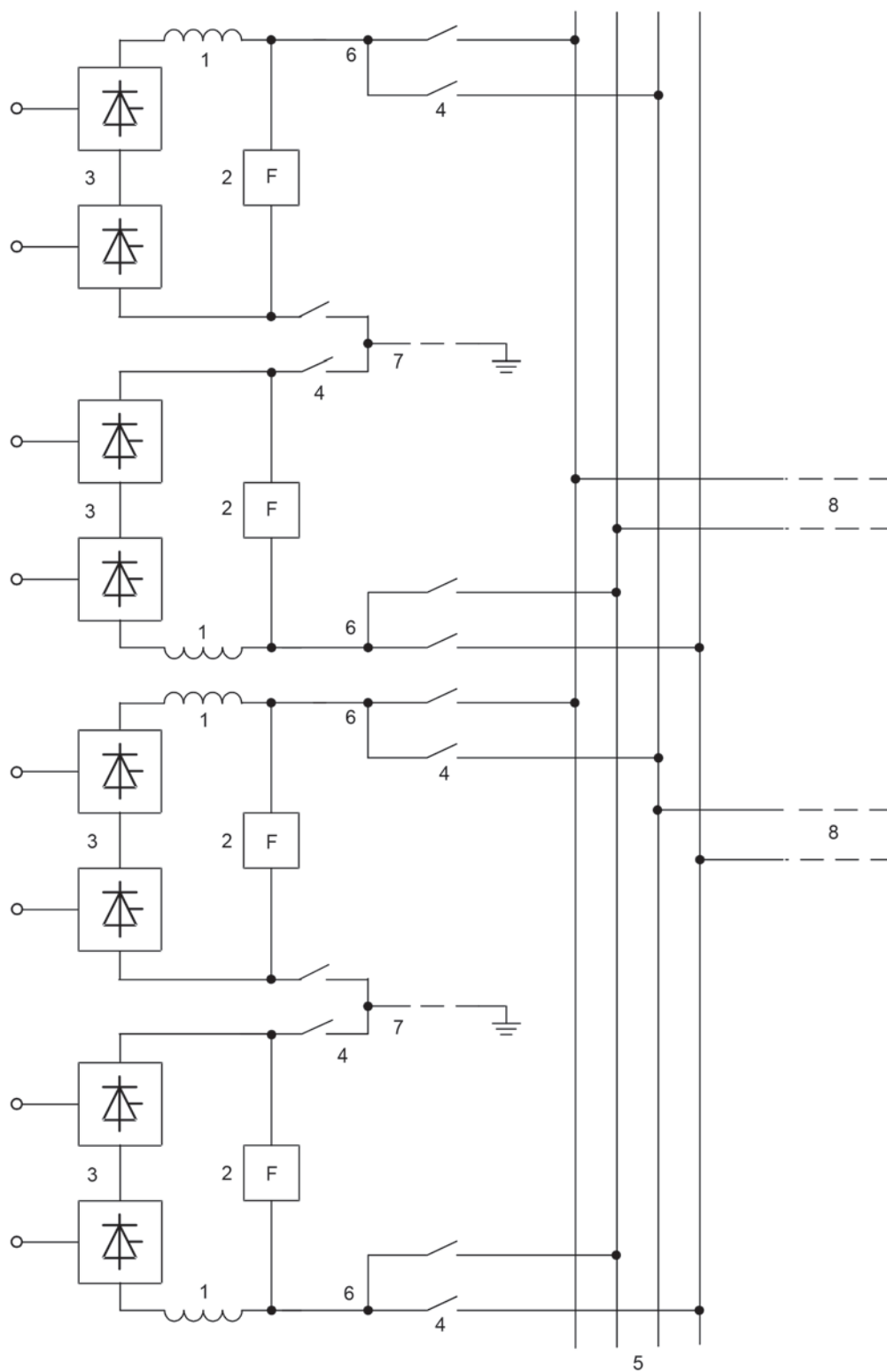
Although the conventional line-commutated converter technology has reached maturity, such converters still have two weaknesses:

- a) a large amount of reactive power consumption, roughly 50 % of its active power;
- b) susceptibility to a.c. 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 a.c. filter bus and the a.c. network. Occurrence of ferro-resonance with the CSCC option is eliminated by controlling the amount of series compensation.



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Key

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

Figure 15 — DC switching - Two-bipolar converters and lines