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colour inside

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

IEC TR 62543:2011-03+AMD1:2013-07+AMD2:2017-05 CSV(en)

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CONTENTS

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HIGH-VOLTAGE DIRECT CURRENT (HVDC) POWER TRANSMISSION USING VOLTAGE SOURCED CONVERTERS (VSC)

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In this Redline version, a vertical line in the margin shows where the technical content is modified by amendments 1 and 2. Additions are in green text, deletions are in strikethrough red text. A separate Final version with all changes accepted is available in this publication.

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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.

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

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

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HIGH-VOLTAGE DIRECT CURRENT (HVDC) POWER TRANSMISSION USING VOLTAGE SOURCED CONVERTERS (VSC)

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. 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.

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.

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

IEC 61975, *High-voltage direct current (HVDC) installations – System tests*

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*

3 Terms and definitions

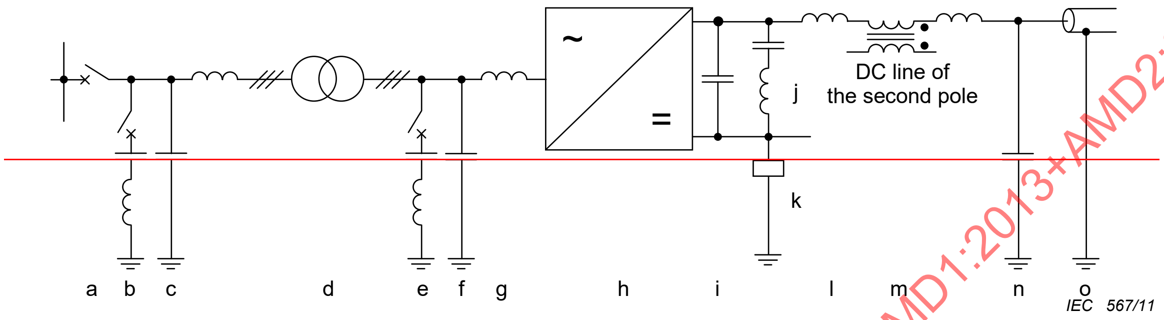
For the purposes of this document, the terms and definitions given in IEC 62747, IEC 62501 and the following apply.

3.1 General

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.

NOTE This report uses the terminology established by IEC 60633 and IEC 61803 for line-commutated HVDC. Only terms which are specific to HVDC transmission using voltage sourced converters are defined in this clause. Those terms that are either identical to or obvious extensions of IEC 60633 or IEC 61803 terminology have not been defined.

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.



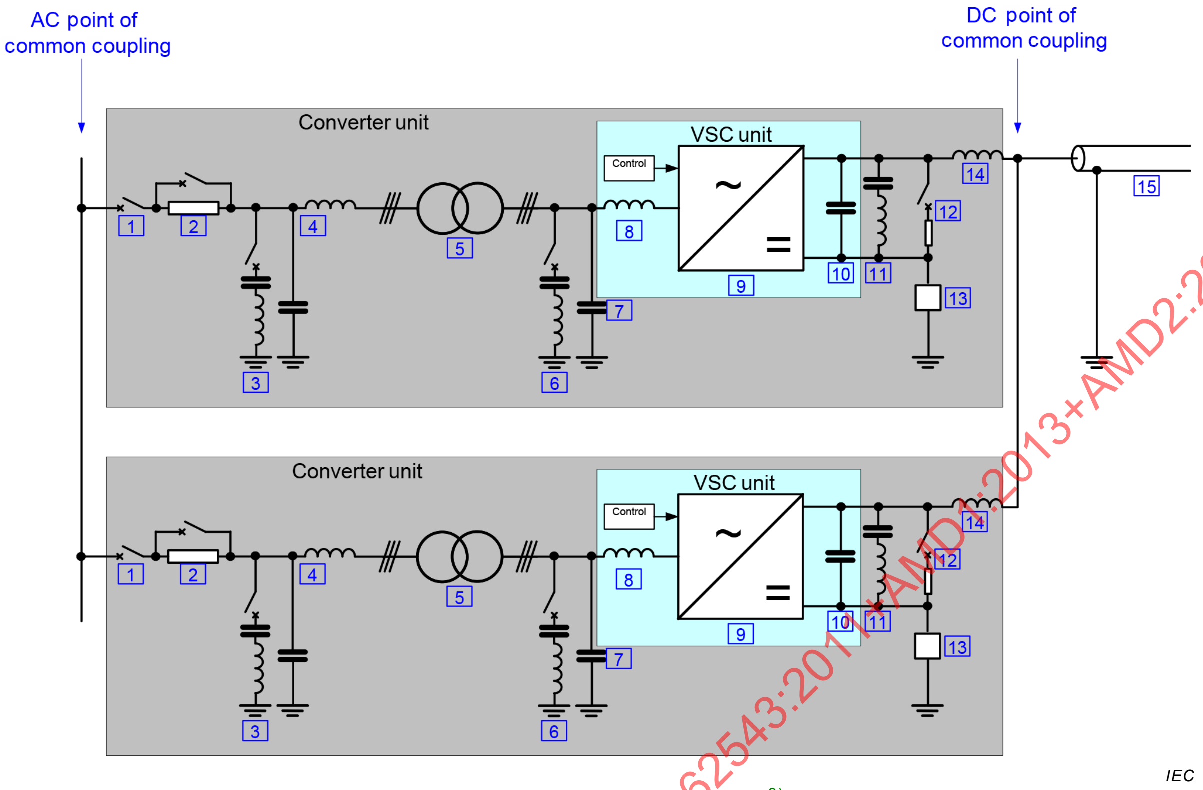
a	circuit breaker	i	VSC d.c. capacitor [b]
b	line side harmonic filter	j	d.c. harmonic filter
c	line side high frequency filter	k	neutral point grounding branch [c]
d	interface transformer	l	d.c. reactor [d]
e	converter side harmonic filter	m	common mode blocking reactor [d]
f + g	converter side high frequency filter [a]	n	d.c. side high frequency filter [d]
g	phase reactor [a]	o	d.c. cable or overhead transmission line [b]
h	VSC unit		

[a] In some designs of VSC, the phase reactor may fulfil part of the function of the converter-side high frequency filter. In addition, in some designs of VSC, part of or all of the phase reactor may be built into the three "Phase units" of the VSC unit, as "Valve reactors".

[b] 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.

[c] The location of the neutral point grounding branch may be different depending on the design of the VSC unit.

[d] Not normally required for back-to-back systems.



1	circuit breaker	9	VSC unit 3)
2	pre-Insertion Resistor	10	VSC d.c. capacitor 4)
3	line side harmonic filter1)	11	d.c. harmonic filter1)
4	line side high frequency filter6)	12	dynamic braking system7)
5	interface transformer	13	neutral point grounding branch 5)
6	converter side harmonic filter1)	14	d.c. reactor8)
7 + 8	converter side high frequency filter2)	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.

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.

3.3 Power semiconductor terms

NOTE There are several types of switched valve devices which can be used in voltage sourced converters (VSC) for HVDC and currently the IGBT is the major device used in such converters. The term IGBT is used throughout this technical report to refer to the switched valve device. However, the technical report is equally applicable to other types of devices with turn-off capability in most of the parts.

3.3.1
switched valve devices
a controllable valve device which may be turned on and off by a control signal, for example IGBT

3.3.2
insulated gate bipolar transistor
IGBT
a controllable switch with the capability to turn-on and turn-off a load current. An IGBT has three terminals: a gate terminal (G) and two load terminals emitter (E) and collector (C).

3.3.3
free-wheeling diode
FWD
power semiconductor device with diode characteristic

3.3.4
IGBT-diode pair
arrangement of IGBT and FWD connected in inverse parallel

3.4 VSC topologies

3.4.1
symmetrical monopole
a single VSC converter with symmetrical d.c. voltage output on the two terminals

3.4.2
asymmetrical monopole
a single VSC converter with asymmetrical d.c. voltage output on the two terminals, normally with one terminal earthed

3.4.3
bipole
two or more VSC asymmetrical monopoles forming a bipolar d.c. circuit

3.4.4
two-level converter
a converter in which the voltage at the a.c. terminals of the VSC unit is switched between two discrete d.c. voltage levels

3.4.5
three-level converter
a converter in which the voltage at the a.c. terminals of the VSC unit is switched between three discrete d.c. voltage levels

3.4.6
multi-level converter
a converter in which the voltage at the a.c. terminals of the VSC unit is switched between more than three discrete d.c. voltage levels

3.4.7
modular multi-level converter
MMC
multi-level converter in which each VSC valve consists of a number of self-contained, single-phase voltage sourced converters connected in series

3.4.8
VSC unit
three VSC phase units, together with VSC unit control equipment, essential protective and switching devices, d.c. storage capacitors, valve reactor and auxiliaries, if any, used for conversion

3.4.9
VSC phase unit
the equipment used to connect the two d.c. busbars to one a.c. terminal

NOTE In the simplest implementation, the VSC phase unit consists of two VSC valves. In some case, it consists of two VSC valves and valve reactors. The VSC phase unit may also include control and protection equipment, and other components.

3.4.10
VSC valve
complete controllable device assembly, which represents a functional unit as part of a VSC phase unit and characterized by switching actions of the power electronic devices upon control signals of the converter base electronics

NOTE Dependent on the converter topology, a valve can either have the function to act like a controllable switch or to act like a controllable voltage source.

3.4.11
diode valve
a semiconductor valve containing diodes but no switched semiconductor devices, which might be used in some VSC topologies

3.4.12
valve
refers to VSC valve or diode valve according to the context

3.4.13
VSC valve level
part of a VSC valve comprising a controllable switch and an associated diode, or controllable switches and diodes connected in parallel, or controllable switches and diodes connected to a half bridge or full bridge arrangement, together with their immediate auxiliaries, storage capacitor, if any

NOTE In the context of modular multi-level converters, the term "submodule" is also used to refer to a VSC valve level.

3.4.14
diode valve level
part of a diode valve composed of a diode and associated circuits and components, if any

3.4.15
redundant levels
the maximum number of VSC valve levels or diode valve levels in a valve that may be short-circuited externally or internally during service without affecting the safe operation of the valve as demonstrated by type tests, and which if and when exceeded, would require shutdown of the valve to replace the failed levels or acceptance of increased risk of failures

3.4.16
valve protective blocking
means of protecting the valve or converter from excessive electrical stress by the emergency turn-off of all IGBTs in one or more valves

3.4.17
submodule d.c. capacitor
a capacitor (if any) used as part of a certain VSC valve level, which is used as energy storage d.c. source

3.4.18
valve reactor
a reactor (if any) which is connected in series to the VSC valve. One or more valve reactors can be associated to one VSC valve and might be connected at different positions within the valve. According to the definition, valve reactors are not part of the VSC valve. However, it is also possible to integrate the valve reactors in the structural design of the VSC valve, e.g. into each valve level.

NOTE At present valve reactors are used in converter topologies with valves acting like a controllable voltage source only.

3.4.19
valve structure
physical structure holding the levels of a valve which is insulated to the appropriate voltage above earth potential

3.4.20
valve support
that part of the valve which mechanically supports and electrically insulates the active part of the valve from earth

NOTE A part of a valve which is clearly identifiable in a discrete form to be a valve support may not exist in all designs of valves.

3.4.21
multiple valve unit
MVU
mechanical arrangement of 2 or more valves or 1 or more VSC phase units sharing a common valve support

NOTE A MVU might not exist in all topologies and physical arrangement of converters.

3.4.22
valve section
electrical assembly, composing a number of VSC or diode valve levels and other components, which exhibits pro-rated electrical properties of a complete valve

~~**3.4.23**~~
~~**valve base electronics**~~
~~**VBE**~~
~~electronic unit, at earth potential, which is the interface between the converter control system and the VSC valves~~

3.5 VSC transmission

~~**3.5.1**~~
~~**VSC substation**~~
~~part of a VSC transmission scheme, consisting of one or more VSC unit(s) installed in a single location together with buildings, VSC d.c. capacitors, reactors, transformers, filters, control, monitoring, protective, measuring and auxiliary equipment, as applicable~~

~~**3.5.2**~~
~~**interface transformer**~~
~~transformer (if any) through which power is transmitted between the a.c. system connection point and one or more VSC units~~

~~**3.5.3**~~
~~**phase reactor**~~
~~reactor connected directly to the a.c. terminal of the VSC phase unit, and combined with interface transformer leakage reactance (if any), in order to provide the commutating reactance~~

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

~~**3.5.5**~~
~~**a.c. system side harmonic filter**~~
~~filter (if any) used to prevent harmonics generated by the VSC from penetrating into the a.c. system. The filter can be located at the point of common coupling (outside the interface transformer) or/ and on the valve side (inside the interface transformer)~~

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

~~**3.5.7**~~
~~**HF-blocking filter**~~
~~filters (if any) used to reduce penetration of high frequency (HF) harmonics into the a.c. system to an acceptable level~~

3.5.8
valve side harmonic filter
filters (if any) used to mitigate the HF stresses of the interface transformer

~~**3.5.9**~~
~~**common mode blocking reactor**~~
~~a reactor (if any) used to reduce common mode harmonic currents flowing into a d.c. overhead line or cable of a bipolar long distance transmission scheme~~

3.5.10
d.c. harmonic filter
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.

3.5.11
d.c. reactor
a reactor (if any) connected in series to a d.c. overhead transmission line or cable 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.

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

3.6 Operating states

NOTE This report only defines some operating states of the components of the VSC system, while the system operating states are not included.

3.6.1
rectifier operation
operation mode of a VSC unit or a VSC substation when energy is transferred from the a.c. side to the d.c. side

3.6.2
inverter operation
operation mode of a VSC unit or a VSC substation when energy is transferred from the d.c. side to the a.c. side

3.6.3
STATCOM operation
mode of operation with reactive power exchange to the a.c. terminals and without energy transfer on the d.c. line

3.6.4
forward valve direction
direction of current through a VSC valve, when current flows from the positive terminal to the negative terminal

3.6.5
reverse valve direction
direction of current through a VSC valve, when current flows from the negative terminal to the positive terminal

3.6.6
forward valve current
current which flows through a VSC valve in forward valve direction

3.6.7
reverse valve current
current which flows through a VSC valve in reverse valve direction

3.6.8
VSC blocking
operation preventing further conversion by a VSC unit by inhibiting valve control signal or applying a signal to turn off IGBTs

3.6.9
VSC deblocking
operation permitting the start of conversion by a converter by removing blocking action

3.6.10
conducting state
the condition in which load current flows through an IGBT-diode pair. In IGBT-diode pair, both positive and negative conducting states may exist.

3.6.11
positive conducting state
the condition of an IGBT-diode pair in which load current flows through the IGBT from collector to emitter

3.6.12
negative conducting state
the condition of an IGBT-diode pair in which load current flows through the free-wheeling diode from anode to cathode

3.6.13
blocked state
the condition of an IGBT-diode pair in which load current does not flow and a voltage is applied to the IGBT-diode pair such that a positive voltage exists on the collector of the IGBT with respect to the emitter

3.6.14
reverse recovery state
the condition in which the FWD carries reverse current during commutation at the specified conditions, starting at the zero-crossing of the current and ending when the reverse current has decayed to the reverse off-state current after the tail-current phase

3.6.15
modulation index of PWM converters
M
modulation index *M* is the ratio of the modulating wave amplitude to the carrier amplitude

$$M = \frac{V_{\text{control}}}{V_{\text{triangle}}} = \frac{Peak\_of\_(V_{A0})_1}{(V_{\text{dc}}/2)} \qquad (1)$$

where

$(V_{A0})_1$ is the fundamental frequency component of V_{A0};

V_{A0} is the output voltage of one VSC phase unit at its a.c. terminal.

NOTE In addition, there are various definitions of modulation index for VSC converters available. All of these modulation indices represent secondary quantities which are derived from physical properties and operating principles of VSC converters. It is to be noted that for a specific application any modulation index and its usage should be defined clearly.

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

~~3.10 Insulation co-ordination terms~~

~~**3.10.1**~~
~~**test withstand voltage**~~
~~value of a test voltage of standard wave shape at which a new valve, with unimpaired integrity, does not show any disruptive discharge and meets all other acceptance criteria specified for the particular test, when subjected to a specified number of applications or a specified duration of the test voltage, under specified conditions~~

~~**3.10.2**~~
~~**internal and external insulation**~~
~~air external to the components and insulating materials of the valve, but contained within the profile of the valve or multiple valve unit is considered as part of the internal insulation system of the valve. The external insulation is the air between the external surface of the valve or multiple valve unit and its surroundings.~~

3.11 Power losses

3.11.1
auxiliary losses
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.

3.11.2
~~standby~~ no-load operating losses
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
~~no-load~~ 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

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.

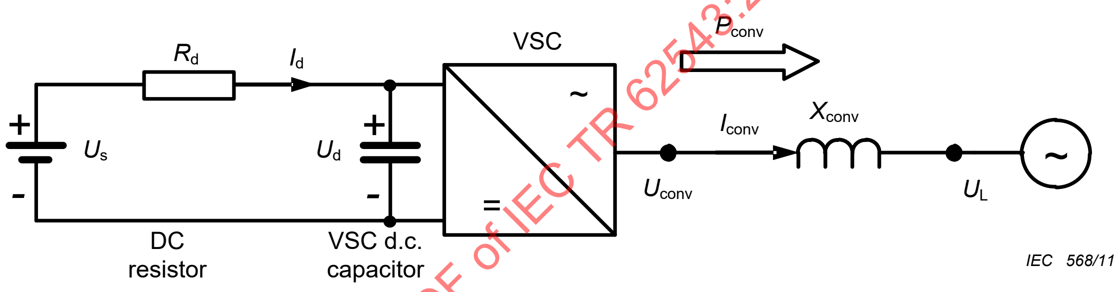


Figure 2 – Diagram of a generic voltage source converter (a.c. filters not shown)

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 ($\mathrm{Im}(U_L \cdot I_L) > 0$) , or inductively, absorbing reactive power from the a.c. network ($\mathrm{Im}(U_L \cdot I_L) < 0$). 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.

~~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:

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

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

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.

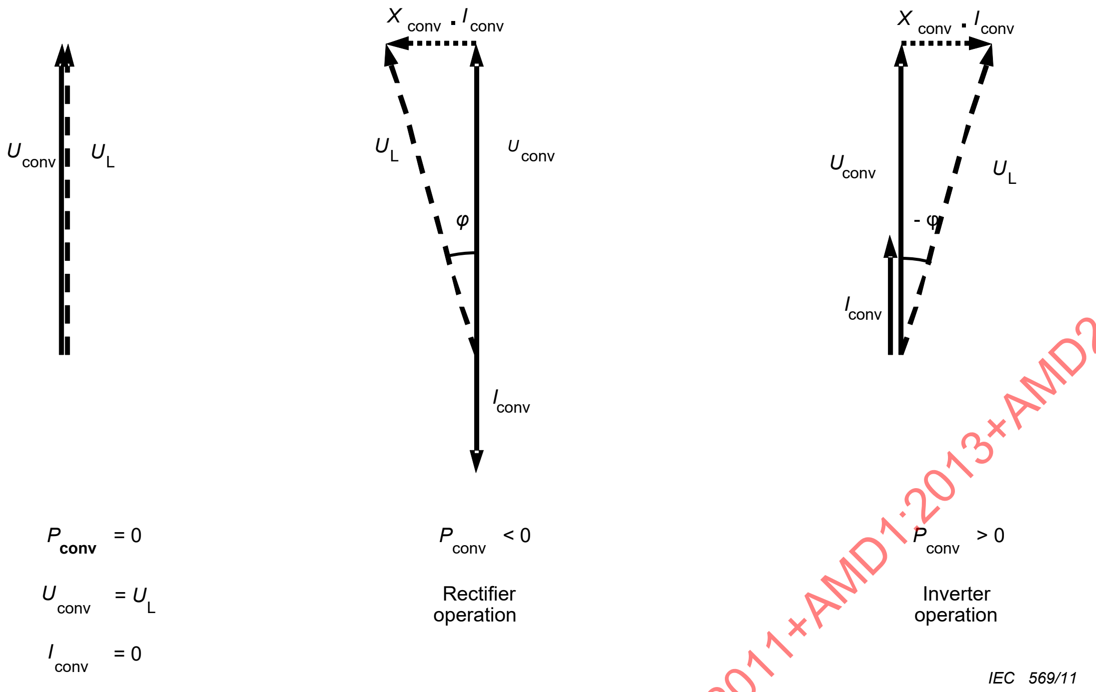


Figure 3 – The principle of active power control

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.

