



BSI Standards Publication

High-voltage direct current (HVDC) power transmission using voltage sourced converters (VSC)

National foreword

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TECHNICAL REPORT



High-voltage direct current (HVDC) power transmission using voltage sourced converters (VSC)

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FOREWORD

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IEC/TR 62543, 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.

The present technical report cancels and replaces [IEC/PAS 62543:2008](#) (Ed.1) which was published by IEC and CIGRÉ jointly, and combined with engineering experience.

The present IEC/TR 62543 bears the edition number 1.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
22F/230/DTR	22F/239A/RVC

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

The committee has decided that the contents of this publication 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- withdrawn,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.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

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

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1 Scope

This technical report gives general guidance on the subject of voltage-sourced converters used for transmission of power by high voltage direct current (HVDC). It describes converters that are not only voltage-sourced (containing a capacitive energy storage medium and where the polarity of d.c. voltage remains fixed) but also self-commutated, using semiconductor devices which can both be turned on and turned off by control action. ^[A1] The scope includes 2-level and 3-level converters with pulse-width modulation (PWM), along with multi-level converters, modular multi-level converters and cascaded two-level converters, but excludes 2-level and 3-level converters operated without PWM, in square-wave output mode. ^[A1]

HVDC power transmission using voltage sourced converters is known as “VSC transmission”.

The various types of circuit that can be used for VSC transmission are described in the report, along with their principal operational characteristics and typical applications. The overall aim is to provide a guide for purchasers to assist with the task of specifying a VSC transmission scheme.

Line-commutated and current-sourced converters are specifically excluded from this report.

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.

^[A2] *Text deleted* ^[A2]

[IEC 61975](#), *High-voltage direct current (HVDC) installations — System tests*

^[A2] [IEC 62501](#), *Voltage sourced converter (VSC) valves for high-voltage direct current (HVDC) power transmission — Electrical testing*

[IEC 62747](#), *Terminology for voltage-sourced converters (VSC) for high-voltage direct current (HVDC) systems*

IEC 62751 (all parts), *Power losses in voltage sourced converter (VSC) valves for high voltage direct current (HVDC) systems* ^[A2]

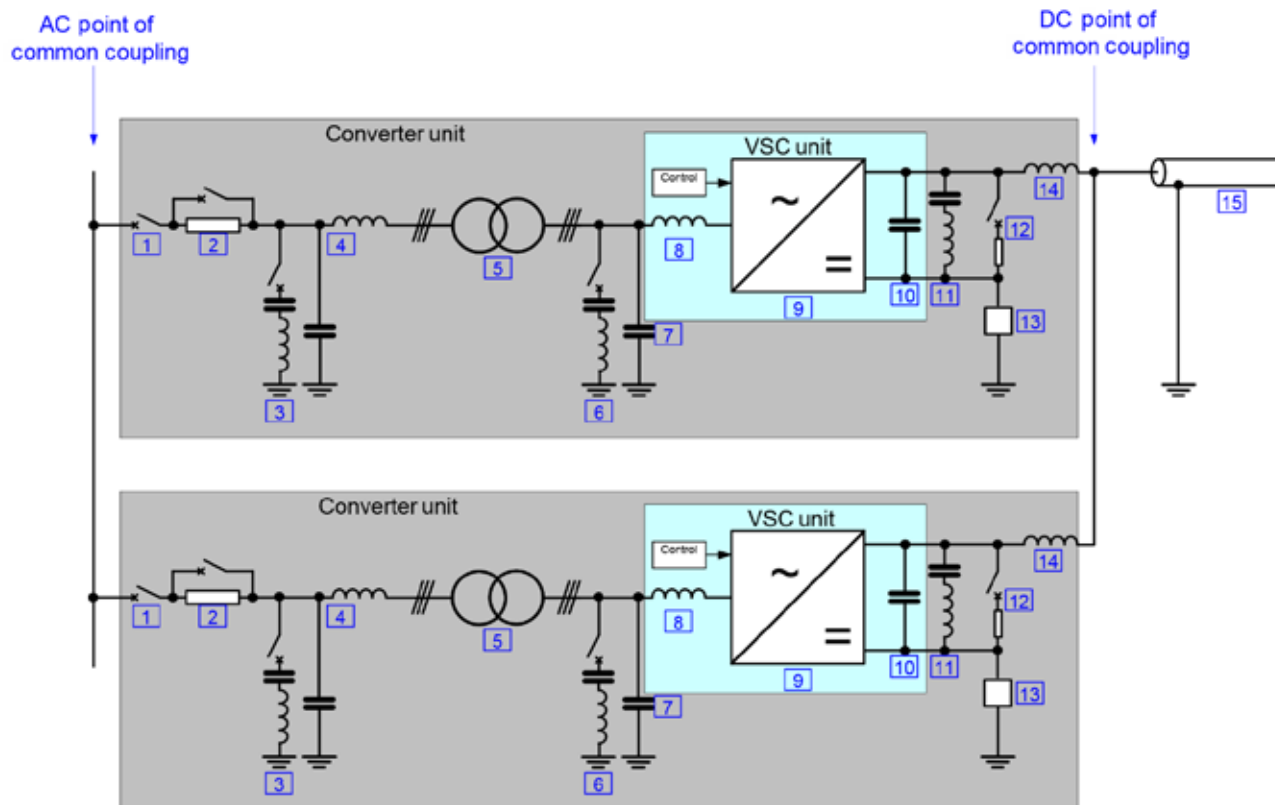
3 Terms and definitions

^[A2] For the purposes of this document, the terms and definitions given in [IEC 62747](#), [IEC 62501](#) and the following apply. ^[A2]

3.1 General

^[A2] Basic terms and definitions for voltage sourced converters used for HVDC transmission are given in [IEC 62747](#). Terminology on electrical testing of VSC valves for HVDC transmission is given in [IEC 62501](#).