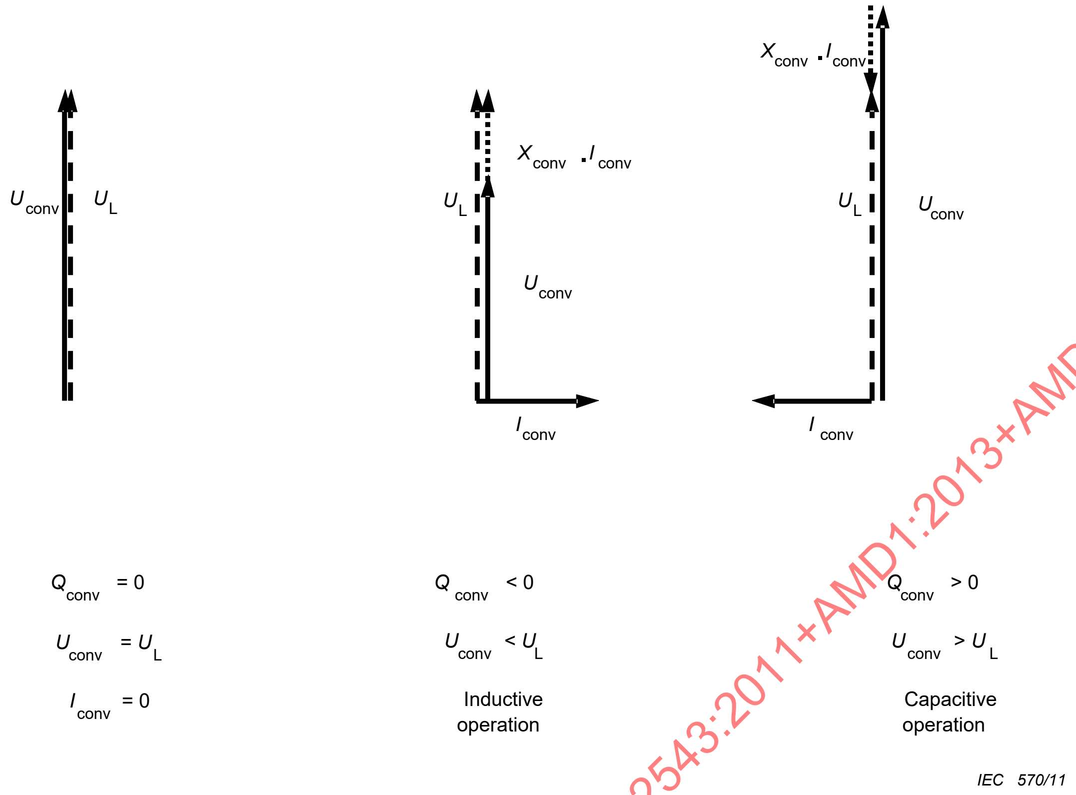


Figure 4 – The principle of reactive power control

4.1.3 Operating principles of a VSC transmission scheme

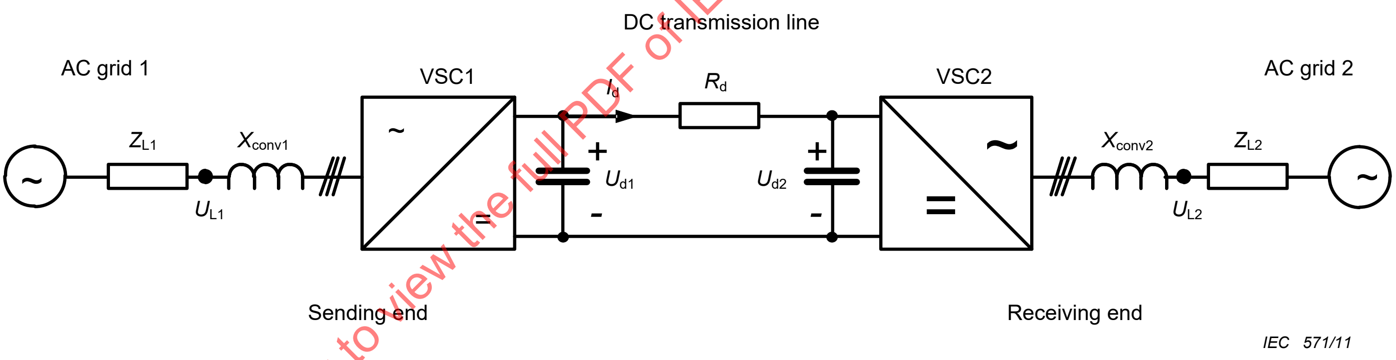


Figure 5 – A point-to-point VSC transmission scheme

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 $I_d = (U_{d1}-U_{d2})/R_d$.

For example, 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.
- In most cases, 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.

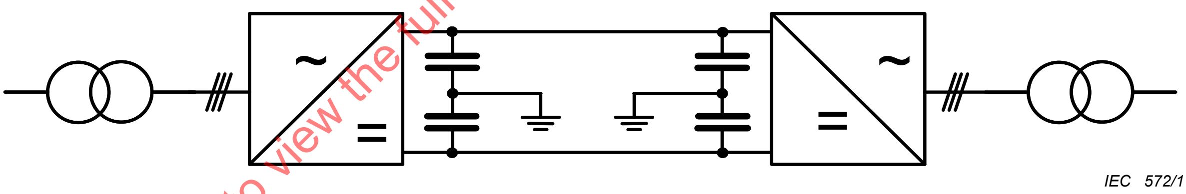


Figure 6 – VSC transmission with a symmetrical monopole

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.

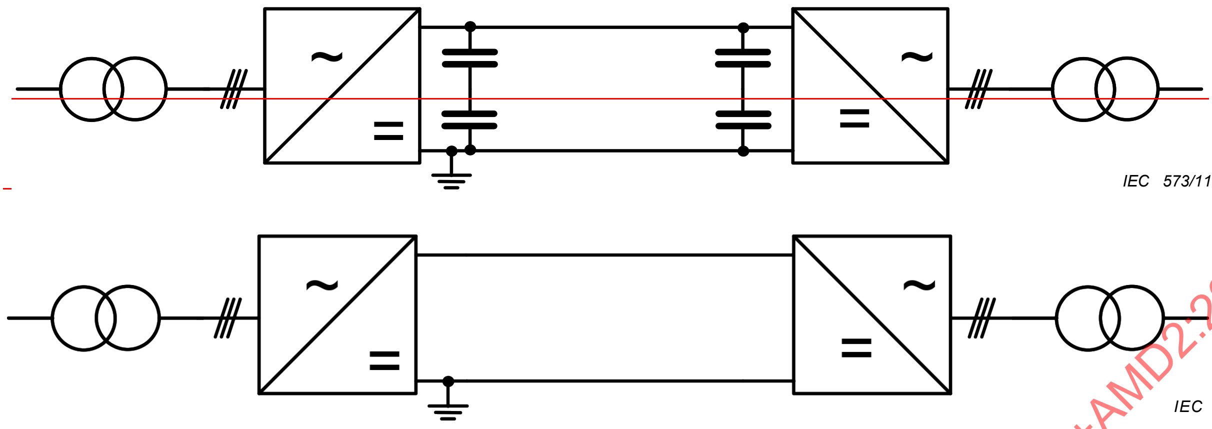


Figure 7 – VSC transmission with an asymmetrical monopole with metallic return

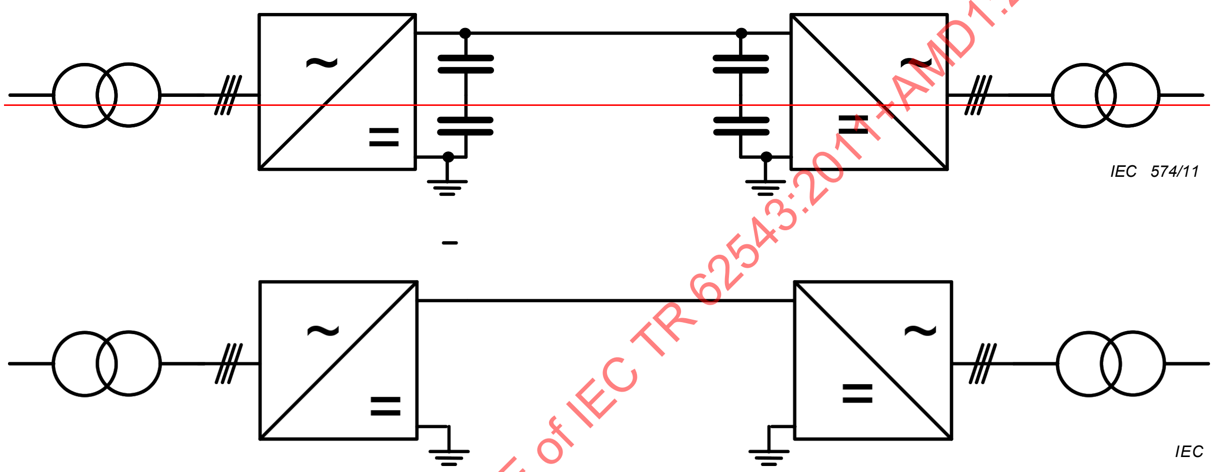


Figure 8 – VSC transmission with an asymmetrical monopole with earth return

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.

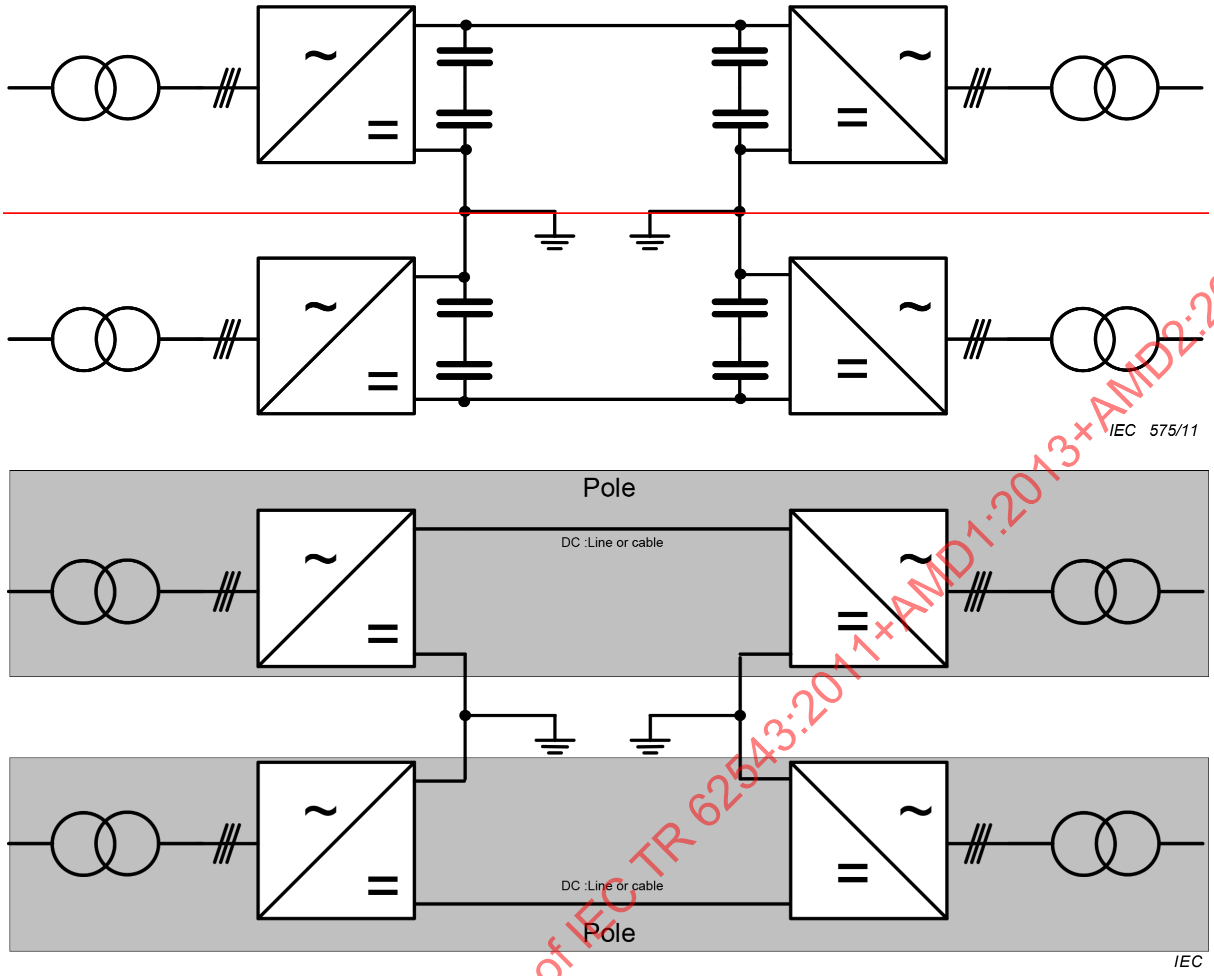


Figure 9 – VSC transmission in bipolar configuration

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.

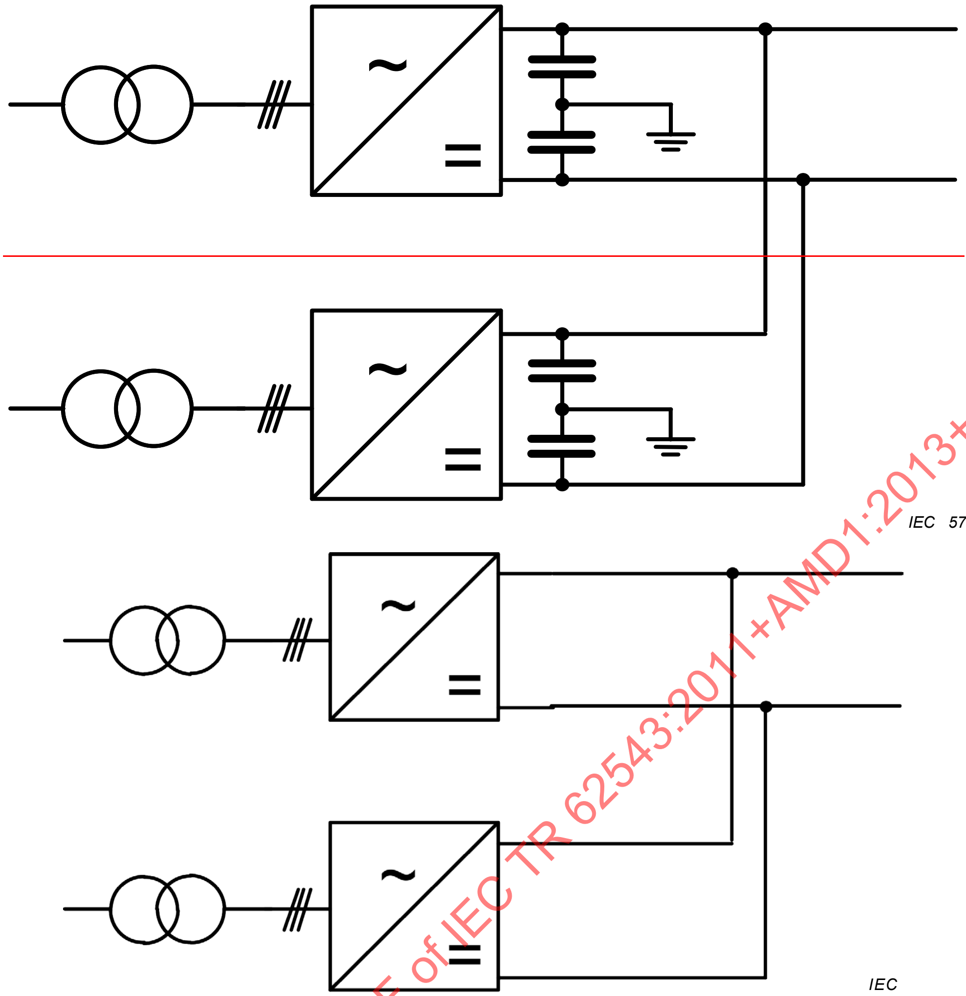


Figure 10 – Parallel connection of two converter units

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

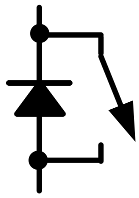
In principle, it is also possible to connect more than two converter units in parallel or in series. Connections of each converter units are either to separate windings of a common transformer or to separate transformers.

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 ~~controllable switch~~ turn-off semiconductor device and a so called free-wheeling diode as shown in Figure 11.

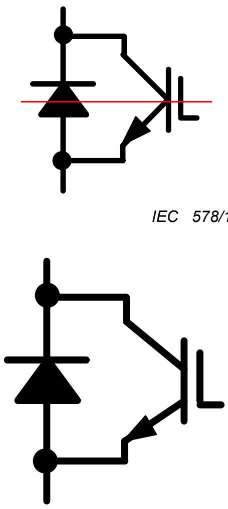


IEC 577/11

Figure 11 – Symbol of a ~~controllable switch~~ turn-off semiconductor device and associated free-wheeling diode

Various different turn-off semiconductor ~~switches~~ devices 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 turn-off semiconductor ~~switches~~ devices 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.



IEC 578/11

IEC 1904/13

Figure 12 – Symbol of an IGBT and associated free-wheeling diode

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 kiloampers. 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 limits are not necessary in many cases. The gate drivers for IGBTs can be quite simple, since they have to deliver only a few watts of control power to the gate.

High power IGBTs are made up by a parallel connection of chips to achieve the required current capability. The chips are mounted in press packs or module housings. In most cases the FWD chips are included in the same housing.

Press pack housings are intended to be clamped between heat sinks; the paths for current and heat are the copper poles of collector and emitter of the devices that are separated by a ring of insulating material. For high voltage devices, this material is high strength porcelain in most cases, though glass fiber reinforced resin is also used.

Module IGBTs are designed for single sided cooling and are mounted on heat sinks by screws; spring loaded clamping is not necessary. The electrical terminals are on the top side of the module; the heat flows through the base plate of the module to the heat sink. Since the electrical part of the module is insulated to the base plate, it is possible to mount modules with different voltage potentials on a shared heat sink.

5 VSC transmission converter topologies

5.1 General

For a high power VSC transmission system, the key issue that determines the cost and operating losses of the overall system is the power circuit structure to construct the a.c. output voltage waveform. The output voltage waveform should approximate a sine-wave in order to eliminate or minimize the need for harmonic filtering. The switching converter considered for practical implementation is a voltage sourced converter operated with a fixed d.c. voltage. The converter is a combination of ~~controlled solid-state switches~~ turn-off semiconductor devices that connect the d.c. input voltage periodically to the output for some intervals to produce the a.c. output voltage. The converters at each end of a VSC transmission system can be arranged in a number of different ways, with the configuration of the converter normally being referred to as its topology. A the time of writing, two different converter types ~~can be identified~~ have been used for commercial projects: those in which the converter valves act as controllable switches and those in which the converter valves act as controllable voltage sources. These two types are described in subclauses 5.2 and 5.3 respectively.

Some other converter topologies which share the characteristics of both the “controllable switch” and “controllable voltage source” types have been described in the literature. The reader is referred to CIGRÉ Technical Brochure No. 492 “Voltage Source Converter (VSC) HVDC for Power Transmission – Economic Aspects and Comparison with other AC and DC Technologies”, for details.

It is a fundamental criterion for any viable topology that it enables the functional requirements to be met. Different topologies have different technical characteristics, and therefore allow the overall scheme to be optimized in different ways. Manufacturers may have different preferred topologies and be able to best optimize their proposals around this preferred topology. It is recommended that customers do not stipulate the topology to be used for a VSC transmission system, unless there are compelling reasons for doing so.

It is possible to arrange the converters to have a single-, three- or multi-phase a.c. output/input. For the purpose of this report, only the three-phase arrangement will be discussed.

5.2 Converter topologies with VSC valves of "switch" type

5.2.1 General

The converter switches (normally called VSC valves) perform the function of connecting the a.c. bus to the d.c. terminals. If the connection is direct through two alternately operating switches, the a.c. bus voltage will change between the voltage levels at the two d.c. terminals. Such a converter is known as a 2-level converter. In the 2-level converter, each of the VSC valves has to withstand the voltage between the two d.c. terminals.

If the d.c. capacitor is subdivided, or additional d.c. capacitors are added, it is possible to arrange for the a.c. voltage to move not only to the voltage at the two d.c. terminals but also to intermediate levels. The number of voltage levels to which the a.c. bus voltage can be switched will depend on the number of valves and the number of d.c. capacitor subdivisions or additional d.c. capacitors. These arrangements are known as 3-level or multi-level converters, depending on the number of voltage levels that can be achieved. The term multilevel refers to a converter phase unit topology where the a.c. bus can be switched to attain more than three different voltage levels.

In 3-level or multi-level topologies, the VSC valves do not normally have to be designed for the full d.c. terminal-to-terminal voltage. For example, in normal operation each valve in a 3-level converter topology experiences only 50 % of the terminal-to-terminal d.c. voltage. Similarly, in normal operation each VSC valve in an *n*-level topology experiences only the terminal-to-terminal d.c. voltage of the phase unit divided by (*n*-1).

In the following paragraphs, converter topologies suitable for VSC transmission systems will be described in more detail. It should be noted that a considerable research and development effort is being invested in voltage sourced converter technology, so additional suitable topologies will likely become available subsequent to the issue of this report.

5.2.2 Operating principle

The basic operating mechanism of an ideal VSC is covered in this section. The description is initially limited to a 2-level VSC. The 2-level VSC is the simplest structure needed to convert a d.c. voltage into a.c. voltages. Although other types of multi-level VSCs are more complex, their basic operating principle does not differ from that of the 2-level VSC.

For the purpose of illustration, the VSC valves are described as ideal switches without any switching losses. A VSC valve in a real application consists of a large number of series-connected semiconductor devices, and is described in greater detail in Clause 5. The stray inductances are neglected here, and the d.c. capacitors have been assumed to have infinite capacitance—i.e., no d.c. voltage ripple is shown.

As explained in Subclause 4.1, the output of the VSC needs to be connected in series with a phase reactor. The phase reactor enables the VSC to control power flow in addition to smoothing the output current.

5.2.3 Topologies

5.2.3.1 Two-level converters

A 2-level converter is the simplest switching arrangement capable of producing a.c. output from a d.c. source in the form of a simple square-wave. A three-phase converter using three 2-level phase units is illustrated in Figure 13.

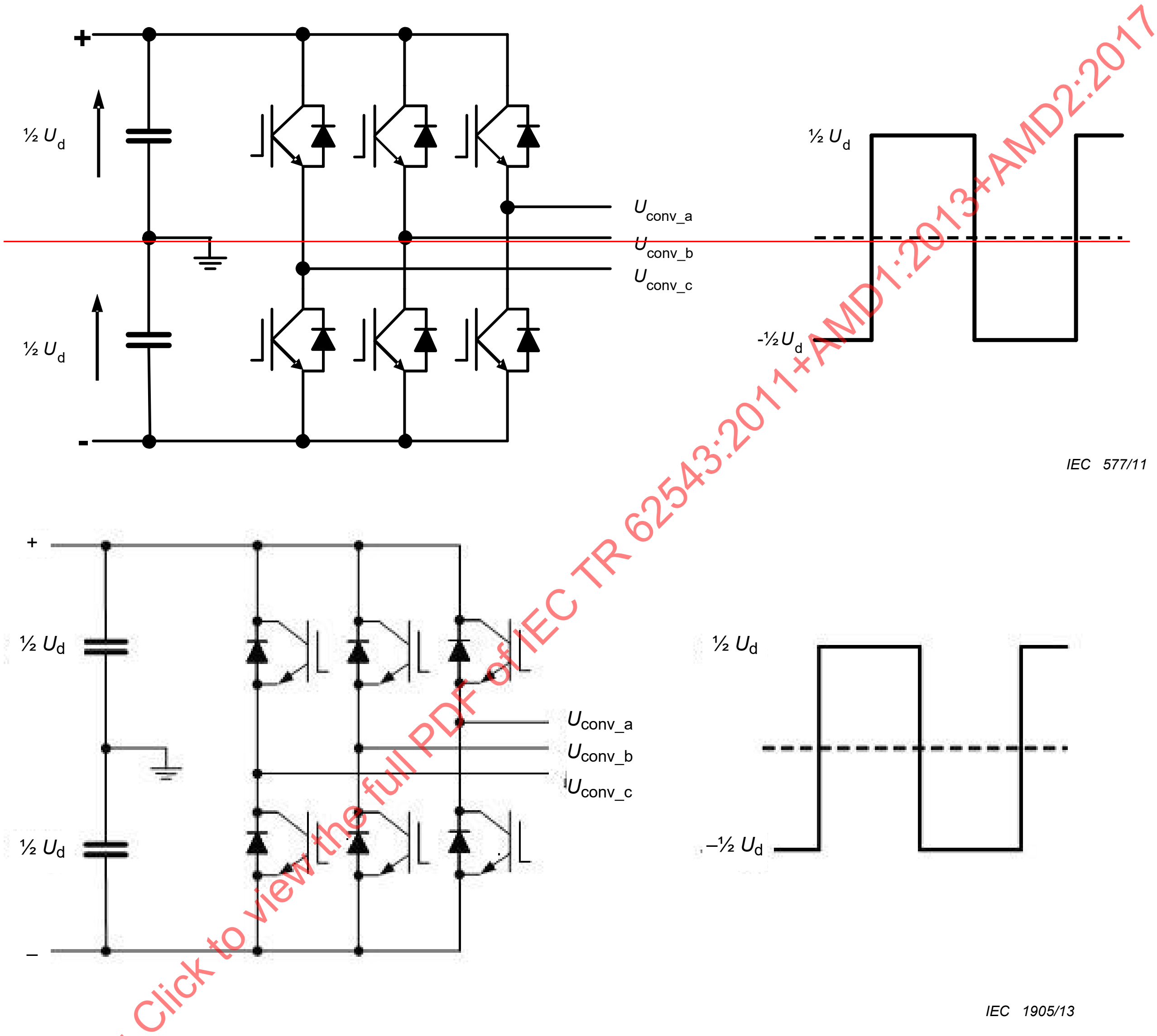


Figure 13 – Diagram of a three-phase 2-level converter and associated a.c. waveform for one phase

The a.c. waveform shown in the figure is the phase-to-neutral voltage. The neutral voltage is the voltage at the midpoint of the d.c. capacitor.

Since the square-wave output voltage shown in Figure 13 is not acceptable in a practical HVDC scheme, this converter type is normally operated with pulse width modulation (PWM) as described in Subclause 9.3.

A typical PWM-switched waveform, using a carrier based control method with a switching frequency of 21 times the fundamental, is given in Figure 14. For the purpose of this illustration, the d.c. capacitor has been assumed to have an infinite capacitance (i.e., no d.c. voltage ripple).

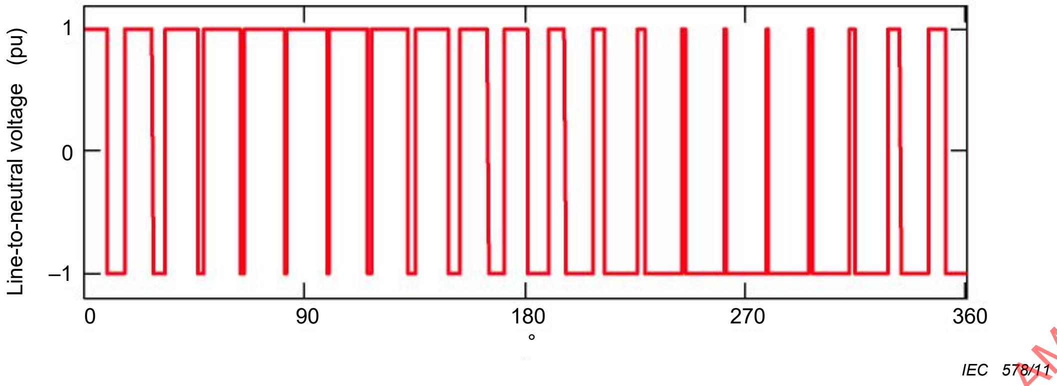


Figure 14 – Single-phase a.c. output for 2-level converter with PWM switching at 21 times fundamental frequency

Other PWM techniques are also available, such as optimised PWM (OPWM) or selective harmonic elimination method (SHEM). These aim to improve the compromise between power transfer capability, switching frequency and harmonic performance.

5.2.3.2 Three-level neutral-point clamped (NPC) converters

A three phase converter consisting of three 3-level phase units is illustrated in Figure 15. The converter has three d.c. terminals to connect to a split or centre-tapped d.c. source. As seen, there are more valves used than in the 2-level phase unit, and additional diodes or valves are required to connect to the d.c. supply centre-tap, which is the reference zero potential. However, with identical valve terminal-to-terminal voltage rating, the total d.c. supply voltage can be doubled so that the output voltage per valve remains the same.

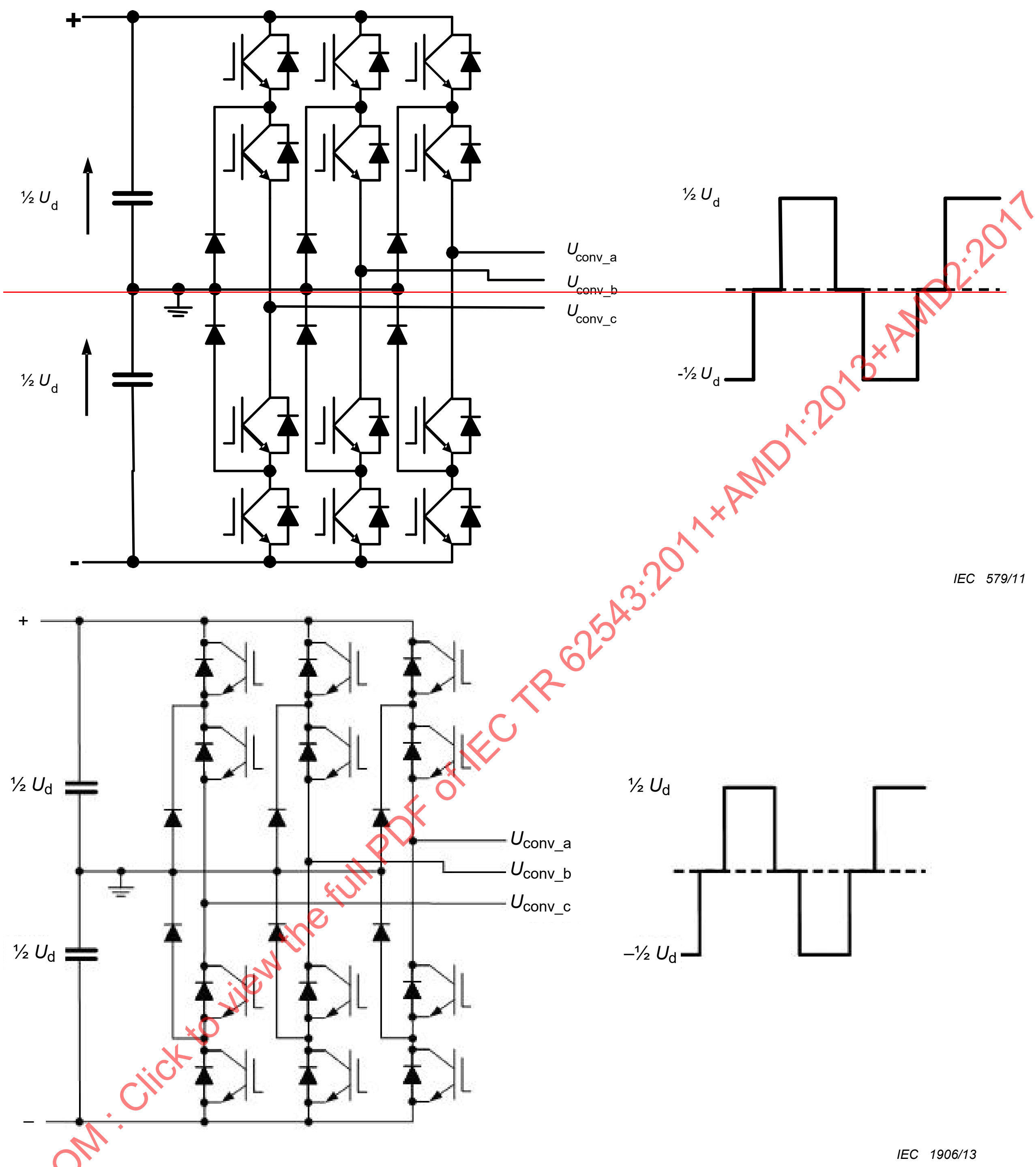


Figure 15 – Diagram of a three-phase 3-level NPC converter and associated a.c. waveform for one phase

NOTE The neutral-point clamping diodes shown in Figure 15 may be replaced by IGBTs in some applications.

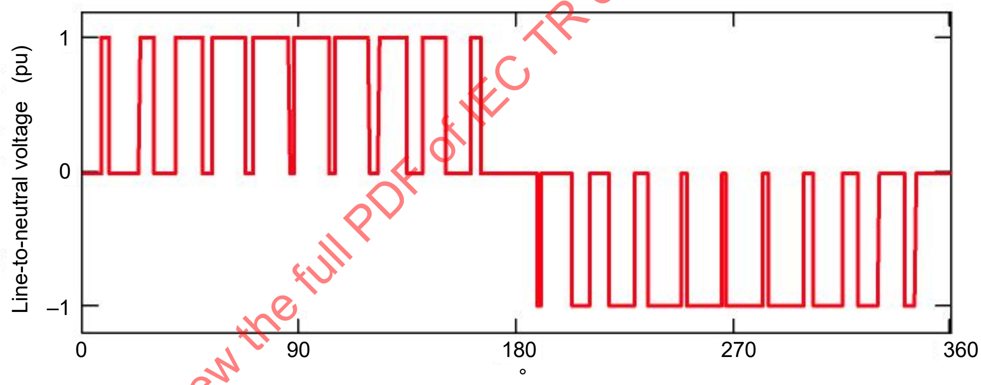
The a.c. waveform shown in the figure is the phase-to-neutral voltage. The neutral voltage is the voltage at the midpoint of the d.c. capacitor. As illustrated in Figure 15, the output voltage of the 3-level phase unit can be positive, negative, or zero. Positive output is produced by gating on both upper valves in the phase unit, while negative output is produced by gating on both lower valves. Zero output is produced when the two middle valves, connecting the centre tap of the d.c. supply via the two diodes to the output, are gated on. At zero output, positive current is conducted by the upper-middle controllable device and the upper centre-tap diode, and negative current by the lower-middle controllable device and the lower centre-tap diode.

As indicated in Figure 15, the relative duration of the positive (and negative) output voltage with respect to the duration of the zero output is a function of control parameter α, which defines the conduction interval of the top upper, and the bottom lower valves. The magnitude of the fundamental frequency component of the output voltage produced by the phase unit is a function of parameter α. When α equals zero degrees it is maximum, while at α equals 90 degrees it is zero. Thus, one advantage of the 3-level phase unit is that it has an internal capability to control the magnitude of the output voltage without changing the number of valve switching events per cycle.

The operating advantages of the 3-level phase unit can only be fully realized with some increase in circuit complexity, as well as more rigorous requirements for managing the proper operation of the converter circuit.

An additional requirement is to accommodate the increased a.c. ripple current with a generally high triplen harmonic content flowing through the mid-point of the d.c. supply. This may necessitate the use of a larger d.c. storage capacitor or the employment of other means to minimize the fluctuation of the mid-point voltage. However, once these problems are solved, the 3-level phase unit provides a useful building block to structure high power converters, particularly when rapid a.c. voltage control is needed.

In common with the two-level converter, this converter is normally operated with PWM. A typical PWM switched waveform, using a carrier based control method with a frequency of 21 times fundamental frequency, is given in Figure 16. For the purpose of this illustration, the d.c. capacitor has been assumed to have an infinite capacitance (i.e., no d.c. voltage ripple).



IEC 580/11

Figure 16 – Single-phase a.c. output for 3-level NPC converter with PWM switching at 21 times fundamental frequency

5.2.3.3 Other multi-level converter topologies

The neutral-point clamped circuit can be extended to higher numbers of output levels, for example 5 levels, but at the expense of disproportionately greater complexity. Another converter type which has been used in some power electronic applications is the "flying capacitor" or "floating capacitor" circuit, which can also exist in 3-level and 5-level forms but suffers the same disproportionately greater complexity as the number of output levels is increased. These and other possible multi-level converter topologies are described in CIGRÉ Technical Brochures 269 and 447 ~~in the Report of CIGRE WG B4-48~~.

5.3 Converter topologies with VSC valves of the "controllable voltage source" type

5.3.1 General

With valves of the "controllable voltage source" type, each VSC level is effectively a single-phase VSC in its own right, and contains power semiconductors and a capacitor for energy storage. Each level has two main terminals used for the series connection of the VSC levels within the valve. By appropriate control of the IGBTs within the valve level, either the voltage of the capacitor or zero volts can be applied to the main terminals of the VSC level.

By individual and appropriate control of the VSC valve levels, a desired voltage can be generated at the valve terminals. The valve voltage is the sum of those capacitor voltages, of which the voltage is applied to the main terminals of the VSC level. The VSC valve submodules or cells are controlled in that way so that the sum of the upper and lower arm of one phase unit equals to the d.c. voltage whereas the instantaneous voltage on the a.c. terminals is determined by the ratio of the voltages of the two converter phase arms of one phase unit.

Assuming infinite storage capacitances with equal voltages in the individual valve levels, n+1 different voltage steps can be applied to the terminals of a valve consisting of n valve levels. Assuming a high number of VSC levels per valve the topology can be approximated by electrical equivalent as shown in Figure 17. Each valve can be considered as a controllable voltage source.

The valve reactors contribute to both the phase reactance and the d.c. reactance, and are essential for the current control within the phase units. Furthermore they also limit the peak current and current gradients in case of severe faults, such as short circuit between the d.c. terminals.

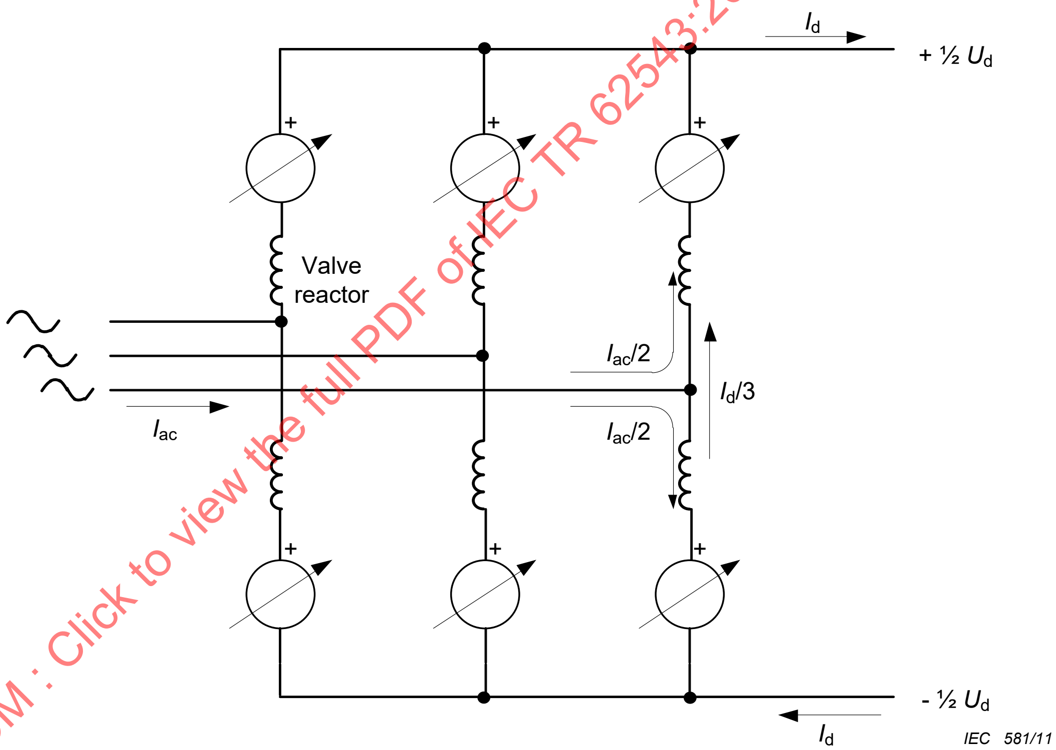


Figure 17 – Electrical equivalent for a converter with VSC valves acting like a controllable voltage source

Because of its modular design and the multi-level technology it is referred to as modular multi-level converter topology. For the design of the individual VSC levels different power building blocks can be used. At the time of writing, two different topologies are used:

- MMC with VSC levels in half-bridge topology;
- MMC with VSC levels in full-bridge topology.

Since the circuit is inherently modular, it is relatively straightforward to obtain high numbers of output levels, without requiring either PWM or series-connected IGBTs. Thus, a.c. filters can be omitted in many cases and considerations of voltage distribution amongst series-connected IGBTs do not arise.

This type of converter can also be realised with multiple IGBTs connected in series in each controllable switch, giving an output voltage waveform with fewer, larger, steps than the MMC. This configuration is referred to as the Cascaded Two Level (CTL) converter but is functionally identical to the MMC in every aspect apart from the harmonic performance which may be slightly poorer.

5.3.2 MMC topology with VSC levels in half-bridge topology

Each of the 6 variable voltage sources shown in Figure 17 is realised with a series connection of identical VSC valve levels with an electrical equivalent as shown in Figure 18. The VSC valve level is a two-terminal component with its own d.c. storage capacitor unit as shown in Figure 18. These VSC valve levels are individually controlled and can be switched between a state with full submodule voltage (voltage of the associated storage capacitor) and a state with zero submodule voltage for both current directions. If the submodule voltage is applied to the VSC valve level terminals, the capacitor can be charged and discharged dependent on the current direction of the converter phase arm.

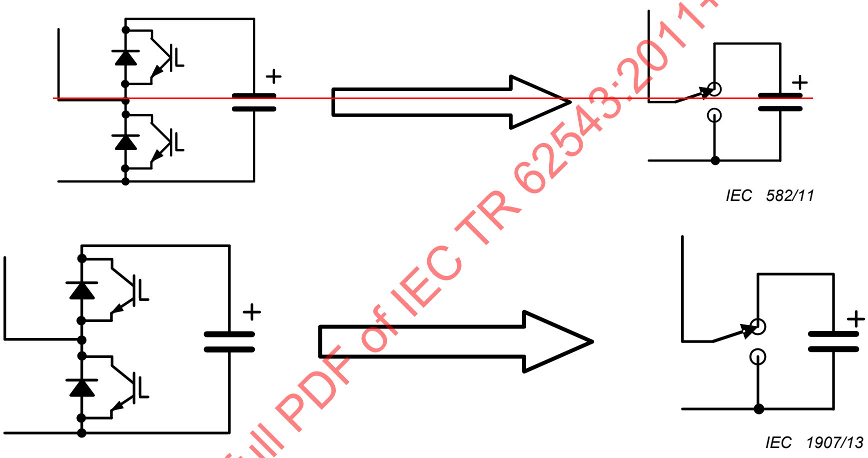
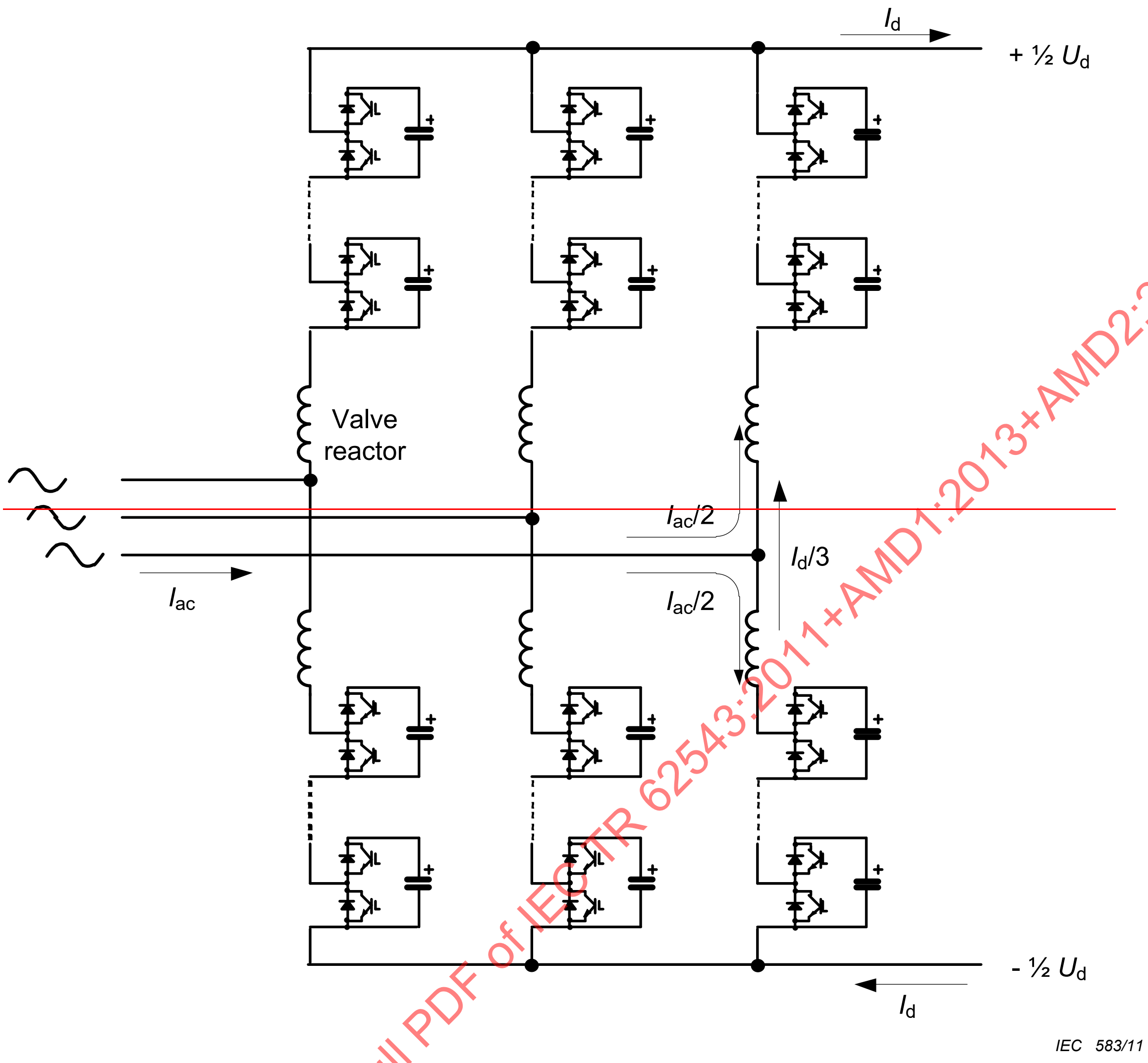


Figure 18 – VSC valve level arrangement and equivalent circuit in MMC topology in half-bridge topology

The electrical arrangement of VSC valve levels and valve reactors in a converter block is shown in Figure 19.