To support the explanations, [Figure 1](#) presents the basic diagram of a VSC system. Dependent on the converter topology and the requirements in the project, some components can be omitted or can differ.



IEC

- | | | | |
|-------|--|----|--|
| 1 | circuit breaker | 9 | VSC unit ³⁾ |
| 2 | pre-Insertion Resistor | 10 | VSC d.c. capacitor ⁴⁾ |
| 3 | line side harmonic filter ¹⁾ | 11 | d.c. harmonic filter ¹⁾ |
| 4 | line side high frequency filter ⁶⁾ | 12 | dynamic braking system ⁷⁾ |
| 5 | interface transformer | 13 | neutral point grounding branch ⁵⁾ |
| 6 | converter side harmonic filter ¹⁾ | 14 | d.c. reactor ⁸⁾ |
| 7 + 8 | converter side high frequency filter ²⁾ | 15 | d.c. cable or overhead transmission line |
| 8 | phase reactor ²⁾ | | |

¹⁾ In some designs of VSC based on "controllable voltage source" valves, the harmonic filters may not be required.

²⁾ In some designs of VSC, the phase reactor may fulfill part of the function of the converter-side high frequency filter.

³⁾ In some VSC topologies, each valve of the VSC unit may include a "valve reactor", which may be built into the valve or provided as a separate component.

⁴⁾ In some designs of VSC, the VSC d.c. capacitor may be partly or entirely distributed amongst the three phase units of the VSC Unit, where it is referred to as the d.c. submodule capacitors.

⁵⁾ The philosophy and location of the neutral point grounding branch may be different depending on the design of the VSC unit.

⁶⁾ In some designs of VSC, the interface transformer may fulfill part of the function of the line-side high frequency filter.

⁷⁾ Optional.

⁸⁾ Optional, if phase reactors are located on the d.c. side of the converter. $\overline{A_2}$

Figure 1 — Major components that may be found in a VSC substation

3.2 Letter symbols

U_{conv} line-to-line a.c. voltage of the converter unit(s), r.m.s. value, including harmonics;

I_{conv}	alternating current of the converter unit(s), r.m.s. value, including harmonics;
U_L	line-to-line a.c. voltage of the a.c. system, r.m.s. value, including harmonics;
I_L	alternating current of the a.c. system, r.m.s. value, including harmonics;
U_d	d.c. line-to-line voltage of the d.c. bus of the VSC transmission system;
I_d	d.c. current of the d.c. bus of the VSC transmission system.

A2 Text deleted **A2**

3.5 VSC transmission

A2 Text deleted **A2**

3.5.4

VSC d.c. capacitor

capacitor bank (s) (if any) connected between two d.c. terminals of the VSC, used as energy storage and / or filtering purposes

A2 Text deleted **A2**

3.5.6

a.c. side radio frequency interference filter (RFI filter)

filters (if any) used to reduce penetration of radio frequency interference (RFI) into the a.c. system to an acceptable level

A2 Text deleted **A2**

3.5.8

valve side harmonic filter

filters (if any) used to mitigate the HF stresses of the interface transformer

A2 Text deleted **A2**

3.5.10

d.c. harmonic filter

A1 d.c. filters (if any) used to prevent harmonics generated by VSC valve from penetrating into the d.c. system.

NOTE The filter can consist of a tuned shunt branch, smoothing reactor or common mode blocking reactor or combinations thereof. **A1**

3.5.11

d.c. reactor

A1 a reactor (if any) connected in series to a d.c. busbar

NOTE DC reactor is used to reduce harmonic currents flowing in the d.c. line or cable and to detune critical resonances within the d.c. circuit. A d.c. reactor might also be used for protection purposes. **A1**

3.5.12

d.c. side radio frequency interference filter

filters (if any) used to reduce penetration of radio frequency (RF) into the d.c. system to acceptable limits

A2 Text deleted **A2**

3.7 Type tests

Those tests which are carried out to verify that the components of VSC transmission system design will meet the requirements specified. In this report, type tests are classified under two major categories: dielectric tests and operational tests.