The VSC valve levels are controlled in that way that the sum of the upper and lower arm of one phase unit equals to the d.c. voltage whereas the instantaneous voltage on the a.c. terminals is determined by the ratio of the voltages of the two converter phase arms of one phase unit.



I_d
+ ½ U_d
Valve
reactor
$I_{ac}/2$
$I_d/3$
I_{ac}
$I_{ac}/2$
- ½ U_d
I_d
IEC 583/11

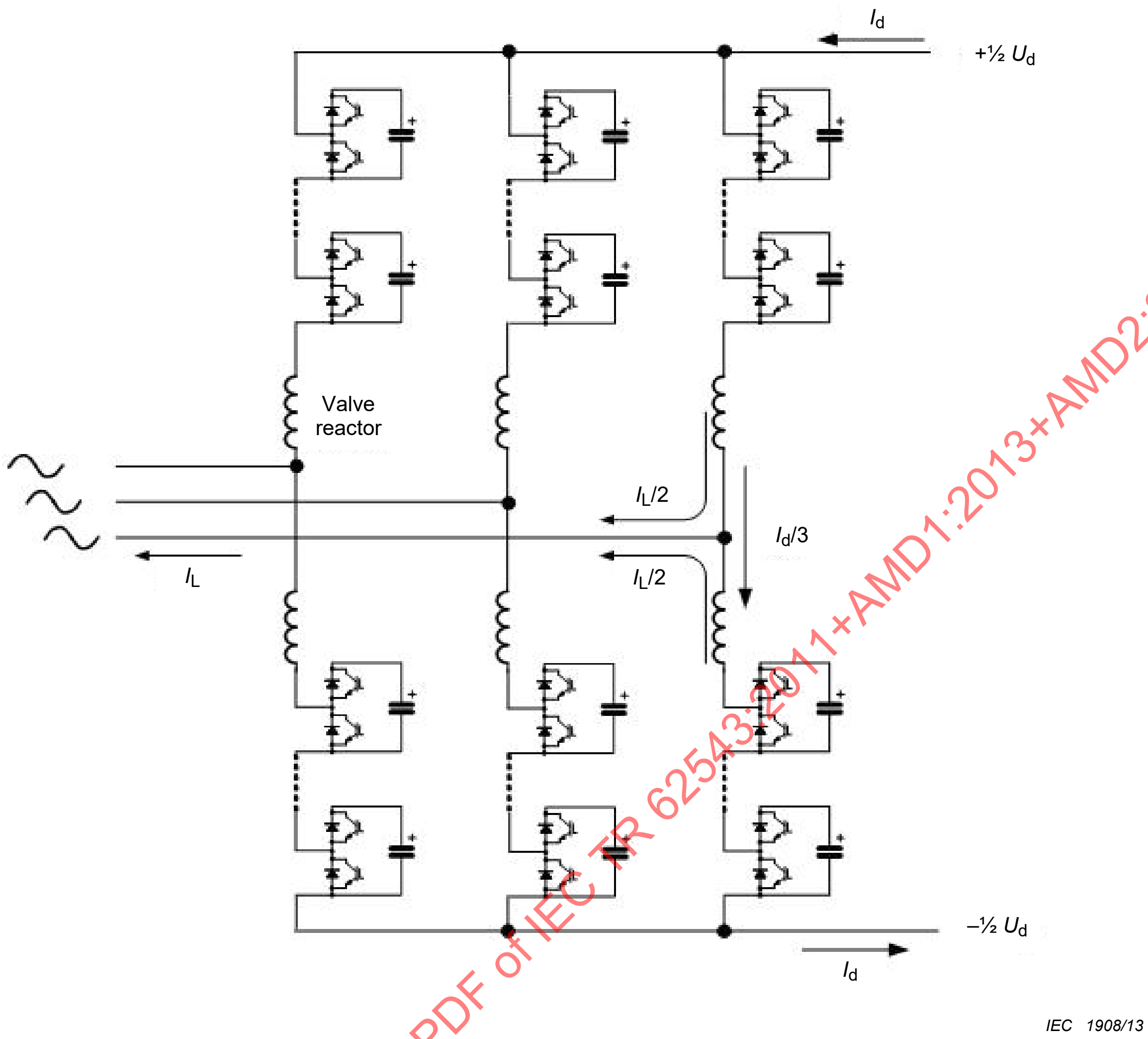


Figure 19 – Converter block arrangement with MMC topology in half-bridge topology

5.3.3 MMC topology with VSC levels in full-bridge topology

The MMC topology with "full-bridge" VSC levels operates on very similar principles to that based on half-bridge VSC levels. The principal difference is that each VSC level consists of one storage capacitor and four IGBTs in a bridge configuration as shown on Figure 20.

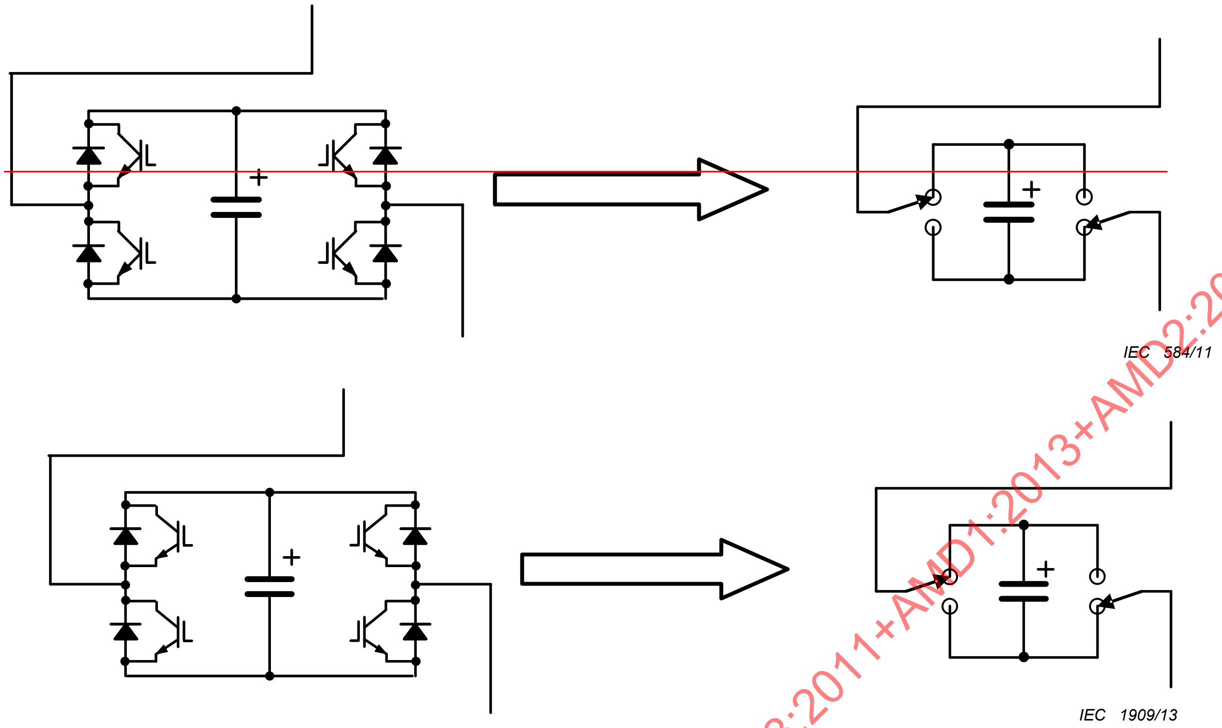


Figure 20 – VSC valve level arrangement and equivalent circuit in MMC topology with full-bridge topology

In common with the half-bridge sub-module configuration, each VSC level in the full-bridge configuration is capable of producing an output voltage of zero or a positive output voltage equal to the capacitor voltage. However, it can alternatively produce a negative output voltage equal to the capacitor voltage.

In contrast to the converter arrangements outlined in Subclauses 5.2 and 5.3.2, this converter arrangement is capable of producing a d.c. output voltage of either polarity, a feature which can be beneficial in applications where a VSC transmission station is connected as a tap onto an existing line commutated HVDC link.

A second advantage of the full-bridge circuit is that it permits faults on the d.c. side of the converter to be cleared by using only the power semiconductors in the valve, without requiring any additional switchgear.

On the other hand the full-bridge circuit requires, in principle, twice the number of IGBTs compared with the half-bridge circuit.

5.3.4 CTL topology with VSC cells in half-bridge topology

Each of the 6 variable voltage sources shown in Figure 17 is realized with a series connection of identical VSC valve cells. One VSC valve cell acts as a single-phase two-level converter and functions electrically equivalent to one level of the MMC described in Subclause 5.3.2, except that the voltage rating is higher. Instead of a single IGBT/diode level in one MMC level, multiple IGBT/diode levels are connected in series and synchronously controlled as one switch in one CTL cell.

The electrical arrangement of VSC valve cells and valve reactors in a converter block is similar to Figure 19. The IGBT/diode levels depicted in Figure 19 are substituted by valve cells in CTL topology.

The cell d.c. capacitor voltage in the CTL topology corresponds to one valve voltage step.

5.3.5 CTL topology with VSC cells in full-bridge topology

The CTL topology with "full-bridge" VSC cells functions similarly, in principle, to the MMC topology with VSC levels in full-bridge topology, in Subclause 5.3.3. The main difference between CTL topology with VSC cells in full-bridge topology and MMC topology with VSC levels in full-bridge topology is the number of IGBT/diode levels per CTL cell or MMC level. Each CTL cell consists of multiple IGBT/diode levels in series connection and each MMC level is of one IGBT/diode level.

5.4 VSC valve design considerations

5.4.1 Reliability and failure mode

In addition to the number of series-connected valve levels that are needed to sustain the converter voltage rating, each single valve in a VSC transmission scheme shall include a few redundant valve levels. In case of failure of an individual valve level component, uninterrupted operation of the remaining healthy valve levels is mandatory. Therefore, a faulty valve level shall safely and controllably enter into a short-circuit mode and be capable of conducting current until it can be changed out, e.g., during a scheduled maintenance period.

This capability of short-circuit failure mode (SCFM) operation is very critical for series-connected valve levels, and shall be verified by appropriate tests under conditions that are relevant for a particular application. Some special designs of Presspack IGBT allow SCFM to be assured. Module IGBTs, however, do not exhibit this behaviour and a faulty Module IGBTs may result in an open circuit. Thus, additional components in parallel to the valve level terminals are required to ensure SCFM.

The operating voltage of the IGBT shall be selected to be low enough to achieve an adequately low failure-in-time (FIT) rate.

In selecting the operating voltage and current of the IGBT, due consideration should be given to the load cycling requirements for the VSC system.

5.4.2 Current rating

One of the important design bases of the semiconductor in the VSC valve is rated current. In addition, the valve should also be able to handle peak current, including ripple and transients, as well as margins for control and protection actions. The rated phase current gives the nominal stress on the component and shall be considered regarding power losses and junction temperature on the IGBT.

5.4.3 Transient current and voltage requirements

An important aspect of IGBTs is their capability to turn off current and voltage. This capability is defined in the switching safe operating area (SSOA) shown in Figure 21.

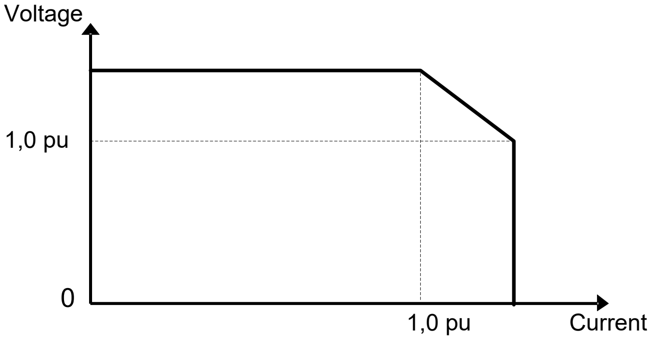


Figure 21 – Typical SSOA for the IGBT

During switching, the IGBT shall be able to turn-off the peak current, including ripple. Additionally, a margin is added to handle current control regulation and protection actions during transient conditions. The valve shall also be capable of turning off the current which results from a short circuit occurring close to the valve. The IGBT short circuit operation capability is defined by the SCSOA (short circuit safe operating area), which is slightly different from the SSOA under normal operation.

5.4.4 Diode requirements

In many converter topologies (including the 2-level and 3-level converters and the MMC with half-bridge topology), the free-wheeling diodes (FWD) in a VSC bridge act as an uncontrolled rectifier bridge. Thus they can be exposed to severe transient overcurrents, for example during d.c.-side short circuits or at energisation.

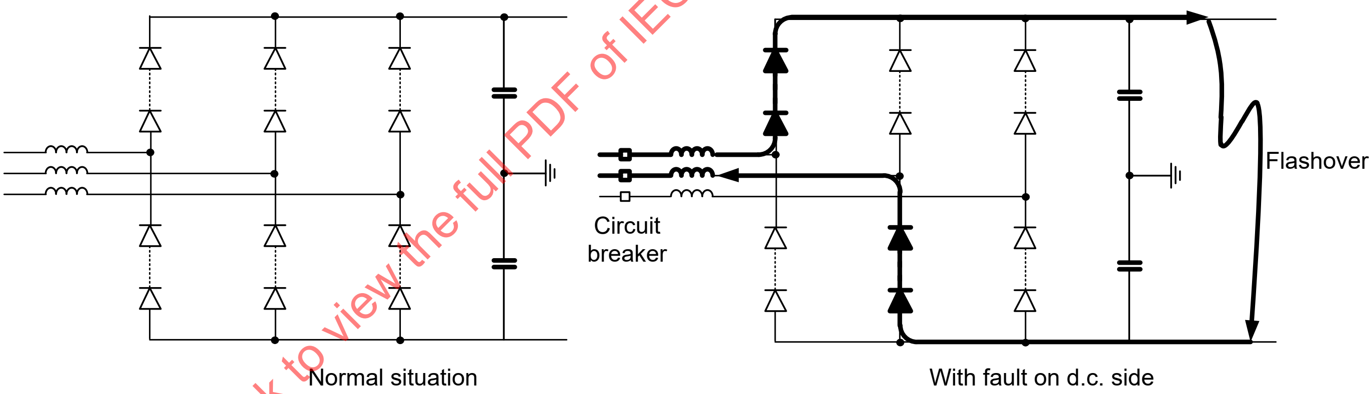


Figure 22 – A 2-level VSC bridge with the IGBTs turned off

In case of a d.c. side fault, as shown in Figure 22, a short circuit between the two d.c. terminals creates a fault current path through the diodes. The current in the a.c. phases in the VSC bridge is limited only by the short-circuit impedance of the a.c. network and the reactance in the converter, e.g., the phase or valve reactors and/or transformers. The fault current is detected by the protection system, which will open the breaker on the a.c. side and thereby eliminate the fault current. A normal protection and breaker scheme takes a time equivalent of three 50/60 Hz fundamental frequency cycles before the fault current is extinguished. If the d.c. system only consists of cables, a fault will be very unlikely. However, the consequences may not be acceptable if the system is not designed to handle the fault. The valve should be designed to handle the fault current with an asymmetrical offset as a worst case. Here, no reapplied voltage occurs since the breaker has disconnected the a.c. system.

Another transient that the diode may experience occurs if the VSC is energized through the a.c. breaker when there is either no voltage, or a low voltage, on the d.c. side. In this case, the converter experiences a surge inrush current and an overvoltage will occur on the d.c. bus. The valve shall be designed to handle the inrush current, or the current will have to be limited. The normal method for doing this is to include pre-insertion resistors.

5.4.5 Additional design details

Besides controlling the ~~switching~~ turn-off semiconductor device in regular operation, the gate unit should keep the switching device within the safe operating area in all other operational and short-circuit conditions. IGBTs have proven comparatively easy to handle in this respect, thereby facilitating precise control of switching waveforms. This, in turn, is necessary for achieving proper control and protection strategies for the converter.

The switching transients which appear when the IGBT turns on or off give stress to the IGBT and other components in the valve levels. The energy stored in stray inductances and capacitances will generate transient voltages and currents respectively.

Gate voltage control makes it possible to control the voltage between the main two terminals of the IGBT at its turn off process. Suppressing the speed of turn off makes the energy stored in the loop stray inductance dissipate in the IGBT itself. Applying the gate voltage control technology, the snubber circuit can be omitted from the circuit, although switching losses in the IGBT become larger.

For converter topologies with VSC valves of “switch” type it is possible to design the VSC valve such that it does not use traditional snubber circuits for protecting the individual IGBTs. In this case, the IGBTs shall themselves maintain sufficient voltage sharing, both during switching and blocked conditions, by means of gate control and d.c. grading resistors. This, in turn, requires a small spread in device data concerning characteristic switching times, switching transient properties, and leakage currents in the blocked state.

Converter topologies with VSC valves of the “controllable voltage source” type ~~do not rely on~~ only require synchronized switching of individual valve levels when multiple IGBTs are connected in series in each switch position (as in the cascaded two level converter). ~~Thus~~ Where no direct series connection of IGBTs is used, a coordination of IGBTs switching properties of individual valve levels is not required.

5.5 Other converter topologies

The technical field of VSC transmission is developing rapidly. Accordingly it is to be expected that other converter topologies in addition to those described above will emerge. Some existing known topologies are already described in ~~the work of~~ CIGRÉ ~~B4-48~~ Technical Brochure 447.

Purchasers of VSC transmission schemes should consider such alternative converter topologies on their merits and not limit the permitted circuit topologies to those that have been described in Subclauses 5.2 and 5.3.

5.6 Other equipment for VSC transmission schemes

5.6.1 General

According to its principle of operation, only a few components are essential in a voltage sourced converter (VSC). These are

- a means to convert d.c. into a.c. voltages provided by a converter comprising VSC valves and controls;
- an a.c. side reactance provided by phase reactors/valve reactors, transformers, or a combination thereof;

- a d.c. voltage source provided by at least one VSC d.c. capacitor, submodule d.c. capacitor or cell d.c. capacitor.

In addition to these key components, a complete VSC substation may also need

- a.c. and d.c. filters;
- surge arresters;
- circuit breakers and switches;
- measuring equipment.

The above equipments are not always necessary in all converter topologies, but differ due to the real requirements because different components are stressed differently in the different topologies.

5.6.2 Power components of a VSC transmission scheme

Figure 1 shows the basic structure of a VSC substation and the location of the major power components. Depending on the design concept and the VSC substation topology, several components might occur more than once in a real structure, while others might not be needed. The functions and important design aspects of each component are briefly explained in the following paragraphs.

5.6.3 VSC substation circuit breaker

The VSC substation circuit breaker is located at the feeder from the a.c. transmission system to the VSC transmission scheme. Its main function is to connect and disconnect the VSC substation to and from the a.c. system. There are no special requirements compared to what is common practice for circuit breakers used for a.c. substation applications.

Depending on the start-up concept of the VSC transmission scheme, a circuit breaker can be equipped with a closing resistor, or a separate resistor, with either a circuit breaker or disconnector in parallel with it, may be provided in series with the main circuit breaker. The resistor reduces the charging currents of the d.c. circuit, resulting in smaller temporary a.c. system disturbances and lower stresses on the free-wheeling diodes during energization.

5.6.4 A.C. system side harmonic filters

Depending on the converter design and a.c. system conditions, filtering may be required to prevent VSC-generated harmonics from penetrating into the a.c. system or to prevent amplification of background harmonics on the a.c. system.

As a side effect, harmonic filters generate fundamental frequency reactive power which needs to be considered in the overall P-Q operating range of the VSC system. The design principles of system side harmonic filters and any associated circuit breakers do not differ from the design practice for HVDC systems with line-commutated converters (LCC) or flexible alternating current transmission systems (FACTS). High pass, single, double or triple tuned filters may be used as described in IEC/TR 62001.

5.6.5 Radio frequency interference filters

Radio frequency interference (RFI) filters reduce to acceptable limits the penetration of high frequency (HF) harmonics into the a.c. system.

HF harmonics generated require special attention during the design of a VSC substation. To calculate line-carried HF harmonics, a detailed representation of the VSC substation layout is necessary, including the structure and geometry of power components, busbars and grounding system. Additionally, the current and voltage waveforms experienced during the conversion process shall be known.

The design principles for the RFI filter do not differ from the design practice for LCC HVDC or FACTS.

5.6.6 Interface transformers and phase reactors

In many cases, the VSC substation design will include interface transformers. In general, they can fulfill the following tasks:

1) provide a reactance between the a.c. system and VSC unit;
2) adapt a standard a.c. system voltage to a value matching the VSC a.c. output voltage and allow optimal utilisation of VSC valve ratings;
3) connect several VSC units together on the a.c. side that have different d.c. voltage potentials;
4) prevent zero sequence currents from flowing between the a.c. system and VSC unit.

Depending on the design concept applied to the VSC substation, the reactance mentioned under point 1) can be provided by a phase reactor, a transformer, or a combination thereof. The reactance is necessary to allow control of the a.c. output current of the VSC. Design criteria to determine the size of the reactance are

- the required dynamic behaviour of the system;
- the tolerable harmonic content of the converter a.c. current;
- constraints revealed from analysis of transient conditions and fault scenarios.

If points 2) to 4) do not apply under specific circumstances, the required reactance could be provided by phase reactors, which would eliminate the need for a transformer.

For the design of reactors or transformers, the following points have to be taken into account:

- DC voltage stress on converter winding insulation to ground, for the cases of asymmetrical monopole or bipole;
- stresses due to fundamental current;
- saturation characteristics with respect to possible a.c. harmonic and d.c. flux components;
- stresses due to harmonics in the lower and middle frequency range;
- dielectric stresses due to harmonics in the middle and upper frequency range, particularly for VSC valves of the “switch” type;
- dielectric stresses due to normal operating voltage and transient voltages occurring during fault scenarios.

Particularly in the case of high-voltage VSC valves of the “switch” type, the magnitudes of the harmonic voltages generated require detailed design studies to provide reliable information about the voltage and current profiles along windings. The interface transformer does not require a tap changer. However, if a tap changer is used, it is possible to optimise the VSC operation, e.g., to achieve reduced power losses or to increase power capability under low-voltage conditions.

5.6.7 Valve reactor

For valves of the “controllable voltage source” type, valve reactors are connected in series to the VSC valve levels as shown in Figure 17. These reactors have several different functions:

- the three phase units represent three d.c. voltage sources, connected in parallel. During operation, these voltages cannot be exactly equal, resulting in circulating currents between the three phase units. The valve reactors limit these circulating currents and enable to control them;
- the valve reactors limit the valve short circuit current;

- the valve reactors are a contribution to the interface impedance between the converter and the a.c. network;
- in some designs, the valve reactors may be combined with tuning capacitors and play a role in limiting circulating harmonic currents between phases.

NOTE The valve reactors can be placed in several locations, for example at the DC terminals, at the AC terminals, distributed amongst the valve submodules or integrated into the same tank as the interface transformer.

5.6.8 D.C. capacitors

5.6.8.1 VSC d.c. capacitor

5.6.8.1.1 General

The VSC d.c. capacitor, in conjunction with the d.c. cable (where used) provides the d.c. voltage necessary to operate the VSC. It is connected directly in parallel to the d.c. terminals of the VSC phase units. For the design of the VSC d.c. capacitor, the following aspects need to be considered.

5.6.8.1.2 Commutation circuit inductance

Switching the semiconductor devices of the VSC causes HF commutation current to flow through the commutation circuit formed by the switching valves, the VSC d.c. capacitor, and the connecting bus bars. Due to the stray inductance within the commutation circuit, these HF currents result in transient voltage stresses on the switching valves. To minimize these stresses, the inductance of the connection of the VSC d.c. capacitor to the valves should be as low as possible.

5.6.8.1.3 D.C. voltage ripple

VSC operation results in harmonic currents flowing in the d.c. circuit. These harmonic currents cause harmonic voltages (also known as d.c. voltage ripple). The following factors will influence the size of the d.c. voltage ripple:

- imbalances in the a.c. system and/or converter operation;
- pre-existing harmonics in the a.c. network;
- VSC valve switching strategy.

5.6.8.1.4 Capacitance of the VSC d.c. capacitor

The VSC d.c. capacitance shall be large enough to keep the d.c. voltage ripple within tolerable limits.

5.6.8.1.5 Control aspects

The d.c. voltage influences active and reactive power exchange with the a.c. system. To achieve stable operation of the transmission system, it is important to keep the d.c. voltage within tight limits. Changing power orders, a.c. system unbalances, or system transients change the operating conditions of the VSC and can cause d.c. voltage fluctuations or oscillations. Due to its energy storage capability, the VSC d.c. capacitor stabilises the operation of the VSC.

Important design parameters of the VSC d.c. capacitor are as follows:

- maximum d.c. voltage for continuous operation;
- maximum acceptable d.c. voltage variations under transient conditions, such as faults on the a.c. system.

5.6.8.1.6 Harmonic coupling of different VSC substations connected to one d.c. circuit

Harmonic currents generated by a VSC cause harmonic voltages not only on their own VSC d.c. capacitor, but also on the VSC d.c. capacitors in other VSC substations connected to the same d.c. circuit. As a result, the different VSC substations in a transmission scheme become mutually coupled via the d.c. circuit. To avoid unwanted interactions between the VSC substations, this coupling should be reduced to the largest extent possible. The capacitance of the VSC d.c. capacitor is an important factor influencing the coupling between the VSC substations.

5.6.8.2 Submodule/cell d.c. capacitor

5.6.8.2.1 General

In principle, the design and function of the submodule/cell capacitors for the MMC and CTL ~~technology is~~ technologies are similar to that of the VSC d.c. capacitors.

However, due to their operation principle, the current stresses are different for d.c. submodule or cell capacitors. The individual submodules or cells can be individually switched "off" or "on" depending on output voltage generation. When the submodule is switched "off" the valve current does not pass through the d.c. submodule/cell capacitor and the capacitor current is zero. Conversely, when the submodule or cell is switched "on", the full valve current flows through the capacitor. In the "on" state, components of d.c. current and fundamental and low order currents have to be considered. The current flow in the "on" state results in a significant ripple voltage of the submodule/cell capacitors per power cycle. The average and RMS capacitor current stresses are calculated based on current contribution in the "on" state.

5.6.8.2.2 Commutation circuit inductance

Similar to the VSC d.c. capacitor, switching the semiconductor devices of the submodule causes HF commutation current to flow through the commutation circuit of the submodule. Due to the stray inductance within the commutation circuit, these HF currents result in transient voltage stresses on the submodule. To minimize these stresses, the inductance of the submodule should be as low as possible.

5.6.8.2.3 D.C. voltage ripple

a) Submodule capacitor voltage ripple

As mentioned before, the ratio of the voltage ripple to d.c. voltage of the submodule capacitor is larger than that of VSC d.c. capacitors.

b) D.C. link voltage ripple

The d.c. link voltage ripple of the MMC is much lower than that of the VSC d.c. capacitors of 2-level or NPC converters, because the MMC d.c. link voltage is almost the same as the sum of the output voltage of submodules in a phase leg. By shifting the output voltage pulse of the each submodule, the d.c. link voltage ripple of the MMC is small.

5.6.8.2.4 Capacitance of the MMC submodule capacitor

The MMC submodule capacitance shall be large enough to keep the voltage ripple of submodule capacitor within tolerable limits.

5.6.8.2.5 Control aspects

In addition to the control aspects of the VSC d.c. capacitors, the submodule capacitors have some control aspects described below.

- MMCs have many submodule capacitors, whose voltages may tend to become unbalanced. ~~So the voltage of submodule capacitors should be balanced.~~ Therefore, a balancing control is required in order to ensure that any unbalance does not become excessive and result in equipment ratings being exceeded.
- Discharge of the MMC submodule capacitors caused by a d.c. fault can be prevented by blocking the converter.

5.6.8.2.6 Harmonic coupling of different MMC substations connected to one d.c. circuit

Between the submodule capacitors of different substations, there are some semiconductor devices. So harmonic coupling is less serious for the MMC VSC systems than that of 2-level or NPC VSC systems.

5.6.9 D.C. reactor

For long distance transmission, a d.c. reactor can be connected in series with a d.c. overhead transmission line or cable. Its main purpose is to reduce harmonic currents flowing in the d.c. line or cable.

The d.c. reactor also serves a secondary function in limiting short-circuit currents.

If a d.c. reactor is used in a VSC transmission system, its size can normally be considerably smaller than one used in an LCC HVDC scheme.

5.6.10 Common mode blocking reactor

A common mode blocking reactor consists of two magnetically-coupled windings having the same self impedance. Due to the winding arrangement, the reactor provides low impedance for differential mode currents but high impedance for common mode currents. The reactor, therefore, serves to block the common mode currents and leaves the differential mode currents largely undisturbed and, in consequence, does not affect the dynamic behaviour of the transmission system.

The design of the reactor depends largely on the system grounding arrangement, transmission line type, environmental conditions and electrical stresses associated to the project.

5.6.11 D.C. filter

Filtering of harmonics on the d.c. side is achieved by the VSC d.c. capacitor, d.c. reactor, common-mode blocking reactor and, in some cases, by a dedicated d.c. filter.

The design principles of the d.c. filters for VSC-based HVDC systems are similar to those for LCC HVDC systems, as described in CIGRE Technical Brochure 92.

5.6.12 Dynamic braking system

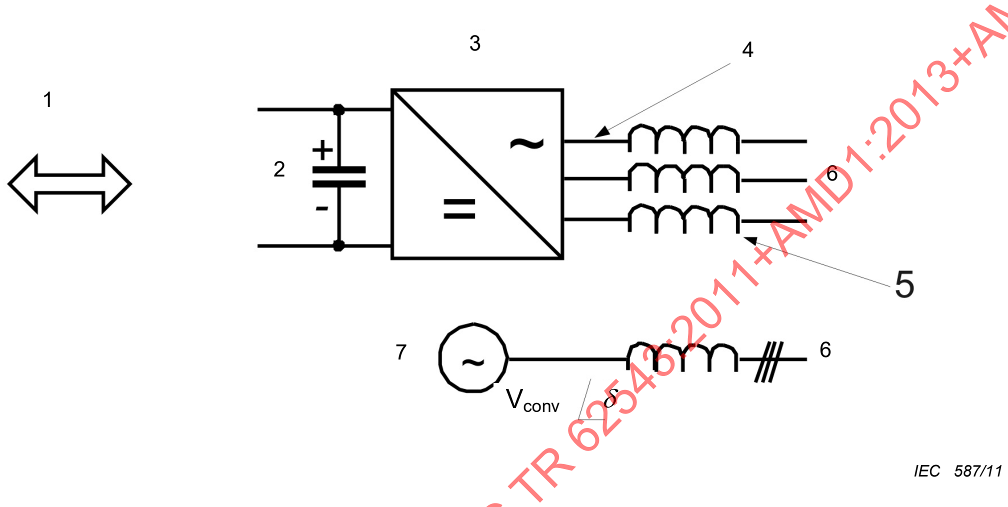
In some VSC HVDC schemes, but particularly where the HVDC system is exporting power from a small islanded a.c. system with little or no load (for example an offshore wind farm) the HVDC system may be required to include a dynamic braking system, for example as a chopper connected to the d.c. terminals of the VSC system. The function of the dynamic braking system is to absorb and dissipate the power generated in the islanded AC system during faults in the receiving-end AC system, typically for durations of 1 to 2 s.

There are several possible ways of implementing such a dynamic braking system but the valves in this system will, in general, be of similar design to the main VSC valves used for power transmission.

6 Overview of VSC controls

6.1 General

Although there are many configurations for voltage sourced converters (VSCs), they all can be considered to exhibit a common operating concept. All configurations possess a series inductive interface separating the switching valves from the a.c. system. The switching valves generate a fundamental frequency a.c. voltage from a d.c. voltage. The magnitude and phase of the fundamental frequency component of this a.c. voltage at the valve side of the series inductive interface can be controlled. The control of this voltage magnitude and phase is the essential controlling function common to all VSCs.



Key

1 active power
2 d.c. side
3 voltage sourced converter
4 point of phase and magnitude control of a.c. voltage
5 phase reactor and/or interface transformer
6 a.c. side
7 equivalent representation of a VSC as a voltage behind an inductance

Figure 23 – Representing a VSC unit as an a.c. voltage of magnitude *U* and phase angle *δ* behind reactance

Figure 23 shows that a VSC can be represented as an a.c. voltage source of magnitude U_{conv} and phase angle delta behind the reactance. If the per-unit voltage magnitude U_{conv} is higher than the per-unit line side voltage U_L, then reactive power will be transferred into the line side similarly to an overexcited synchronous machine. Conversely, if the magnitude U_{conv} is low and less than the line side volts, the VSC will be absorbing reactive power similarly to an under-excited synchronous machine.

The control of the phase angle δ is achieved by shifting the phase of the fundamental frequency a.c. voltage with respect to the phase locked loop normally synchronized to the a.c. side voltage. Regulating the phase angle δ causes active power to be transferred through the VSC, because a phase angle in fundamental frequency voltage is developed across the interface reactor so that power flows into or out of the VSC.

A VSC therefore has the capability of acting as a rectifier or as an inverter, and/or as a generator or an absorber of reactive power. It is the control of the magnitude and phase of the converter voltage U_{conv} that dictates the strategies for controlling voltage sourced converters.

6.2 Operational modes and operational options

The normal way of a.c. side voltage control is achieved by controlling the d.c. side capacitor voltage. In turn, the d.c. side capacitor voltage is varied by pumping power from the a.c. side into it or out of it. If power is pumped into the capacitor, its charge will increase and consequently so will its voltage. If power is taken from the capacitor, its voltage will decrease. Power can be taken from or fed into the a.c. side by varying the phase angle δ, as described above. In this way, d.c. voltage control is achieved by regulating a.c. phase angle δ.

Control of the magnitude and phase of the converter voltage U_{conv} for VSC transmission applications is usually achieved by means of vector control strategy. With vector control, three-phase currents are transformed to d and q axis quantities based on the conventional abc to dq transformation, synchronized to the a.c. side three-phase voltage through a phase locked loop (PLL). The d and q axis voltages generated by the vector controls are transformed to three-phase quantities and converted into line voltages by the VSC as shown in Figure 24.

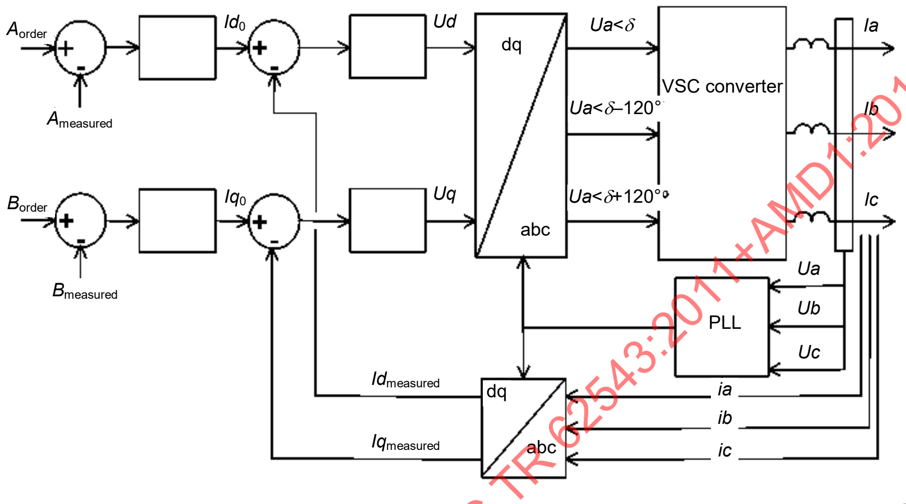


Figure 24 – Concept of vector control

With VSC converters, the degrees of freedom available are as follows:

- frequency control by direct control of the main firing oscillator;
- the various control options provided by phase shifting the a.c. voltage that is generated by the VSC;
- the various control options provided by control of the magnitude of the a.c. voltage that is generated by the VSC.

These degrees of freedom translate into the various control functions discussed below.

6.3 Power transfer

6.3.1 General

To control power into or out of the a.c. system, the VSC shall have a means for transferring power into or out of the d.c. side without over or under charging the capacitor. In a VSC transmission scheme, this means that the converters at the two ends of the scheme shall be controlled to work together. Generally, one of the two converters will have as part of its objective the control of the d.c. voltage.

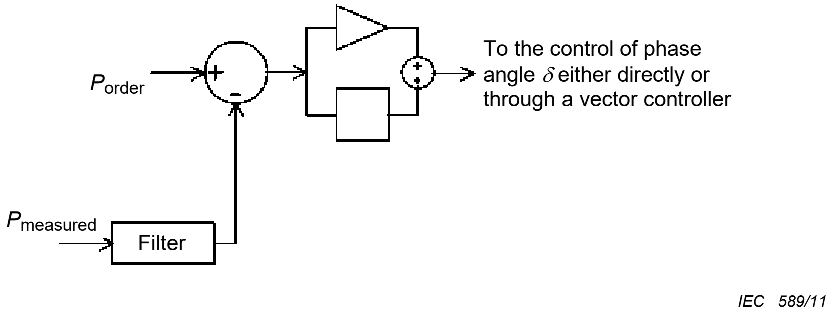


Figure 25 – VSC power controller

Power control is achieved by regulating the phase angle δ of the fundamental frequency component of the a.c. voltage at the converter side of the interface reactance as shown in Figure 25. Power is drawn from or pushed into the a.c. system depending on whether δ lags or leads the phase angle of a.c. bus voltage.

Power is one parameter that can be controlled with fast response to improve the performance of the a.c. transmission system under transient conditions. This can be used to increase a.c. system damping of electromechanical oscillations, as well as to improve the transient stability of the power system following a fault.

6.3.2 Telecommunication between converter stations

For VSC transmission control, there is no need for fast telecommunication signals between the ends. However, telecommunications between the converters may be applied for conditions such as the following:

- when power control is required between converters for a multi-terminal configuration, such as for coordinated damping of electromechanical oscillations;
- when damping of electromechanical oscillations is required at the converter that is not controlling power;
- if it is desired to reconfigure the control modes between converters.

The normal use of communication is however between the converter stations and dispatch centre which requires indications, status signals and alarms for operation of the system.

6.4 Reactive power and a.c. voltage control

6.4.1 A.C. voltage control

A.C. voltage control is achieved by regulating the magnitude of the fundamental frequency component of the a.c. voltage generated at the VSC side of the interface reactor and/or transformer as shown in Figure 26.

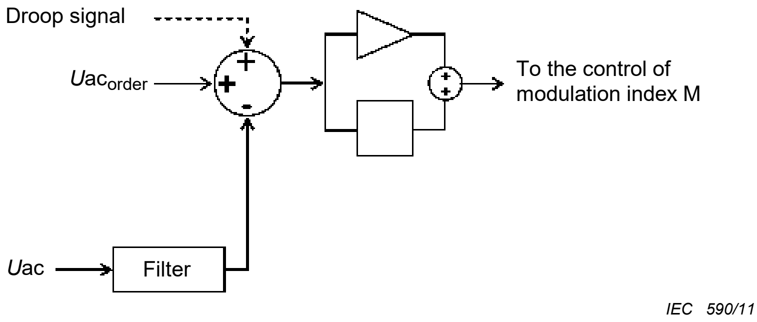


Figure 26 – A.C. voltage controller

If the VSC is feeding into an isolated a.c. system with no other form of active power source of any significance, the a.c. voltage controller will automatically control power to the load. This assumes another converter, such as the sending end of a VSC transmission link, independently controls the d.c. side voltage.

6.4.2 Reactive power control

The need to use reactive power control arises when other nearby controllers are acting to maintain a.c. voltage. To avoid interference between the various controllers, it is preferable to retain those VSCs not needed for a.c. voltage to provide reactive power control.

If all VSCs in close proximity to each other are controlling the same quantities, then it may be possible for each to participate in a.c. voltage control through a carefully designed droop characteristic. However, if the controlling functions of the VSC are quite different, such as separate and independent power controllers, the droop characteristic may be difficult to define. Under these circumstances, a reactive power control may be preferable, with the settings either at zero MVARs or slowly controlled by a joint VAR controller or an order from the SCADA system.

6.5 Black start capability

To supply an a.c. load that has no other source of generation, the rectifier connected to the main grid or generation may have the following controls.

- D.C. voltage control.
- A.C. voltage or reactive power control at the sending end system.

The receiving end should have controls as follows:

- frequency control (defining the frequency of the load);
- a.c. voltage control of the receiving end system.

With these control modes in place, the load-side a.c. voltage and frequency can be controlled within acceptable limits. As the load changes, the transmission self-regulates the power flow simply by maintaining a.c. voltage and frequency.

If an a.c. synchronous generator or an a.c. transmission line is added or switched on-line so that the VSC transmission is relieved of providing the frequency control and all the a.c. voltage control to the load, the firing pulses may be switched from an independent clock to being phase locked onto the a.c. voltage. Alternatively, a droop characteristic for the frequency control and the a.c. voltage control may be invoked so that the VSC transmission can operate in concert with the active system that the receiving end has changed to.

6.6 Supply from a wind farm

When d.c. transmission is required to bring power from a wind farm to an a.c. grid, VSC transmission can be integrated into the wind turbine design for maximum performance and economy. This technology may be particularly applicable for offshore wind farms. This is an important and fast-growing use of VSC transmission, which is described in detail in CIGRE Technical Brochure 370.

At the sending end the VSC converter controls the a.c. voltage and frequency of the system. The converter at the a.c. grid side transfers the incoming d.c. power to the a.c. grid. The a.c. grid shall be strong enough to accept fluctuating wind farm infeed.

One important aspect is how to handle energy surplus in case there is a temporary network disturbance where the a.c. grid is unable to absorb the energy from the wind farm.

Alternatives to handle this energy surplus include to store the surplus energy in the wind turbine by temporarily increasing rotor speed or to dissipate the energy via resistors, for example

- in the wind turbine itself;
- on the offshore a.c. grid;
- on the d.c. side of the VSC transmission, via a ~~chopper circuit~~ dynamic braking system.

7 Steady state operation

7.1 Steady state capability

The VSC can be considered as an equivalent of a synchronous machine, which has the capability of individually controlling active and reactive power, albeit normally with limited inertia.

The active and reactive power can be controlled simultaneously and independently of each other as described in Subclauses 6.3 and 6.4.

The PQ capability diagram of a VSC shows its possible operating regime. The diagram normally gives the capability at the a.c. interface point. When active output power P is positive, the VSC is operated as an inverter, either in capacitive mode, when Q is positive, or in inductive mode when Q is negative. When P is negative, the VSC is operated as a rectifier, either in capacitive or inductive mode. A simplified PQ diagram at minimum (U_{min}) and maximum (U_{max}) a.c. grid voltage, in which filters are not considered, is shown in Figure 27. The VSC can be operated within all four quadrants of the PQ plane.