3.7.1

dielectric tests

those tests which are carried out to verify the high voltage withstanding capability of the components of VSC transmission system

3.7.2

operational tests

those tests which are carried out to verify the turn-on (if applicable), turn-off (if applicable), and current related capabilities of the components of VSC transmission system

3.8 Production tests

Those tests which are carried out to verify proper manufacture, so that the properties of the certain component of VSC transmission system correspond to those specified

3.9 Sample tests

Those production tests which are carried out on a small number of certain VSC transmission components, e.g. valve sections or special components taken at random from a batch

[A₂] *Text deleted* **[A₂]**

3.11 Power losses

3.11.1

auxiliary losses

[A₁] electric power required to feed the VSC substation auxiliary loads

NOTE The auxiliary losses depend on whether the substation is in no-load or carrying load, in which case the auxiliary losses depend on the load level. **[A₁]**

3.11.2

[A₁] no-load operating losses **[A₁]**

the losses produced in an item of equipment with the VSC substation energized but with the VSCs blocked and all substation service loads and auxiliary equipment connected as required for immediate pick-up of load

3.11.3

[A₁] idling operating losses

losses produced in an item of equipment with the VSC substation energized and with the VSCs de-blocked but with no real or reactive power output **[A₁]**

3.11.4

operating losses

the losses produced in an item of equipment at a given load level with the VSC substation energized and the converters operating

3.11.5

total system losses

the total system loss is the sum of all operating losses, including the corresponding auxiliary losses

3.11.6

station essential auxiliary load

the loads whose failure will affect the conversion capability of the HVDC converter station (e.g. valve cooling), as well as the loads that shall remain working in case of complete loss of a.c. power supply (e.g. battery chargers, operating mechanisms)

NOTE Total “operating losses” minus “no load operating losses” may be considered as being quantitatively equivalent to “load losses” as in conventional a.c. substation practice.

4 VSC transmission overview

4.1 Basic operating principles of VSC transmission

4.1.1 The voltage sourced converter as a black box

The operation of a voltage sourced converter is described in greater detail in [Clause 5](#). In this clause the converter is treated as a black box that can convert from a.c. to d.c. and vice versa, and only steady-state operation is considered.

[Figure 2](#) depicts a schematic diagram of a generic voltage sourced converter connected to a d.c. circuit on one side and to an a.c. circuit on the other.

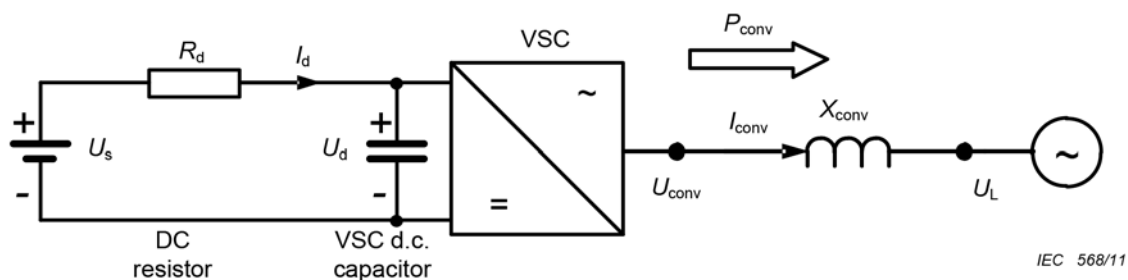


Figure 2 — Diagram of a generic voltage source converter (a.c. filters not shown)

The VSC can be operated as either an inverter, injecting real power into the a.c. network ($I_d \times U_d > 0$), or as a rectifier absorbing power from the a.c. network ($I_d \times U_d < 0$). Similarly, the VSC can be operated either capacitively, injecting reactive power into the a.c. network ($\text{Im}(U_L \cdot I_L) > 0$), or inductively, absorbing reactive power from the a.c. network ($\text{Im}(U_L \cdot I_L) < 0$). The VSC can be operated capacitively or inductively in both the inverter and the rectifier mode.

The designation voltage sourced converter is used because the function of the VSC is predicated on the connection of a voltage source on the d.c. side.

To the left in [Figure 2](#), a d.c. voltage source U_s is shown with a d.c. resistor R_d representing the d.c. circuit resistance, and a d.c. capacitor connected. The d.c. shunt capacitor serves the purpose of stabilising the d.c. voltage U_d . Depending on the VSC converter topology, the d.c. storage capacitor is realised either as a central d.c. storage capacitor between both poles or as multiple storage capacitors distributed within the converter phase units. The conversion from d.c. to a.c. takes place in the VSC as explained in [Clause 5](#).

On the a.c. side, an interface inductance is provided which serves two purposes: first, it stabilises the a.c. current, and secondly, it enables the control of active and reactive output power from the VSC, as explained in [Subclause 4.1.2](#). The interface inductance can be implemented as reactors, as leakage inductances in transformers, or as a combination thereof. The d.c. capacitor on the input side and the a.c. interface inductance on the output side are important components for the proper functioning of a VSC.

A passive or active a.c. network can be connected on the a.c. side of the VSC. If the VSC is connected to a passive network on its a.c. side, the power flow can be only from the d.c. input side towards the passive

load on the a.c. side. However, if the a.c. side is connected to an active a.c. network, the power flow can be in both directions by controlling the a.c. voltage output U_{conv} of the VSC.

By controlling the phase angle of U_{conv} , the active power through the VSC can be controlled as explained in [Subclause 4.1.2.2](#). By controlling the voltage amplitude of U_{conv} , the reactive power through the VSC can be controlled, as explained in [Subclause 4.1.2.3](#).

4.1.2 The principles of active and reactive power control

4.1.2.1 General

The VSC can be considered as an equivalent of a synchronous generator without inertia, which has the capability of individually controlling active and reactive power.