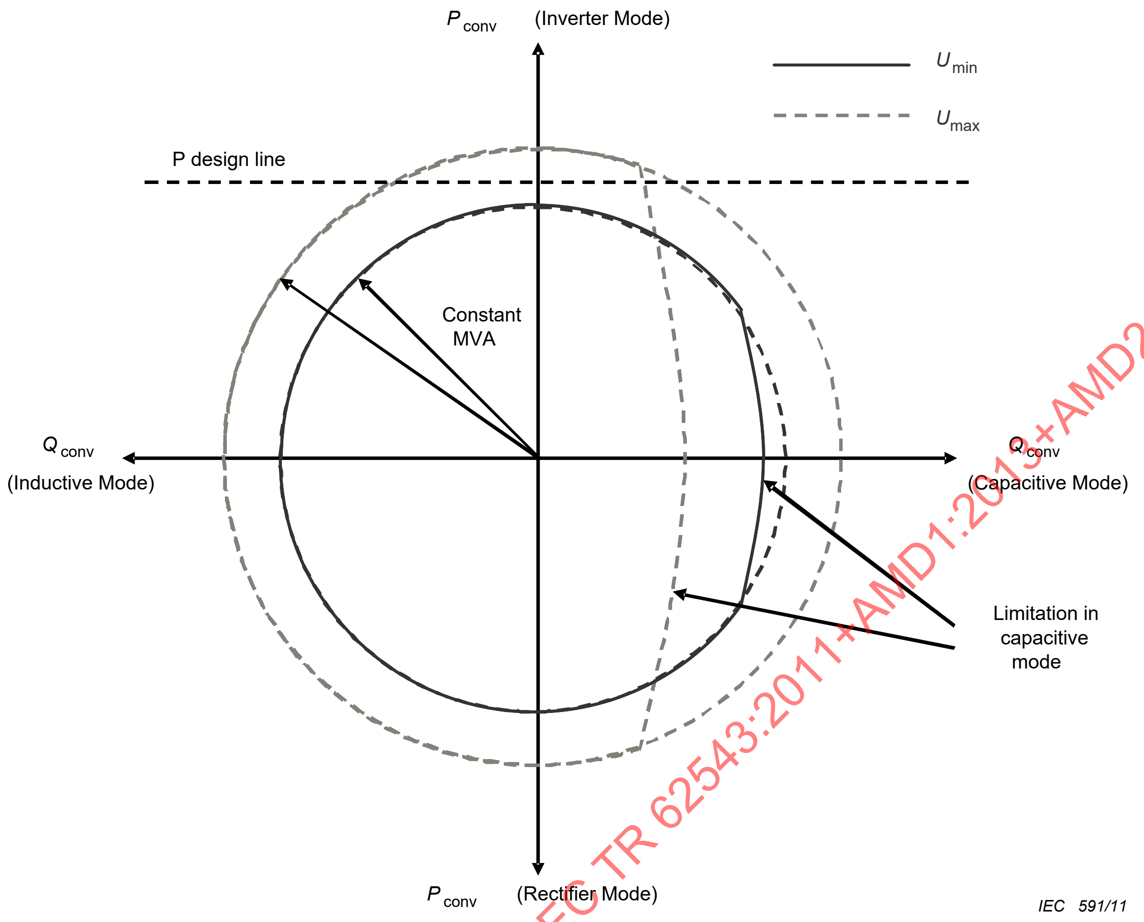


Figure 27 – A typical simplified PQ diagram

The PQ diagram shows that the capability of the VSC depends on the a.c. grid voltage. At low a.c. voltage, a higher current is necessary to produce a given output power, and the output capability is limited by the current capability of the converter. Therefore, if an interface transformer is provided, the transformer ratio can be used to optimize the PQ characteristic. With an on-load tap changer, the transformer ratio can be continuously optimized to maximize the steady-state power capability of the converter. Note that the centre of the circles is dependent on the design of the converter, and may not be at the origin of the diagram.

The diagram also indicates an active and a reactive power design line. The design line is the maximum power rating of the VSC and it is mainly determined by the maximum current for which the converter is designed. In addition to the limitation by the maximum converter current there might be other design limitations, for example affecting reactive power capability. In capacitive mode, the peak converter a.c. voltage U_{conv} needs to exceed the peak line-side a.c. voltage U_L; however U_{conv} generally cannot exceed 0,5 U_d. Therefore the capacitive output rating is limited, particularly at high values of U_L. The active power design line in the PQ diagram indicates the desired rated power of the VSC. In the example shown, the required power capability in inverter operation is less than the potential capability of the VSC.

7.2 Converter power losses

One of the main obstacles to using voltage sourced converters in bulk power transmission is the comparatively high power losses, including IGBT, filter and interface transformer losses, in comparison with LCC HVDC. However, VSC technology is developing rapidly and power losses are decreasing.

The 2-level VSC topology is attractive because of its simplicity. However, the switching frequency chosen shall be comparatively high in order to keep the current ripple reasonably low, and this will result in high switching losses. One way of reducing the losses is to use more advanced converter topologies, but at the expense of greater complexity. The on-going semiconductor device development and converter topology optimization will contribute to a further reduction in overall losses in the future.

In common with LCC-HVDC, it is recommended that power losses in VSC be determined by a combination of calculation and factory measurement, rather than direct measurement on site.

For most equipment, the overall principles are the same as described in IEC 61803 for LCC-HVDC, although adjustments need to be made to reflect, for example, differences of harmonic spectra. For converter valve losses, ~~the methods described in IEC 61803 do not apply~~ the IEC 62751 series shall be used instead of IEC 61803 (see also [31], [32]). ~~There is not yet a detailed procedure for determining losses in the converter; however the general principles outlined in Annex B may be used for guidance.~~

The power losses in the VSC substation depend on a variety of operating conditions, but chiefly the real transmitted power and the reactive power absorption or generation. In general, losses in the VSC substation will be lowest when the real and reactive power are both close to zero and will increase progressively as either the real or reactive power is increased.

8 Dynamic performance

8.1 A.C. system disturbances

Fast control of active and reactive power of VSC systems can improve power grid dynamic performance under disturbances. For example, if a severe disturbance threatens system transient stability, fast power run-back and even instant power reversal control functions can be used to help maintain synchronized power grid operation. VSC systems can also provide effective damping to mitigate electromechanical oscillations by active and reactive power modulation.

A VSC system can support the network during disturbances in the following ways:

- emergency power control;
- voltage support;
- short circuit current contribution.

The ability of the VSC converter to rapidly control active power makes it a tool for emergency power support during network disturbances where power can be transferred to/from the disturbed area in a controlled way. This is also possible with LCC-HVDC but VSC has better possibility to rapidly reverse power.

The VSC converter can operate as a local STATCOM with possibilities for fast voltage support. This can be used to support the connected a.c. network during a fault or disturbance where the a.c. voltage drop can be limited by the converter.

The short circuit power contribution from a VSC converter can be controlled. In systems where the short circuit currents are already high there is a large benefit in a low contribution. In systems fed solely by the VSC converter, higher short circuit currents are desirable in order to have the standard overcurrent protections in the a.c. network operating as normal. The maximum short circuit current is normally limited by the dynamic limitations of the converter which are equal to or higher than rated current.

8.2 D.C. system disturbances

8.2.1 D.C. cable fault

Mechanism: cable or junction failure, external mechanical stress.

Type: permanent fault, for which repair is needed.

Detected by: d.c. cable faults are detected by measuring the d.c. voltage and current, both amplitude and rate of change.

Protective actions: since any fault in a cable shall be thoroughly investigated and will most likely require a lengthy repair, the d.c. link has to be tripped when such faults are detected. It is therefore very important to correctly detect these faults.

8.2.2 D.C. overhead line fault

Mechanism: insulation failure between one d.c. conductor and ground or between the two d.c. conductors, due to lightning strike, brushfires, trees, pollution, external mechanical stress, etc.

Type: can be a non-permanent fault, but may be permanent if the d.c. insulators have been damaged.

Detected by: d.c. overhead line faults are detected by measuring the d.c. voltage and current, both amplitude and rate of change.

Protective actions: it should be noted that when insulation breaks down on overhead transmission lines, the VSC's free-wheeling diodes normally continue to feed current into the fault even if the converter is blocked. This means that besides blocking the converters, they normally also need to be isolated from the a.c. system by opening the a.c. breakers, to enable the air insulation to de-ionize. After this, re-starting the system may take a time of the order of 10 s. Another method is to introduce d.c. breakers and open these when a fault is detected, or to use a special VSC topology which gives an inherent capability to clear d.c. line faults (see Subclause 5.3.3).

8.3 Internal faults

VSC systems should be designed, where practical, to permit operation of the rest of the system to continue in the presence of internal faults within one converter station.

A typical protection diagram for a VSC substation is shown on Figure 28; however, VSC substation protection against internal faults will differ depending on the VSC design and protection philosophy. Therefore, the protection system shown in Figure 28 is only representative.

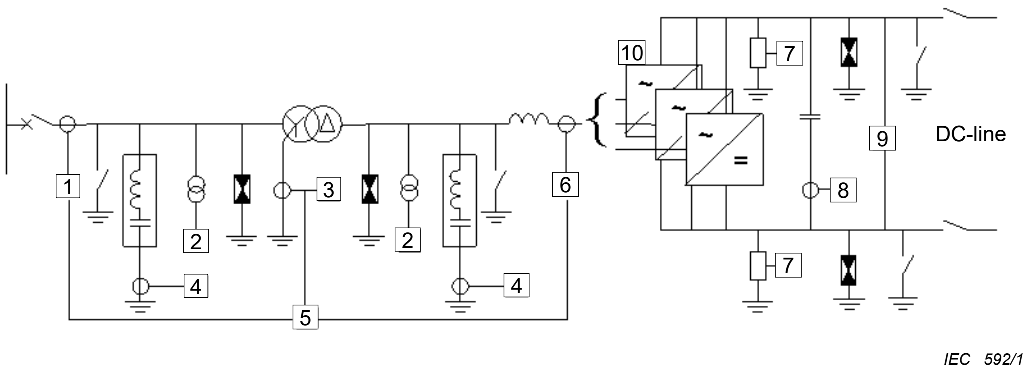


Figure 28 – Protection concept of a VSC substation

Typical protective functions include the following:

1 overcurrent protection of a.c. circuit breakers;
2 abnormal a.c. voltage protection;
3 earth fault protection;
4 a.c. filter protections;
5 differential protection;
6 overcurrent protection of the converter;
7 abnormal d.c. voltage protection;
8 overcurrent protection of the VSC d.c. capacitors;
9 d.c. discharge unit;
10 valve protection, e.g., in the valve gate electronics.

Depending on the VSC substation design and the application, the following additional protections are usually applicable:

- loss of cooling protection;
- d.c. line/cable earth fault protection/supervision;
- frequency protection;
- impedance relay protection;
- fire protection;
- mechanical protection.

9 HVDC performance requirements

9.1 Harmonic performance

Many aspects of the harmonic performance of a VSC transmission scheme are similar to those of an LCC HVDC scheme, as described in IEC/TR 62001. The main difference between the two comes from the different switching strategies used in the different types of converter. Different VSC topologies also have widely differing harmonic performance.

~~For the purpose of this clause the converters are treated as ideal sources. For real systems, however, the impedances and susceptances are finite. Consequently, the simple calculations presented here may not give results with acceptable accuracy.~~

In common with LCC converters, the interaction of VSC converters with the network is quite complex and, for an accurate calculation, the pre-existing (background) harmonics on the AC network need to be taken into account and the network impedance at harmonic frequencies is very important. Pre-existing harmonics may be damped or amplified due to operation of the VSC. In order to perform these calculations, accurate information about background harmonic distortion and network impedances for the frequency range of interest is necessary. More guidance on these topics can be found in the IEC 62001 series.

VSCs generate harmonics on both the a.c. and d.c. sides. Measures shall be taken to limit the amplitude of the harmonics entering the a.c. network and the d.c. line. The main methods of reducing the harmonics to acceptable levels are as follows:

- pulse width modulation (PWM) techniques;
- multi-level techniques;
- harmonic filters (series and/or shunt combinations);
- multi-pulse (12-pulse, 24-pulse etc) techniques;
- combinations of the above.

Since a VSC can operate at any desired power factor, the design of the filters is normally based only on harmonic performance and (unlike for LCC-HVDC) is not affected by reactive power considerations. Some multi-level converter topologies may generate sufficiently low levels of harmonics that harmonic filters can in some cases be omitted.

9.2 Wave distortion

The individual voltage distortion factor (D_n), total harmonic distortion (THD), telephone harmonic form factor (THFF), telephone influence factor (TIF) and total harmonic current factor (IT), as defined in IEC/TR 62001, are relevant also to VSC transmission schemes.

It should be noted that with VSC technology it is relatively easy to shift the spectrum of harmonics to higher orders of the fundamental frequency. When setting the distortion limits for a VSC transmission scheme, it may be appropriate to assess harmonics to a higher order than has been the case for LCC HVDC schemes, e.g., to increase the order to be included from the 50th harmonic to, for example, the 100th harmonic.

It also has to be noted that the accuracy of modelling of harmonic impedance decreases at such high frequencies.

9.3 Fundamental and harmonics

9.3.1 Three-phase 2-level VSC

A 2-level converter is shown in Figure 14.

The a.c. wave shape at a VSC phase unit output may consist of a sequence of square waves, as shown in Figure 29. Many different modulation methods can be used to control the converters to achieve a specific wave shape. The most commonly used method is the carrier-modulated method (voltage reference as sine wave or other with a triangular carrier wave shape). Some typical modulation strategies used with 2-level VSC are discussed in Annex B.

~~Figure 29a shows the control signals (the carriers and the voltage references as sine wave) for a PWM VSC. Figure 29b shows the resulting voltage V_{am} at the a.c. terminal a, with respect to a hypothetical midpoint m of the d.c. capacitor. In this example the frequency of the carrier (triangular wave signal) is nine times the fundamental frequency.~~

~~The general harmonic form of the switched waveform of Figure 29b can be written as follows:~~

$$v_{am}(t) = \frac{U_d}{2} M\cos(\omega_1 t + \theta_1) + \sum_{m=1}^{\infty} \sum_{n=-\infty}^{\infty} C_{mn} \cos[m(\omega_c t + \theta_c) + n(\omega_1 t + \theta_1)] \quad (2)$$

where

M is the modulation index,

ω_1 is the fundamental frequency,

ω_c is the carrier frequency,

m is a multiple of the carrier frequency,

n is a multiple of the fundamental frequency,

θ_1 is an arbitrary phase offset of the fundamental waveform, and

θ_c is an arbitrary phase offset of the carrier waveform.

The most effective approach to determine the harmonic coefficients C_{mn} is using double integral Fourier form as follows:

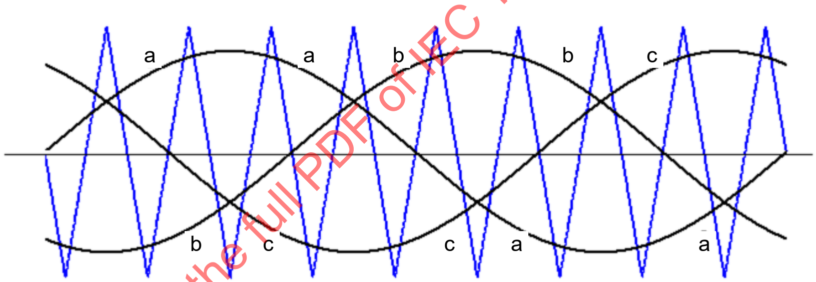
$$C_{mn} = \frac{1}{2\pi^2} \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} F(x,y) e^{j(mx+ny)} \mathrm{d}x\mathrm{d}y \quad (3)$$

where

$F(x,y)$ is the switched waveform for one fundamental cycle,

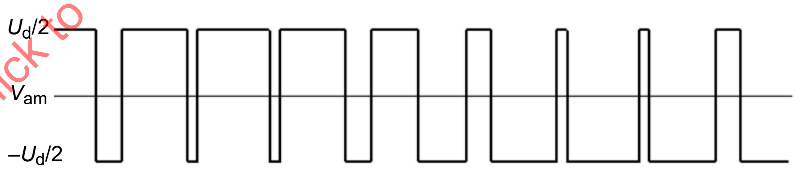
$X = \omega_c t$ and

$Y = \omega_1 t$.



IEC 593/11

a) Control signals for a PWM VSC



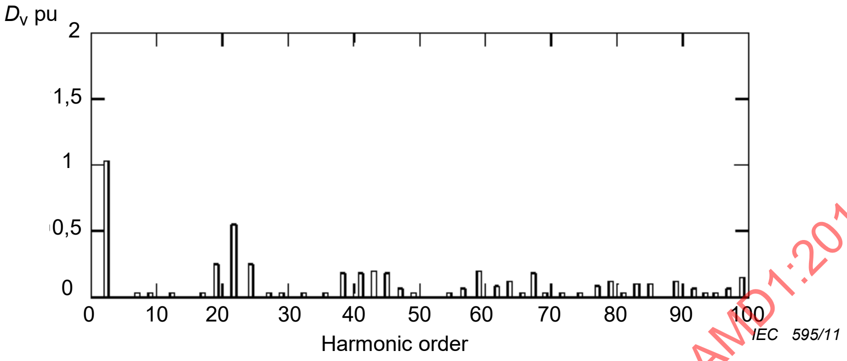
IEC 594/11

b) Phase a output voltage (V_{am})

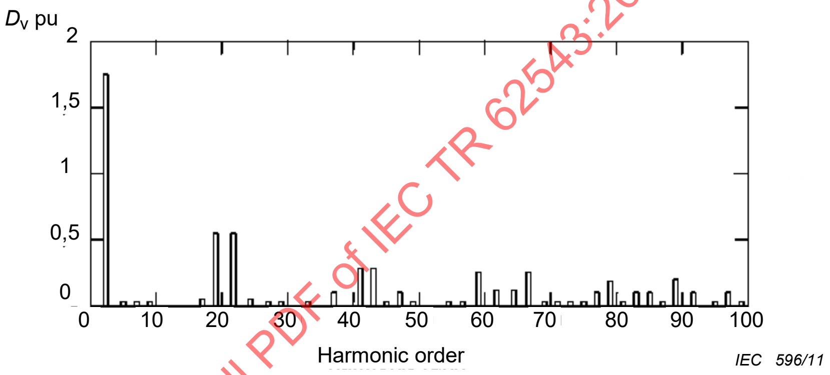
Figure 29 – Waveforms for three-phase 2-level VSC

The general harmonic form of the switched waveform defines carrier multiple harmonics (when $m \neq 0$ and $n = 0$) and sideband harmonics around the carrier multiples (when $m \neq 0$ and $n \neq 0$). Figures 30a and 30b show the typical harmonic spectra of the voltage waveforms for phase-to-floating neutral and phase-to-phase, respectively, for a 2-level VSC using PWM switched waveforms with a carrier-based control method using 21 times fundamental frequency and assuming infinite d.c. capacitance (i.e., no d.c. voltage ripple). These harmonic spectra would be changed under different specific operating conditions.

For a three-phase 2-level VSC, a balanced set of three-phase line-line output voltages is obtained if the phase leg references are displaced by 120° . In this case, the triplen sideband harmonics around each carrier multiple are cancelled in the line-line output voltages. It is important to note that the harmonic cancellation is a consequence of the triplen sideband harmonics. The carrier/fundamental ratio has no influence, and it can be odd, even or not integer.



b) Phase-to-floating neutral amplitude versus harmonic rank



a) Phase-to-phase voltage amplitude versus harmonic rank

Figure 30 – Voltage harmonics spectra of a 2-level VSC with carrier frequency at 21st harmonic

9.3.2 Selective harmonic elimination modulation

Selective harmonic elimination modulation (SHEM) is known as a modulation method to eliminate the undesirable low order harmonics. SHEM approach is an effective way to eliminate the selected most significant harmonics using lower switching frequency. Figure 31 shows the waveform switched at predetermined angles. The switched waveform has odd half-wave symmetry and even quarter-wave symmetry. The *K* switching angles can be used to eliminate *K*-1 significant harmonic component and control the fundamental voltage.

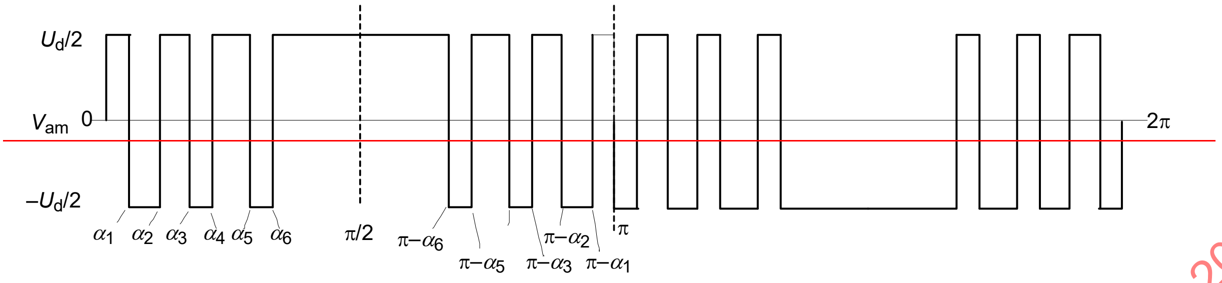


Figure 31 – Phase output voltage for selective harmonic elimination modulation (SHEM)

The general Fourier series of the switched waveforms shown in Figure 31 can be given as

$$v_{am}(t) = \sum_{n=1}^{\infty}(a_n \cos n\omega t + b_n \sin n\omega t) \quad (4)$$

For a waveform with quarter-wave symmetry, only the odd harmonics with sine component will be present. Therefore,

$$a_n = 0$$
$$b_n = \frac{4}{n\pi}\left[1 + 2\sum_{k=1}^{K}(-1)^k \cos n\alpha_k\right] \quad (5)$$

Note that K number of simultaneous equations are required to solve the K number of switching angles. The fundamental voltage can be controlled using one equation and K-1 harmonics can be eliminated using the other K-1 equations. Usually the lowest significant harmonics are to be eliminated. For a three-phase three-wire 2-level VSC, the triplen harmonics can be ignored if the phase references are displaced by 120°.

9.3.3 Multi-pulse and multi-level converters

Multi-pulse and multi-level converter topologies can also be used to reduce the harmonic output. The harmonics are calculated by Fourier analysis of the individual waveforms.

The individual levels of such converters are switched to obtain desired output voltage at the a.c. and d.c. terminals of the converters. The methods for switching individual levels can be distinguished in two main categories:

- methods resulting in a random type pulse pattern;
- methods creating a fixed pulse pattern (for given output voltages).