The exchange of active and reactive power between a VSC and the a.c. grid is controlled by the phase angle and amplitude of the VSC output voltage in relation to the voltage of the a.c. grid.

A2 The active and reactive power can be controlled simultaneously and independently of each other. The active and reactive power are related to the AC voltages U_L and U_{conv} of the AC system and converter respectively, the reactance X between these voltages and the phase angle δ between them, according to the following:

$$P = \frac{U_L \times U_{\text{conv}} \times \sin \delta}{X}$$

$$Q = \frac{U_L \times (U_L - U_{\text{conv}} \times \cos \delta)}{X}$$

A2

If U_{conv} is in phase with the line voltage U_L and its amplitude is equal to U_L , there is no a.c. current I_{conv} from the VSC. Under these conditions, the d.c. current I_d becomes zero and the d.c. capacitor voltage U_d becomes equal to the d.c. source voltage U_s .

4.1.2.2 The principle of active power control

The principle of active power control is depicted in [Figure 3](#), where the active power through the interface inductance is controlled by regulating the VSC voltage angle.

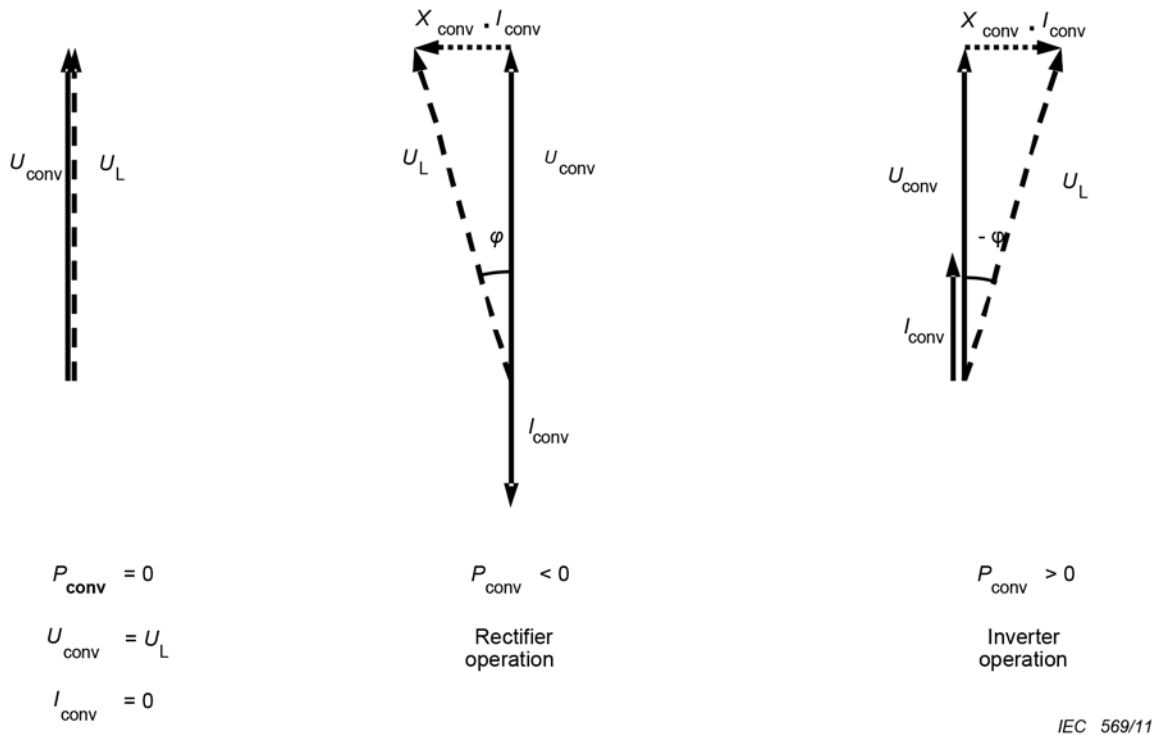


Figure 3 — The principle of active power control

If the angle of the VSC output voltage leads the a.c. grid voltage, the VSC will inject active power to the a.c. grid, i.e., it operates as an inverter. On the d.c. side, an equivalent current will be drawn from the d.c. source and the voltage U_d will decrease in accordance with Ohm's law ($U_d = U_s - R_d \cdot I_d$).

If, on the other hand, the VSC output voltage lags the voltage of the a.c. grid, the VSC will absorb active power from the a.c. grid, i.e., it operates as a rectifier. On the d.c. side, an equivalent current will be injected into the d.c. source and the voltage U_d will increase in accordance with Ohm's law ($U_d = U_s + R_d \cdot I_d$).

If the VSC is connected to a passive load, an a.c. output current will be drawn from the VSC determined by Ohm's law $I_{conv} = U_{conv}/Z$. Again, an equivalent d.c. current will be drawn from the source and the voltage U_d on the d.c. capacitor will drop to a value determined by Ohm's law. No active power can be drawn from the a.c. side, because it is a passive a.c. circuit.

4.1.2.3 The principle of reactive power control

The principle of reactive power control is depicted in [Figure 4](#), where the reactive power through the interface inductance is controlled by regulating the amplitude of the VSC output a.c. voltage.

If the amplitude of the VSC output voltage U_{conv} is higher than the a.c. grid voltage U_L , the VSC will inject reactive power in the a.c. grid, i.e., will operate in the capacitive mode. If the amplitude of the VSC output voltage is lower than the a.c. grid voltage, the VSC absorbs reactive power from the a.c. grid, i.e., the inductive operating mode.

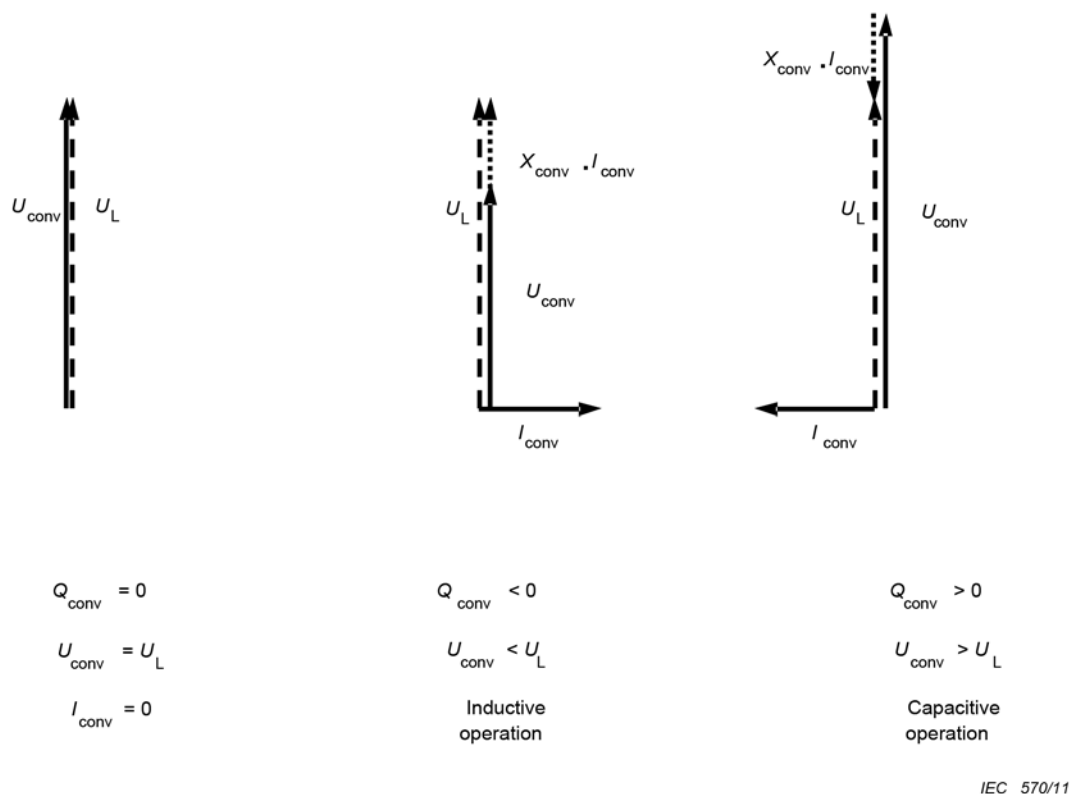


Figure 4 — The principle of reactive power control

4.1.3 Operating principles of a VSC transmission scheme

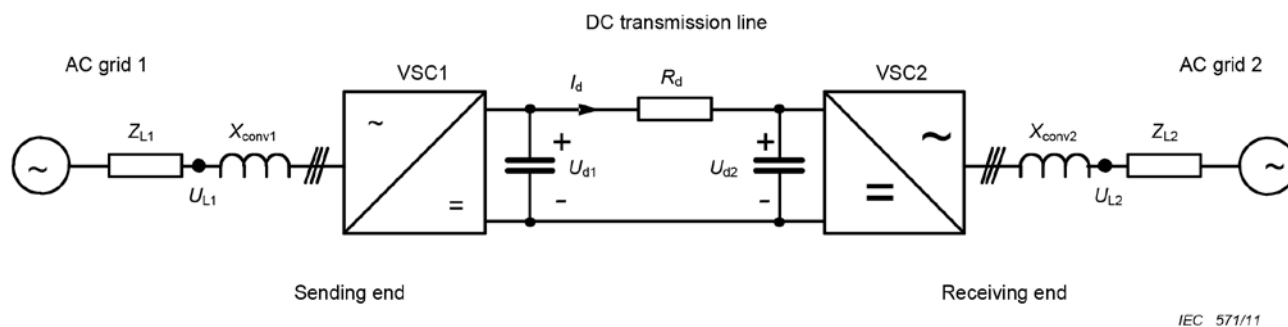


Figure 5 — A point-to-point VSC transmission scheme

The point-to-point VSC transmission scheme shown in [Figure 5](#) consists of two VSCs interconnected on the d.c. side via a d.c. transmission line and connected to two different a.c. grids on the a.c. side. The basic characteristics of a VSC have been described in the previous clauses. One of these characteristics is that the d.c. voltage polarity is always the same (in contrast with LCC HVDC, where the polarity of d.c. voltage depends on the direction of power transfer). Therefore, the direction of the power flow on the d.c. line is determined by the direction of the d.c. current. In [Figure 5](#) the current flow and the power flow are from VSC1 (the sending or rectifier end) to VSC2 (the receiving or inverter end) of the d.c. line.