Random type pulse patterns distribute the harmonic distortion over the full frequency range, resulting in a "white noise" with moderate amplitudes. Due to their random nature, these harmonics are not easy to predict on a pure analytical basis. In contrast, fixed pulse patterns can be easily predicted and analysed.

9.4 Harmonic voltages on power systems due to VSC operation

One possible method for calculating the harmonic performance of the VSC is to consider it to be a harmonic generator of equivalent voltage E_n at each individual harmonic. At the point of common connection (PCC) of the VSC and the power system, the equivalent circuit is shown in Figure 32, where $Z_{s(n)}$ is the system impedance at the harmonic n and $Z_{(n)}$ is the harmonic impedance of the VSC, including the interface transformer, phase reactor and a.c. filters (as appropriate). If shunt filters are used either as part of the network or as part of the converter they should be included in respective impedance.

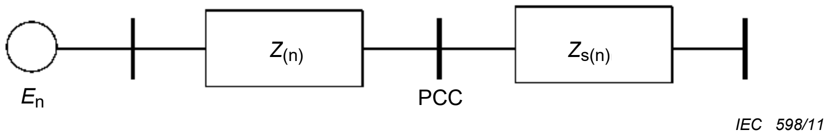


Figure 32 – Equivalent circuit at the PCC of the VSC

Since both $Z_{(n)}$ and $Z_{s(n)}$ are a complex impedance, a resonance may occur. Therefore, it is essential to have knowledge of the purchaser harmonic system impedance at the PCC.

9.5 Design considerations for harmonic filters (a.c. side)

If the evaluation indicates that the VSC contribution to harmonics at the PCC will exceed the permissible level, harmonic filters shall be designed and installed to keep the harmonics within the required limits. The filter configuration for the VSC is determined in a similar manner as those for LCC HVDC (see IEC/TR 62001). However, one important difference is that the VSC behaves as a harmonic voltage source on the a.c. side, and hence the series filtering action of the phase reactor and associated equipment is more important than the effects of any shunt filters.

9.6 D.C. side filtering

If the VSC is part of a d.c. transmission scheme connected by a d.c. overhead line, or a combination of d.c. cable and d.c. overhead line, its d.c.-side harmonics may interfere with other equipment and substations near the transmission line. VSC systems frequently use land cables which may be installed in trenches alongside telecommunication cables. If there are copper telecommunication cables close to d.c. cables over a long distance, the potential interference between these cables shall be considered. The frequencies used in commercial voice transmission range from 200 Hz to 3500 Hz. Telephone noise evaluation is performed according to various weighting factors (such as CCITT and BTSEEI) according to local practices. The coupling between power circuits and telephone circuits is through both electric and magnetic fields. However, unless the spacing between the two circuits is small, the magnetic coupling predominates and the electric coupling is negligible. For bipolar d.c. lines, this coupling is usually calculated using the “Equivalent Disturbing Current” [20][1].

If filtering is required on the d.c. side, a common mode reactor, d.c. reactor, or a d.c. filter can also be used to perform the role of RF filtering.

10 Environmental impact

10.1 General

This clause covers the main environmental impact resulting from the development of a VSC substation. The environmental aspects discussed are audible noise, visual impact, EMF and EMC. Other factors of a more generic character that result from VSC substation development are not covered, nor are the impacts from the development of a cable or overhead line system. End-of-life issues like recycling and disposal, are similar to those for an LCC HVDC scheme, as are power losses.

[1] Figures in square brackets refer to the bibliography

10.2 Audible noise

IEC 61973 covers in a comprehensive manner the audible noise related to line commutated HVDC converter stations, and is applicable also to VSC transmission. Audible noise theory is, therefore, not covered here.

The noise characteristics of the cooling equipment and auxiliaries are similar to those used in a conventional a.c. substation. Dependent on the converter topology used, the noise characteristics of the transformer may be similar to those of a substation transformer, as the use of filters on the converter side results in a very low level of harmonics in the transformer. For some converter designs the noise characteristics may be different. For converters using valves of the “switch”-type, the filters, VSC valves, phase reactor and VSC d.c. capacitors typically have noise components at higher frequency than for an LCC HVDC scheme. For converters using valves of the “controllable voltage source” type, the noise spectrum may have a significant component at fundamental frequency, with higher harmonics being more characteristic of “white noise”.

Noise attenuation can be achieved by a number of reduction measures that can be incorporated into the design of a VSC station. For many components, such as transformers, cooling equipment and auxiliaries, the measures taken to reduce noise are similar to those for a conventional a.c. substation.

10.3 Electric and magnetic fields (EMF)

The electric and magnetic fields (EMF) associated with a VSC scheme can be separated into a.c. and d.c. fields. The a.c. fields are produced by the a.c. components of the substation, and the connection between the VSC and the a.c. grid. The d.c. fields (also referred to as static fields) are produced by the cable/OH line, by connections to the d.c. equipment, and by the d.c. equipment itself.

In general, the electric and magnetic fields around a VSC facility, including the substation, connections and d.c. overhead line or cable, are similar to those for an LCC HVDC scheme.

10.4 Electromagnetic compatibility (EMC)

The operation of high-voltage electrical equipment can generate electromagnetic fields over a wide range of frequencies, from power frequencies to television frequencies. It is possible for electrical or electronic equipment in the vicinity of such electromagnetic fields to be affected, or to have their proper operation interfered with. Interference limits imposed on facilities typically consider

- radio interference (RI),
- television interference (TVI),
- telephone interference (see Clause 9),
- power line carrier interference (see Clause 9).

VSC valve switching can generate high frequency emissions up to several hundred MHz. The VSC design shall ensure that such noise does not cause unacceptable interference for others. Different mitigation methods can be employed, such as proper grounding, the use of passive radio interference filters, and shielding of the sources by EMC barriers.

Radio interference is associated with noise in the frequency range of 150 kHz to several hundred MHz. Television interference, on the other hand, results from noise in the frequency range 54 MHz to 1 GHz. Consequently, the whole frequency range up to 1 GHz shall be taken into account when designing the VSC substation.

Electrical interference and noise are transmitted in three forms: radiated, conducted and electro-magnetically induced.. For the VSC, conduction on power lines is a more significant source than radiation. Housing a VSC in a metal enclosure generally reduces the radiated component of disturbances.

The conducted phenomena consist of two categories, commonly known as the differential mode and the common mode. The differential-mode disturbance is a current or a voltage measured between the power lines of the VSC, while the common-mode is a current or a voltage measured between the power lines and ground. Any filter design has to take into account both modes of noise.

The path of the common-mode disturbance is through stray capacitance. These stray capacitances exist between any system components and ground. In close proximity to the source, other predominant coupling paths should be considered, such as electric fields (high impedance field) and/or magnetic fields (low impedance field). Except in far field conditions, one of these will be predominant.

A proper design of a VSC valve and converter layout can reduce the disturbance emissions at their source. In addition it may be necessary to use filters. Emission level can be assessed by simulation and measurement in-situ.

The IEC 61000 series on electromagnetic compatibility covers emission and immunity for phenomena in the 0 to 400 GHz frequency range. This range is split into several frequency bands, according to measurement techniques.

11 Testing and commissioning

11.1 General

This clause provides general guidelines for testing and commissioning of VSC transmission systems. Emphasis has been put on subsystem and system tests rather than those for components.

Testing and commissioning are part of a process that begins in the factory and ends with the handing over of the equipment for commercial operation. There are two distinct phases: factory or off-site testing, and commissioning testing. Off-site testing is usually performed to prove that equipment, including the control system, meets the design criteria. Commissioning tests are performed after the equipment has been delivered to the site and installed. The tests are organised to test subsystems, systems and overall performance.

As a general rule, all parties involved in the project should be included in the tests and all responsibilities clearly defined.

General requirements for system testing are similar to those described for LCC-HVDC in IEC 61975.

11.2 Factory tests

11.2.1 Component tests

These tests concern the verification of the single components, including control and protection equipment, before they are sent to site. They may be subdivided into routine tests, aimed essentially at quality control, and type tests which verify that a component has been properly designed to sustain the stresses from potential transients and service conditions. Factory testing of VSC converter valves is covered by IEC 62501. Traditional components such as switchgear, transformers, capacitors, capacitor fuses, reactors, resistors, insulators, voltage and current transformers, surge arresters, etc, are covered by the CIGRÉ ~~B4.48 report~~ Technical Brochure 447, in which the available standards (IEC, IEEE, ANSI) are pointed out and the special tests are introduced.

11.2.2 Control system tests

As with the controls for LCC HVDC systems, the control system for a VSC transmission system, including hardware, software and documentation, can be tested and verified in a factory system test (FST). A real time simulator will be required that can represent power components and parts of the a.c. system in a sufficiently detailed way. Every effort should be made to test as complete a system as practical, including redundancy, so as to minimise work on site. Factory system testing is an extensive and thorough check of the control and protection system under normal and fault conditions, without the constraints imposed by the real system. Selected on-site system tests will repeat some of the factory system tests, but will include the actual transducers and main circuit equipment, as well as actual system conditions (as permitted within system constraints). All software and hardware functions, including redundancies, should be tested before the equipment is shipped to site for installation and commissioning.

Besides simulator tests identical to those for LCC-HVDC, other tests should be considered that account for the additional modes of operation possible with a VSC. Each mode should be tested both in the factory and during commissioning (e.g., operation of the converter as a STATCOM, black start capabilities, and feeding a passive network). The results obtained from real time simulator tests and system studies (in particular the dynamic performances studies) are the main references used to define the commissioning plan and validate the test results in the field.

11.3 Commissioning tests / System tests

11.3.1 General

Commissioning tests are organised in a succession of phases.

The first phase is the so-called "precommissioning tests" executed on single station components in order to check their condition and functionality after transport and assembly. This phase is followed by the "subsystem tests," which test several components working together to perform a specific function. These are followed by the "system tests," which involve all converter stations and full power transmission. The system tests require careful coordination between all interested parties, in particular the system operators, utilities and industrial customers that could be affected by the tests.

During inspection and testing, all applicable health, safety and environmental requirements and regulations shall be followed. Any deviations should be discussed and resolved at site meetings. Often there is an overlap between commissioning and installation, especially in the area of cable termination. Care must be taken when interconnected subsystems are energised and started up that personnel are notified so that no potentially hazardous conditions exist. For an efficient process, it is important to complete as many as possible of the equipment pre-commissioning checks before energisation of the equipment. Most utilities have extensive safety rules that protect workers from accidental electrical contact.

11.3.2 Precommissioning tests

Precommissioning consists mainly of inspection and equipment tests. Equipment tests include electrical and mechanical tests and simple functional tests confined to a single installed unit. The purpose of these tests is to check the condition of the equipment and verify proper installation. If normal auxiliary power is not yet available, electrical tests can be performed with portable or temporary power supplies. At this stage, settings are verified in protection and control equipment.

In those cases where disconnection and reconnection would be required for the equipment tests, precommissioning tests on main circuit equipment should be performed before the main conductors are connected. Equipment tests should be performed as soon as possible after installation, and according to the manufacturer's recommendations.

11.3.3 Subsystem tests

Subsystem tests verify the proper operation of a group of interconnected or related equipment. Subsystem testing should be done in stages from small to progressively larger sub-systems, and should check as many functions as possible.

Typical subsystem tests are

- subsystem functional testing,
- start-up of auxiliary systems,
- low-voltage energisation.

11.3.4 System tests

11.3.4.1 General

The system tests involve operating the converter(s) in conjunction with the interconnected a.c. transmission system. These tests should not only check for proper performance of the automatic controls during normal changes in references, set points or operating modes, but also take place, in so far as possible, under different network conditions. System tests should also include selected disturbances to verify dynamic performance and robustness. Disturbances can consist of nearby capacitor bank switching, transformer energisation, line switching, generator tripping, step responses, or even staged faults where specified, and should cover the most critical conditions evidenced by the system studies and by simulator tests, in so far as the networks allow. Some tests with high potential impact may require special provisions to mitigate the possible adverse system impact of large reactive/active power variations. These will require tight coordination with the transmission system operator (TSO)/utilities of a.c. networks to which the VSC transmission system is connected.

Usually, tests with lower impact on a.c. networks are performed first, followed by the more onerous ones.

11.3.4.2 High-voltage energisation

When all prerequisites for high-voltage energisation have been completed, operational authority is transferred to system operators to ensure that all safety rules are followed and that any system constraints are observed. Operational procedures should be formalised beforehand. High-voltage energisation is preceded by final trip tests and “dry run” tests where the operators execute the procedure without actually energising the equipment.

Energisation of a.c. equipment follows a step-by-step sequence for the a.c. buses, bays, filters and transformers. This may require temporary disconnection of some high-voltage terminations where disconnect switches are not provided. Equipment should be initially energised for several hours. Checks are made for corona and any abnormal audible noise. Phasing and phase rotation are rechecked with full voltage. During filter energisation, unbalance protections are checked and load checks are made. Visual inspections of all equipment and surge arrester counters are made before and after energisation.

Energisation of the converter and d.c. equipment follows that of the a.c. equipment. In most cases, valve cooling should be running before energising the converter. With the VSC, the connected d.c. side equipment (i.e., d.c. buswork, d.c. capacitors and d.c. transducers) is energised through the valve anti-parallel diodes when the main a.c. breaker is closed thereby energising the converter.

As an additional check, the converter may be energised via the d.c. side, with the a.c. connection open. A special d.c. power supply could be provided for this purpose, or the converter at the opposite end of the link could be used as a rectifier to provide this function.

During energisation, d.c. voltage measurements and status signals from individual semiconductor positions should be checked via the valve monitoring.

If other converters or d.c. cables are included in the particular application, they should be initially energised separately while isolated from the other converter(s) and interconnecting cables or buswork.

11.3.4.3 Converter ~~operational~~ operating tests

11.3.4.3.1 General

Once the converter and d.c. equipment have been energised and checked out, the converter can be deblocked, sending switching pulses to the valves. Initially this is performed one converter at a time, with the VSC operated in a.c. voltage control or reactive power control. The purpose of the converter operational tests is to check that the converter operates properly with the a.c. network.

During converter operational testing all subsystems, e.g., controls, transducers, auxiliaries and main circuit equipment, are tested together for the first time.

Typical tests performed during converter operation are the following:

11.3.4.3.2 Sequences

Check that breakers, disconnects and deblock/block and trip sequences operate properly in response to manual, automatic or protective orders. Check that the initial operating condition is neutral minimising the disturbance to the network, e.g., automatic connection of filters, if any, with net zero reactive power exchange through counterbalancing VSC absorption.

11.3.4.3.3 D.C. voltage control

Check that the d.c. voltage is controlled to its reference voltage, and that all levels of d.c. voltages are balanced.

11.3.4.3.4 Measurements

Check that all controls, indications and measurements have correct polarity, phase and scaling. Take selected measurements of a.c. and d.c. harmonics and distortion.

NOTE Final measurements are usually reserved for acceptance tests.

11.3.4.3.5 Reactive power control

Check that the reactive power control, if relevant, follows the reference at the selected ramp rate for both inductive and capacitive ranges. Check proper converter reactive power limitations.

NOTE Operating restrictions on a.c. voltage may limit the amount of reactive power that can be exchanged with the a.c. network.

11.3.4.3.6 A.C. voltage control

Check that the voltage is controlled to the reference, if relevant, and that the reactive power is stable. Vary slope, reference, deadband and voltage control modes, as provided. Check stability with the a.c. network by reference step response, capacitor bank switching and/or a.c. line switching.

11.3.4.3.7 Load test

Check the capability of the cooling equipment, primarily for the VSC valves. Observe the temperatures and sequencing of the cooling equipment as the load is increased.

NOTE Operating restrictions on a.c. voltage may limit the amount of reactive power that can be exchanged with the a.c. network, and special provisions shall then be made to reach full output.

11.3.4.3.8 Disturbance tests

In addition to the testing of the step responses to regulator references, the converter and its controls should be tested for various internal disturbances (e.g., auxiliary supply changeover, control system changeover, and external disturbances in the a.c. transmission system) to verify proper performance, stability and robustness. External disturbances can consist of switching nearby capacitor banks, transformers, transmission lines, or tripping generators.

11.3.4.4 Transmission tests

11.3.4.4.1 General

Transmission tests involve operation of converters that work together to control the power flow. Such testing requires a very high degree of coordination with the system operator (dispatcher).

Typical tests performed during transmission testing are as follows:

11.3.4.4.2 Sequences

Check that breakers, disconnects and deblock/block and trip sequences operate properly in response to manual, automatic or protective orders. Check that the initial operating condition is neutral, minimising the disturbance to the network, e.g., zero net reactive or active power exchange.

11.3.4.4.3 D.C. voltage control

Energisation of high-voltage d.c. cables, bus work or lines interconnecting the converters. Repeat with the other converter connected. Depending on application and protective strategy, check that the d.c. voltage is controlled to a reference during power transfer and blocking/tripping of one of the other converters.

11.3.4.4.4 Power control

Check that the power flow and power ramp rate follow the reference values. Check the power control stability by step response or system disturbance, such as line switching. Check transmission in both directions. Check proper converter real power limitations.

11.3.4.4.5 Reactive power control

Check, if relevant, the joint operation of the reactive power control and active power control at the different converters by changing their respective references during the different operating modes. Check proper converter reactive power limitations.

11.3.4.4.6 A.C. voltage control

Check, if relevant, the joint operation of the a.c. voltage control and active power control at the different converters. Check the stability by step response in the power and voltage references, or during system disturbances such as capacitor bank or line switching.

11.3.4.4.7 Load test

Ramp up to full power transmission or MVA converter rating for the different operating modes, as permitted by a.c. system and other conditions.

11.3.4.4.8 Measurements

Take selected measurements of a.c. and d.c. harmonics and a.c. voltage distortion.

NOTE Final measurements are usually reserved for acceptance tests.

11.3.4.4.9 Redundancy checks

If the system is equipped with redundant control and protection systems, perform transfers from the active to standby system. Transfers between redundant auxiliary systems should also be checked during operation, e.g., auxiliary power, cooling pumps.

11.3.4.4.10 Remote control

Test operation from remote locations. Check all remote indications and control functions.

NOTE Much of this work is done beforehand during subsystem testing, but this is the first time that remote system operators have direct control of the system. Previously, operation was from the local level with authorisation only from the system operator.

11.3.4.4.11 Disturbance tests

In addition to testing the step responses to regulator references, the converter and its controls should be tested again for various external disturbances in the a.c. transmission system to verify proper performance, stability and robustness. External disturbances can consist of switching nearby capacitor banks, transformers, transmission lines, tripping generators, or even staged faults, e.g., d.c. or a.c. overhead line faults, as relevant.

11.3.4.5 Trial operation

Trial operation allows the owner to operate the integrated system according to its intended purpose from the normal control location. Trial operation does not start until almost all system tests have been successfully completed. During trial operation, observation of the complete system and subsystems takes place. All alarms or abnormal conditions are dealt with as required.

11.3.4.6 Acceptance tests

11.3.4.6.1 General

Acceptance tests verify the performance of the system according to the specification on a selected basis. Acceptance tests may involve measurements to verify that interference levels are within the design limits and that other fundamental performance criteria are met.

11.3.4.6.2 Heat run

Operate at rated and overload capacity for specified periods of time in different operating modes, if applicable. Monitor temperatures and cooling systems. This test usually takes several hours due to the slow heating of the transformers.

11.3.4.6.3 Interference measurements

Verify that harmonics on the a.c. and d.c. sides, audible noise, radio interference, PLC interference, etc., meet the performance requirements.

11.3.4.6.4 Disturbance response

Test auxiliary supply changeover, control system changeover, line switching, shunt bank switching, generator tripping or staged faults, as necessary.

Annex A
(informative)

Functional specification requirements for VSC transmission systems

A.1 Introduction

This annex presents the minimum requirements of a functional specification for a VSC transmission system. Once the technical requirements of the VSC transmission system have been defined and confirmed by basic system studies, a functional specification can be prepared. Supplemented by the commercial conditions, the specification allows the purchaser to invite tenders from manufacturers for the equipment required. The functional specification shall provide adequate information from the purchaser to the manufacturer and the required information exchange between the purchaser, the manufacturers and relevant subcontractors.

The specification should include parts where a minimum requirement is specified, as well as those parts where a performance above the minimum standard is desired but not essential. The specification should include a method for evaluating the above-minimum performance criteria.

In the following sections the minimum technical information that needs to be provided by the purchaser and manufacturer are summarized. These summaries describe

- general requirements of the VSC transmission system;
- power system configuration to which the VSC transmission system is connected, including all the parallel transmission systems, if any;
- requirements of the d.c. line, i.e., type of cable or overhead line or combination thereof. If the d.c. line is not within the scope of supply, the converter manufacturer should provide information that would be needed for a proper line specification. The type of line chosen should be approved by the converter manufacturer as to its applicability;
- site and environment;
- operating function of the VSC;
- maintenance, performance tests and spare parts requirements;
- VSC site, transmission right of way, and environmental constraints and consideration;
- factory and commissioning tests;
- other considerations relating to loss evaluation, tender evaluation, health and safety, and other ancillary requirements.

The purchaser shall provide a detailed description of the power systems connected to the VSC transmission system to enable the suppliers to offer the most suitable and economic equipment design. In addition, the purchaser and the manufacturer shall maintain a continuous dialogue starting at the tender stage and continuing until the project is completed. It is recommended that the manufacturer should review the basic studies undertaken by the purchaser, and vice versa.

A.2 Purchaser and manufacturer information requirements

A.2.1 General

In the following tables, information marked with an asterisk (*) may require detailed studies that may not be available before the contract stage.

For some parameters, time varying data may be appropriate, e.g., the range of a.c. system r.m.s. voltage may include excursions outside a normal range during brief periods (hours, minutes, seconds or milliseconds) with different limits for each duration. Such time varying data shall be described in an appropriate manner.