The direction of a d.c. current is always from a higher d.c. voltage level to a lower d.c. voltage level. The d.c. voltage at the sending end of the d.c. line shall therefore be higher than the d.c. voltage at the receiving end. The value of the current is determined by Ohm's law, as the voltage difference between sending and receiving ends divided by the resistance in the d.c. line $I_d = (U_{d1} - U_{d2}) / R_d$.

^{A2} For example, ^{A2} the d.c. line power flow can be controlled by holding the d.c. voltage at the receiving end converter (the inverter) at a constant value, and by letting the sending end converter (the rectifier) control the d.c. current.

4.1.4 Applications of VSC transmission

In general the main fields of application of HVDC transmission are interconnection of asynchronous a.c. systems and long distance transmission via overhead lines and cables. The following characteristic features of VSC transmission are decisive for different applications.

- The smaller amount of external equipment such as a.c. harmonic filters results in a compact design of VSC converter stations. Small footprints are beneficial for applications with spatial limitations such as installations in city centres or on remote offshore platforms.
- Since VSC transmission is based on self-commutating operation, applications with isolated and weak a.c. systems are feasible. During normal operation the VSC provides voltage and frequency control of the a.c. system. Operation during a.c. faults is a major criterion for VSC. The ability of the VSC to inject fault currents facilitates a.c. system protection and fault clearing. Examples are connection of remote wind farms, oil and gas platforms and remote mines.
- ^{A2} In most cases, ^{A2} VSC transmission operates with a fixed d.c. voltage polarity. A reversal of direction of power flow requires the reversal of d.c. current. In case of parallel interconnection of a.c. systems via a.c. and d.c. lines, fast power reversals via d.c. current control provide an accurate measure for load flow stabilisation between the a.c. systems. Since the polarity of d.c. voltage does not reverse, multi-terminal systems are easier to realise with VSC than with LCC HVDC.

4.2 Design life

The selection of VSC transmission as an alternative to LCC HVDC, a.c. transmission, or local generation is normally motivated by financial, technical or environmental advantages. When evaluating different technologies, it is important to compare their life cycle costs.

The technical design life of transmission systems is normally very long—30 years or more. An investment, however, should only last as long as it can provide the highest capital value, and this is designated the “optimal life”. The optimal life will always be equal to or less than the technical design life.

4.3 VSC transmission configurations

4.3.1 General

With VSC transmission there are several possibilities for the d.c. circuit and converter units.

Each VSC substation may be constructed from a single converter unit of a phase unit topology resulting in a monopolar transmission scheme.

In some applications it may be necessary or advantageous to combine several converter units each constructed using the same converter phase unit topology. For example, it may not be technically feasible or economically optimal to achieve the power, voltage or current rating with a single converter unit. Several converter units may be combined to achieve increased availability and limited power outage upon faults.

The combination of two or more converter units can be accomplished in a number of ways. The d.c. terminals of the converter units can be connected in parallel to achieve high output currents or in series to achieve high output voltages.

4.3.2 D.C. circuit configurations

Both cables and overhead transmission lines can be used for VSC transmission. However, there are several aspects associated with the basic principle of VSC transmission that may influence the choice.

- Since a VSC generally allows only one d.c. voltage polarity, the cable does not need to be designed for voltage polarity reversal. This allows the use of extruded cross-linked polyethylene (XLPE) d.c. cables. Faults on d.c. cables are considered as exceptional scenarios which result in a permanent fault of the affected section and an interruption of power transfer.
- Since overhead transmission lines are always exposed to lightning strikes and pollution, faults along them are likely. Most line outages are temporary and transmission recommences once the fault is cleared and the air insulation is restored.

A back-to-back configuration is a special case of VSC transmission where the d.c. transmission distance is zero.

4.3.3 Monopole configuration

4.3.3.1 General

The VSC converter can be operated in different monopolar configurations.

- Symmetrical monopole
- Asymmetric monopole with metallic return
- Asymmetric monopole with earth return

4.3.3.2 Symmetrical monopole

In a symmetrical monopole, the d.c. output voltages are of equal but opposite magnitude. The midpoint of the d.c. circuit is earthed, either by capacitors as shown in [Figure 6](#) or by other means.

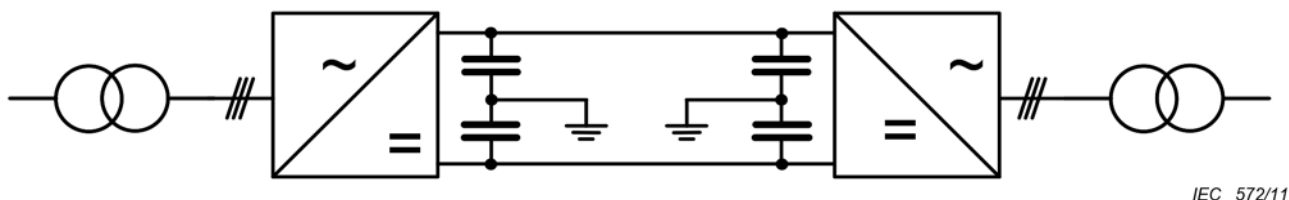


Figure 6 — VSC transmission with a symmetrical monopole

4.3.3.3 Asymmetrical monopole

In an asymmetrical monopole as shown on [Figures 7](#) and [8](#), the d.c. side output from the converter is asymmetrical with one side typically connected to earth. It is possible to operate the transmission system in metallic return or in earth return.

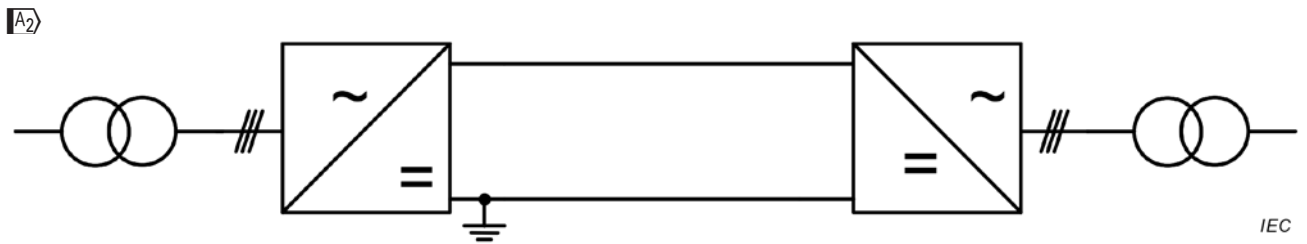


Figure 7 — VSC transmission with an asymmetrical monopole with metallic return



Figure 8 — VSC transmission with an asymmetrical monopole with earth return

A2

4.3.4 Bipolar configuration

Two asymmetrical converters can be connected together in a bipolar configuration either with earth or metallic return.

The neutral return bus can be designed by a similar process to that which is normally used for bipolar LCC HVDC schemes.

When there is an outage of a converter or d.c. line/cable there is normally designed a possibility to operate the remaining system in asymmetrical monopole operation.

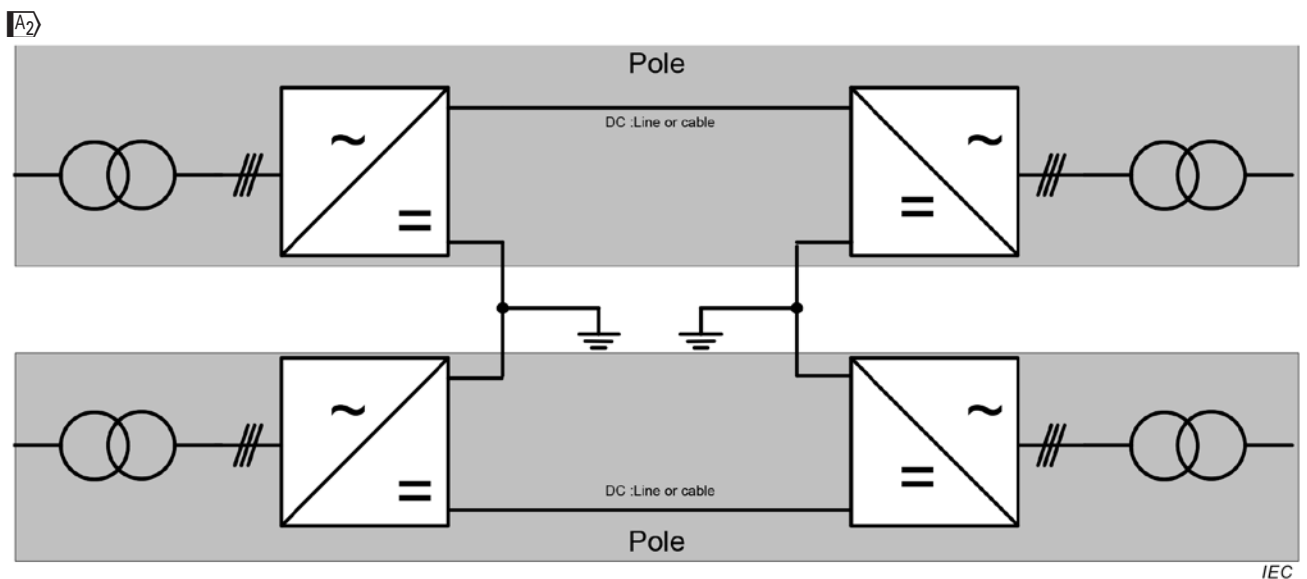


Figure 9 — VSC transmission in bipolar configuration

A2

4.3.5 Parallel connection of two converters

The d.c. terminals of two VSC converters can be connected in parallel resulting in high d.c. currents.

To prevent undesirable interaction between the two parallel-connected converters, some level of impedance shall be provided between the two converters.



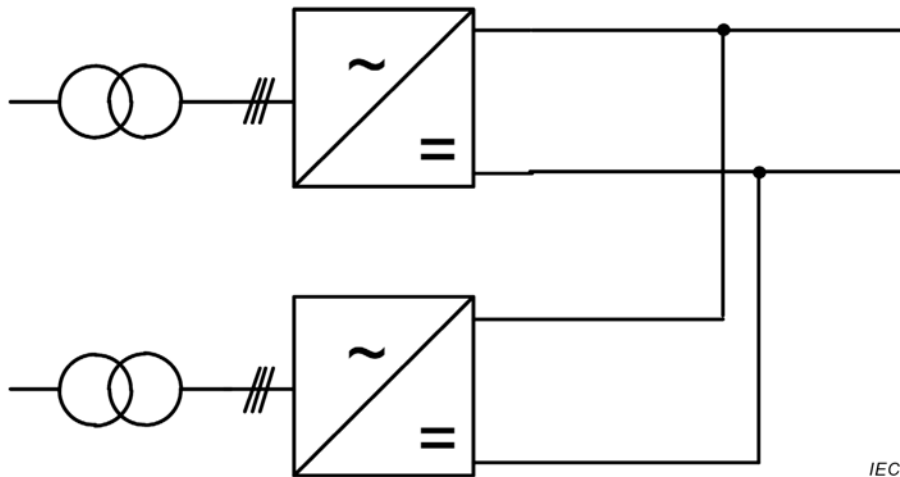


Figure 10 — Parallel connection of two converter units



Where parallel connection of converter units is chosen, a high level control is required in order to coordinate current orders between the converter units.

In order to achieve high reliability upon internal converter unit faults, additional switching and or breaking devices are required to isolate a faulty converter unit. Obviously the common d.c. transmission circuit has no redundancy upon d.c. line faults.

4.3.6 Series connection of two converters

Two VSC converters can be connected in series on their d.c. side. This approach can be used to extend the d.c. voltage capabilities of a VSC transmission relative to the capability of the individual converter units.

The technically most relevant scenario of series connection is the bipolar arrangement outlined in [Subclause 4.3.4](#).

4.3.7 Parallel and series connection of more than two converters

In principle, it is also possible to connect more than two converter units in parallel or in series. Connections of each converter units are either to separate windings of a common transformer or to separate transformers.

In general the increased complexity of multi converter units has to be evaluated with regard to project specific requirements.

4.4 Semiconductors for VSC transmission

In normal operation of voltage-sourced converters the power semiconductors are exposed to a unipolar voltage and have to be able to conduct the current in both directions. Therefore power semiconductor switches with turn-on and turn-off capability and with a high voltage blocking capability (typically several kV) in the forward direction are needed.

Today these requirements are achieved by a parallel connection of a $\boxed{A_1}$ turn-off semiconductor device $\langle A_1 \rangle$ and a so called free-wheeling diode as shown in [Figure 11](#).

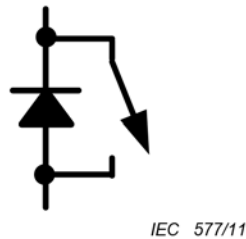


Figure 11 — Symbol of a $\boxed{A_1}$ turn-off semiconductor device $\langle A_1 \rangle$ and associated free-wheeling diode

Various different $\boxed{A_1}$ turn-off semiconductor devices $\langle A_1 \rangle$ are suitable for VSC technology, but only IGBTs (insulated gate bipolar transistor, as shown on [Figure 12](#)) are used in commercial VSC-HVDC projects that have been built to date. Therefore the description of $\boxed{A_1}$ turn-off semiconductor devices $\langle A_1 \rangle$ in this document is concentrated on IGBTs although other semiconductors such as GTOs and IGCTs are also usable.

NOTE Semiconductor devices suitable for VSC transmission type are divided into two categories: the “transistor” type, which includes IGBTs, and the “thyristor” type which includes GTOs and IGCTs. Devices of the “thyristor” type can handle larger powers more efficiently than devices of the “transistor” type, but lack certain control features such as the ability to control the device smoothly between the off and on states using active gate control. Devices of the “thyristor” type also have higher gate power consumption than devices of the “transistor” type, which makes their use in high voltage applications such as VSC transmission more difficult.

$\boxed{A_1}$

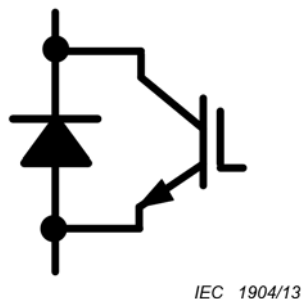


Figure 12 — Symbol of an IGBT and associated free-wheeling diode $\langle A_1 \rangle$

Like all diodes, the free-wheeling diodes, which are connected in parallel to the controllable switch, have a significant reverse recovery current when they turn off. Both the IGBTs as well as the free-wheeling diodes have to cope with these switching transients, particularly current gradients and voltage gradients.

An IGBT is a voltage controlled device; only capacitive currents can flow in the gate terminal. The device can be controlled at any instant, even during the switching transients, i.e. the load current can be influenced by the gate voltage.

IGBTs are short-circuit proof within defined operating conditions. This means that in case of a short circuit the IGBT limits the load current to several kiloamperes. Within some microseconds, an appropriate gate turn-off signal has to be applied to turn off the fault current and not to thermally overstress the device.

Switching times of IGBTs are in the range of microseconds or less. Furthermore, the switching slopes can be adjusted by the gate drive circuit, achieving the optimal waveforms concerning over-voltage peaks and switching losses. Snubbers to keep the rates of rise of current and voltages to acceptable