The confirmation of performance may be demonstrated by any one or a combination of the following methods:

- studies
- computer simulation
- tests

A.2.2 General requirements

Purchaser specification requirement	VSC manufacturer supplied information
Definition of scope of supply	
Location of the VSC	
Role of the VSC	General description of solution
Converter type and d.c. side configurations (if fixed) • Converter type • Topology of d.c. system • Type of d.c. line/Cable • Transmission voltage (if fixed)	Confirmation of the VSC type and configuration and d.c. side configurations
Main ratings of the VSC • Power to be transmitted • Locations of real and reactive power reference points • D.C. voltage and current, if applicable • A.C. sending and receiving voltages • Frequency of the system • Power resolution	Guaranteed rating of the VSC
Important ancillary control requirements e.g.: • Reactive power regulation requirements • Overload requirements • Transient performance	Guaranteed performance of the VSC

Purchaser specification requirement	VSC manufacturer supplied information
Requirement on VSC losses • Definition of operating point(s) for which losses are to be determined • Capitalised Loss evaluation rate	Losses at designated operating conditions and the method of loss calculation and loss distribution between the major components
Standards and codes	Confirmation of the standards and codes
In service date	• Confirmation of the critical dates • Key milestone dates
Tender assessment criteria	
Special premiums applied, e.g., for performance in excess of the minimum requirement	Details of the areas where the minimum required performance is exceeded
Health and safety requirements	

A.2.3 Detailed descriptions

A.2.3.1 Power system configurations

A.2.3.1.1 General

Purchaser specification requirement	VSC manufacturer supplied information
System configuration • Single line diagram of the system connection points • Harmonic impedance envelopes seen from the points of connection • Data on nearby generation • Modelling information for nearby controllable devices, such as static VAR (volt-ampere reactive) compensators (SVCs), wind turbines etc.	

A.2.3.1.2 D.C. line/cable (in case of turnkey, supplied by the converter manufacturer)

Purchaser specification requirement	Converter manufacturer supplied
Main features of d.c. side • Configuration of the d.c. system • Topology of d.c. system • Type of d.c. transmission line (cable or overhead line or a combination thereof) • Length of the overhead line • Length of the cable	Confirmation of the configuration of the d.c. system including cable/ over head line parameters e.g.: • current capability, steady state and overload (if any) • voltage withstand capability • proposed type tests including test levels

Purchaser specification requirement	Converter manufacturer supplied
National safety codes/standards for design of overhead lines and cables	Confirmation of the National safety codes/standards
Information about the overhead line • Air temperature range • Wind conditions • Ice loading requirements • Air pollution level • Risk of vandalism	Confirm that design meets the criteria*
Information about the cable • Length of cable • Minimum required depth of burial • Survey data about the subsea/land terrain • Thermal resistivity of soil/silt/seabed • Temperature conditions • Requirement for fiber optic cable (whether embedded or not)	Confirm that design meets the criteria*
Location of nearby communication cables	Confirm there is no effect on communication cables*

A.2.3.1.3 D.C. line/cable (not supplied by the converter manufacturer)

Since the design of the converter and the cable are interdependent, the design process will be iterative. Therefore the data needs to flow between the VSC manufacturer and the cable supplier as shown below.

Purchaser specification requirement	Converter manufacturer supplied information
Provide data from the d.c. line/cable supplier to the converter manufacturer	• Maximum steady state, dynamic and transient current by the VSC • Maximum steady state, dynamic and transient voltage by the VSC • Harmonic voltage and current at the VSC terminals caused by the VSC • Overvoltage protection provided • Approval of selected d.c. line/cable system
Requirement for VSC data for cable manufacturer	Data provided

A.2.3.2 Site and environment

Purchaser specification requirements	Manufacturer supplied information
Space and footprint restrictions Site accesses and transports limitations	VSC layout and layout options Access and transport requirements
Electromagnetic field limitations	Electromagnetic field generation
Electromagnetic immunity requirements	Electromagnetic immunity levels*
Requirement for VSC grounding conditions	Requirement of appropriate electrode
Ambient temperature, pressure and humidity ranges	Confirm operation under required conditions*
Solar, snow and ice, wind, air pollution, isokeraunic level and seismic conditions	Confirm operation under required conditions*
Noise restriction, acoustic and electromagnetic telephone interference restrictions	Confirmation of the requirement*
Requirements in respect of earthquake resistance	Confirmation that the design meets the requirement with respect to earthquake resistance*

A.2.3.3 Operating function of the VSC

Purchaser specification requirement	Manufacturer supplied information

Requirement for the main operation
• Requirement for the transmitted power
• Main ancillary operation (if needed)
  • Requirement for the reactive power
  • Requirement for the a.c. voltage regulation
  • Requirement for the d.c. voltage regulation
  • Requirement for the control priorities
	Confirm operation ability* including the VSC control modes and control laws

Requirement for the dynamic performance • Requirement for the response time for the output change • Requirement for the over load performance	Confirm operation ability* including short term overload ratings

Purchaser specification requirement	Manufacturer supplied information

Operation range
(Range of conditions over which rated performance or ride-through is required)
• Range of the a.c. system conditions in which the VSC has to operate (both steady-state and transient)
    • A.C. sending and receiving voltage range including temporary overvoltage
    • A.C. frequency range
    • Range of a.c. voltage imbalance
    • Zero sequence voltage range
    • Range of harmonics
    • Switching transient
    • Fault level
    • System configuration
• D.C. conditions
	Confirmation that the system remains operational and description of the performance*

Requirement for protection
• Faults which shall be postulated for the VSC to be turned off safely or to ride-through
    • Fault types
    • Faults levels and clearance times
    • Whether single- or three phase auto reclosure is used and if so, the timing of different periods.
• Protection for the a.c. system
• Protection for the d.c. side
• Protection for the VSC
	Confirmation of the requirement, e.g.:
	• performance during faults, other low-voltage conditions and switching transients
	• control logic and settings for operation during above conditions
	• description of protection system, including protection against internal failures
	• worst case internal faults in terms of duration and effect on Transmission

Acceptable adverse effect to the power system by the VSC • Harmonics • Electromagnetic noise	• Predicted value of harmonics (voltage and current) generated from the VSC • Measured value* of harmonics (voltage and current) generated from the VSC • Individual harmonic distortion D_n* • Total harmonic distortion THD* • Telephone influence factor TIF*

Purchaser specification requirement	Manufacturer supplied information
Requirement for the insulation coordination	Overvoltage withstand capability *

Others
• Requirement for earthquake resistance
• Requirement for salt damage
• Reliability
  • Requirement for the lifetime of the VSC
  • Requirement for the availability
  • Requirement for the outage rate
  • Prerequisite condition for the reliability design
  • Requirement for redundancy
• Requirement for the measurements, alarm, and monitoring
• Requirement for the interface between the power system and the VSC
  • Main circuit
  • Control signal
• Initial energization and shutdown requirement
	Confirmation of the requirement*, e.g.
	• Predicted life, reliability and availability characteristics, forced outage rates, maintenance frequency and periods
	• Failure rate of key components, e.g., semiconductors, d.c. capacitors
	• Transient effect of component failure

A.2.3.4 Maintenance and spares

Purchaser specification requirement	Manufacturer supplied information
Maintenance requirement	Maintenance frequency, duration and recommended maintenance
Special maintenance test equipment requirements	Special test equipment provided
Spares requirements	Recommended spares holdings
Drawings, maintenance manuals, technical notes	Description of documentation provided As-built drawings, maintenance manuals and technical notes provided*

A.2.3.5 Factory and commissioning tests

Purchaser specification requirements	Manufacturer supplied information
Test requirements • Equipment requiring type test approval • Factory tests • Functional testing of control suites	Confirmation of the requirement, e.g.: • type test evidence offered in lieu of new type tests • test schedules
Test standards	Confirmation to perform tests as per specified standard
Commissioning tests and schedule	Provide list of proposed commissioning tests and testing schedule

A.2.3.6 Auxiliary systems

Purchaser specification requirements	Manufacturer supplied information
Auxiliary power and cooling facility prepared by the purchaser side	Auxiliary power facility required and system description Method of initial energizing, restart and shutdown
Requirement for the control facilities	Description of control facilities including remote and local man-machine interfaces, detailing control, alarm, communication and monitoring facilities*
Auxiliary systems on main equipment	
Fire safety requirements	• Description of materials used* • Description of means of protecting against fire* • Fire containment methods*

All information not marked with an Asterisk (*) is normally provided at the tender stage.

Annex B
(informative)

Determination of VSC valve power losses

B.1 General

Power losses in most equipment in a VSC substation can be calculated using similar procedures to those prescribed for LCC-HVDC in IEC 61803. However, losses in VSC and diode valves require separate treatment, as the differences from the applicable practice on LCC-HVDC are significant.

Most of the power losses in VSC valves appear in IGBTs and free-wheeling diodes (FWD). In each case, two mechanisms are involved:

- conduction losses
- switching losses

There may, in addition, be small losses in d.c. capacitors, voltage divider and snubber circuits, gate drive units etc.

Since the technology of VSC transmission is developing rapidly with several quite different VSC topologies being used, a detailed procedure for calculating these power losses is not yet available. As a result, the manufacturer of the VSC equipment should present a detailed report of the VSC valve loss calculation, explaining the method used and justifying any assumptions made. The remainder of this annex presents general guidance to assist with the preparation and interpretation of such a report.

To aid understanding by readers familiar with IEC 61803, the various components of valve losses are subdivided in a similar way into terms referred to as P_{V1} to P_{Vn}. In this annex the following terms are used:

- P_{V1}: IGBT conduction losses
- P_{V2}: FWD conduction losses
- P_{V3}: other valve conduction losses
- P_{V4}: d.c. voltage-dependent losses
- P_{V5}: d.c. submodule capacitor losses
- P_{V6}: IGBT switching losses
- P_{V7}: free-wheeling diode turn-off losses
- P_{V8}: snubber losses
- P_{V9}: valve electronics losses

B.2 Conduction losses

B.2.1 General

When an IGBT or a FWD is in the conducting state, it exhibits a small on-state voltage of a few volts. This on-state voltage, multiplied by the current flowing through the device, gives rise to "conduction losses". The on-state voltage is referred to as V_F in free-wheeling diodes and $V_{CE(sat)}$ in IGBTs.

The on-state voltage depends on current in a non-linear manner, and to a lesser extent also on the "junction temperature" of the device, as shown in Figure B.1.

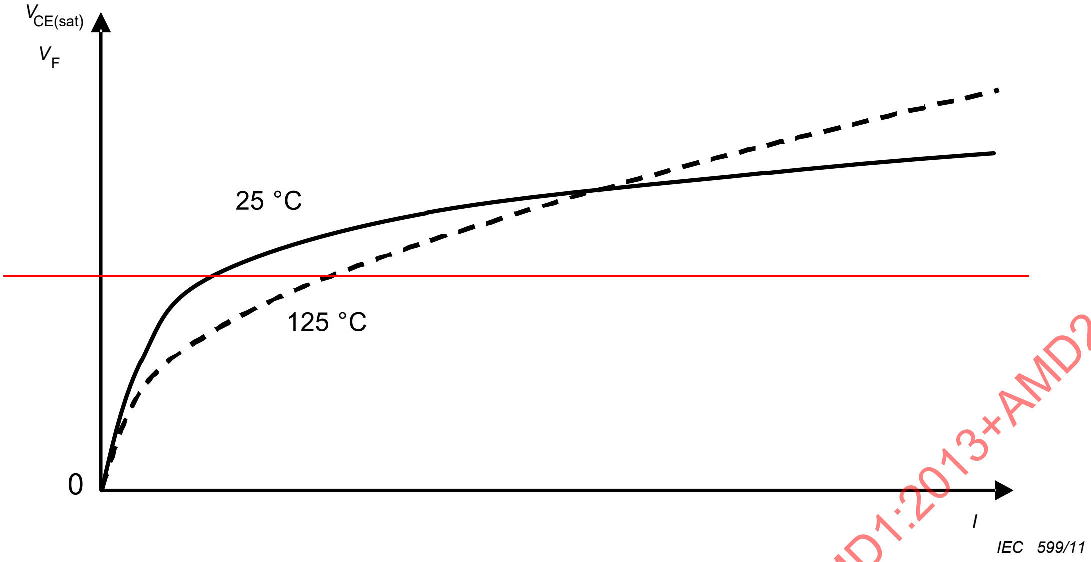


Figure B.1 – On state voltage of an IGBT or free-wheeling diode

NOTE The on-state voltage V_{CE} of an IGBT also depends on the gate-emitter voltage V_{GE}. For low values of V_{GE}, increasing V_{GE} reduces the value of V_{CE}. However, above a certain value of V_{GE}, no further reduction of V_{CE} occurs and the IGBT is said to be "saturated". It is assumed here that V_{GE} is high enough to ensure that the IGBT remains fully saturated. Consequently, $V_{CE(sat)}$ (the saturated value of V_{CE}) can be used for loss calculation.

Calculation of power losses requires that the on-state voltage be represented mathematically, so that the average conduction losses over a complete cycle may be evaluated as follows:

For an IGBT:

$$P_{cond\_T} = \frac{1}{2\pi} \cdot \int_0^{2\pi} I_T(\omega t) \cdot V_{CE(sat)}(I_T) \cdot d(\omega t) \qquad (B.1)$$

For a free-wheeling diode:

$$P_{cond\_D} = \frac{1}{2\pi} \cdot \int_0^{2\pi} I_D(\omega t) \cdot V_F(I_D) \cdot d(\omega t) \qquad (B.2)$$

To simplify this process, the on-state voltage shown on Figure B.1 is usually represented as a piecewise-linear approximation with a threshold voltage V_0 and a slope resistance R_0, as shown on Figure B.2.

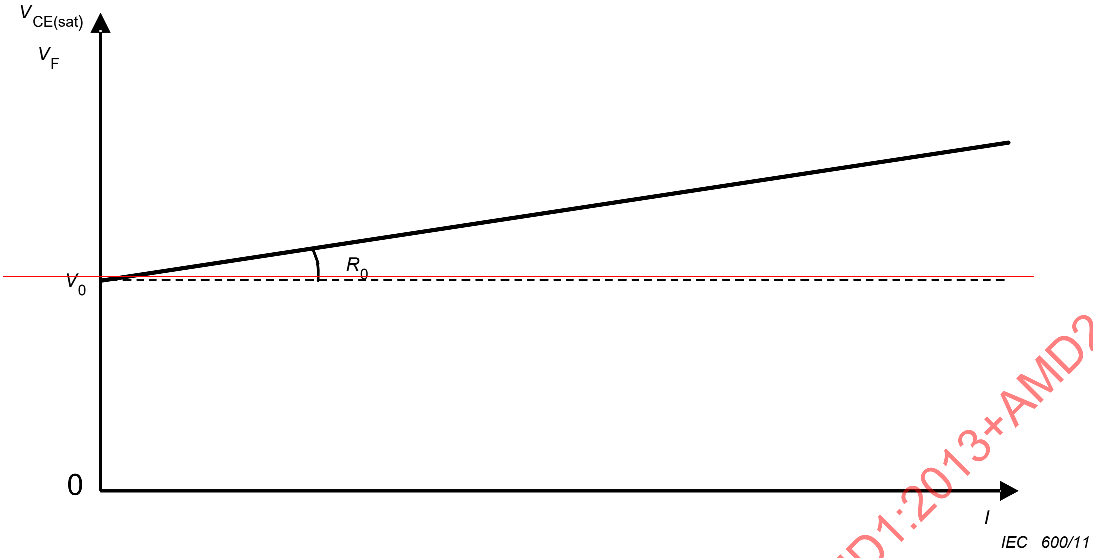


Figure B.2 – Piecewise-linear representation of IGBT or FWD on-state voltage

Having made this approximation, the conduction losses in each semiconductor device are then determined by using the average and r.m.s. currents through that device:

$$P_{cond} = V_0 \cdot I_{av} + R_0 \cdot I_{rms}^2 \qquad (B.3)$$

where

V_0, R_0 are the threshold voltage and slope resistance of the device;

I_{av} is the mean current in the device, averaged over one power-frequency cycle.

$$I_{av} = \frac{1}{2\pi} \cdot \int_0^{2\pi} I(\omega t) \cdot d(\omega t) \qquad (B.4)$$

I_{rms} is the r.m.s. current in the device, averaged over one power-frequency cycle.

$$I_{rms} = \sqrt{\frac{1}{2\pi} \cdot \int_0^{2\pi} I(\omega t)^2 \cdot d(\omega t)} \qquad (B.5)$$

The conduction losses in a complete valve are then found by summing the conduction losses calculated as above for each IGBT and each FWD in the valve.

In general, rectifier mode gives rise to the largest FWD conduction losses, while inverter operation gives rise to the largest IGBT conduction losses.

B.2.2 IGBT conduction losses

In the 2-level converter, all IGBTs experience the same current. Consequently the total IGBT conduction losses per valve may be calculated by multiplying the conduction loss per IGBT by the number of VSC levels per valve:

$$P_{V1} = N_t \cdot \left[V_{0T} \cdot I_{Tav} + R_{0T} \cdot I_{Trms}^2 \right] \qquad (B.6)$$

where

N_t is the number of VSC valve levels per valve;

V_{0T} is the IGBT threshold voltage;

R_{0T} is the IGBT slope resistance;

I_{Tav} is the mean current in the IGBT;

I_{Trms} is the r.m.s. current in the IGBT.

IGBT conduction losses in multi-level converters may be evaluated using similar principles outlined above for 2-level converters. However, the procedure is more complex because not all IGBTs in a given phase unit experience the same current.

In general, the average and r.m.s. currents need to be calculated separately for each different IGBT operating duty, and the results multiplied by the number of such devices in each valve.

B.2.3 Free-wheeling diode conduction losses

In the 2-level converter, all free-wheeling diodes experience the same current. Consequently the total diode conduction losses per valve may be calculated by multiplying the conduction loss per FWD by the number of VSC levels per valve:

$$P_{V2} = N_t \cdot \left[V_{0D} \cdot I_{Dav} + R_{0D} \cdot I_{Drms}^{2} \right] \qquad \text{(B.7)}$$

where

V_{0D} is the free-wheeling diode threshold voltage;

R_{0D} is the free-wheeling diode slope resistance;

I_{Dav} is the mean current in the free-wheeling diode;

I_{Drms} is the r.m.s. current in the free-wheeling diode.

Free-wheeling diode losses in multi-level converters may be calculated using similar principles but, as described for IGBT losses in the preceding subclause, are more complex and generally need to be calculated separately for each different diode operating duty.

B.2.4 Other conduction losses

Conduction losses in components other than the semiconductors and submodule capacitor (for example, busbars) are normally small. However, they may not be negligible and should be included in the calculation of valve losses.

Calculation of such losses is relatively straightforward and depends only on the resistance of each conducting element and the r.m.s. current that flows through it.

Where the same current flows through all conducting elements in a valve, the value of these losses per valve is given by

$$P_{V3} = I_{vrms}^{2} \cdot R_s \qquad \text{(B.8)}$$

where

I_{vrms} is the r.m.s. current flowing in the valve;

R_s is the total resistance of all conducting elements in the valve, other than IGBTs and FWDs.

Where not all conducting elements in the valve carry the same currents, the above principles should be evaluated separately for each element.

B.3 D.C. voltage-dependent losses

D.C. voltage-dependent losses are losses caused by shunt resistive components in parallel with the IGBTs and FWDs. These could include

- resistive voltage grading circuits (d.c. grading circuits);
- resistive voltage dividers for voltage measurement;
- water cooling pipework;
- shunt resistive losses across capacitor dielectric material;
- bleed resistors across d.c. capacitors;

These losses are calculated as follows:

$$P_{V4} = V_{vrms}^{2} / R_{DC} \quad \text{(B.9)}$$

where

V_{vrms} is the r.m.s. value of voltage between the terminals of the valve;

R_{DC} is the effective d.c. resistance of a complete valve.

B.4 Losses in submodule d.c. capacitors

The submodule capacitors in MMC-type valves carry an appreciable component of current at fundamental or low-order harmonic frequencies. As a result, the power losses in the capacitors of valves of this type cannot be neglected.

In general, capacitor losses can be divided into ohmic losses and dielectric losses.

Ohmic losses represent $I^{2} \cdot R$ losses in the metallic components within the capacitor, chiefly the film metallisation and internal leads.

Dielectric losses in a capacitor are related to the energy lost in the dielectric material over each voltage cycle. Dielectric losses are caused by the periodic re-alignment of the molecules within the dielectric as the voltage stress across the dielectric changes during the cycle, and are analogous to hysteresis losses in ferromagnetic materials.

The effects of ohmic and dielectric losses are frequently combined into a single term referred to as the equivalent series resistance R_{ESR} of the capacitor. R_{ESR} is a function of frequency and is related to, but not exactly equal to, the actual internal series resistance.

The total d.c. submodule capacitor losses per valve are then calculated as follows:

$$P_{V5} = N_{t} \cdot I_{crms}^{2} \cdot R_{ESR} \quad \text{(B.10)}$$

where

I_{crms} is the rms current flowing in each d.c. submodule capacitor;

R_{ESR} is the equivalent series resistance of the capacitor.

NOTE 1 Dielectric losses are normally most significant in a.c. applications where the capacitor voltage polarity reverses twice per cycle. For d.c. capacitors the voltage is usually non-reversing and dielectric losses are therefore small, but depending on the capacitor technology used, may not be negligible.

NOTE 2 There may also be a third component of loss caused by the finite insulation resistance of the dielectric material, but this is normally very small. It is covered by d.c. voltage-dependent losses as described in the preceding subclause.

NOTE 3 ESR is a non-linear, frequency-dependent quantity. For accurate results it is important that ESR be determined by real measurements on a capacitor of the same type as used in the valve, under realistic conditions of voltage, current and frequency.

B.5 Switching losses

B.5.1 General

Each time an IGBT turns on or off, or a FWD turns off, it incurs a small switching energy loss of a few Joules. In most VSC topologies, these switching events occur several times per fundamental-frequency cycle. For converters using PWM in particular, the resulting switching loss (switching energy loss multiplied by switching frequency) can be a large proportion of the total valve losses.

However, because different converter topologies use different switching strategies and the switching behaviour depends on the overall control methods used, only general guidance on calculating switching losses can be given here.

B.5.2 IGBT switching losses

During turn-on and turn-off in an IGBT, the device is subjected to high current and high voltage simultaneously during part of the switching process. As a result the IGBT incurs a high peak power dissipation, the time integral of which is known as the switching loss. IGBT switching losses are referred to as the turn-on loss E_{on} and the turn-off loss E_{off}.

Both E_{on} and E_{off} depend nearly linearly on the instantaneous value of collector current I_C at the instant of switching, as shown on Figure B.3.

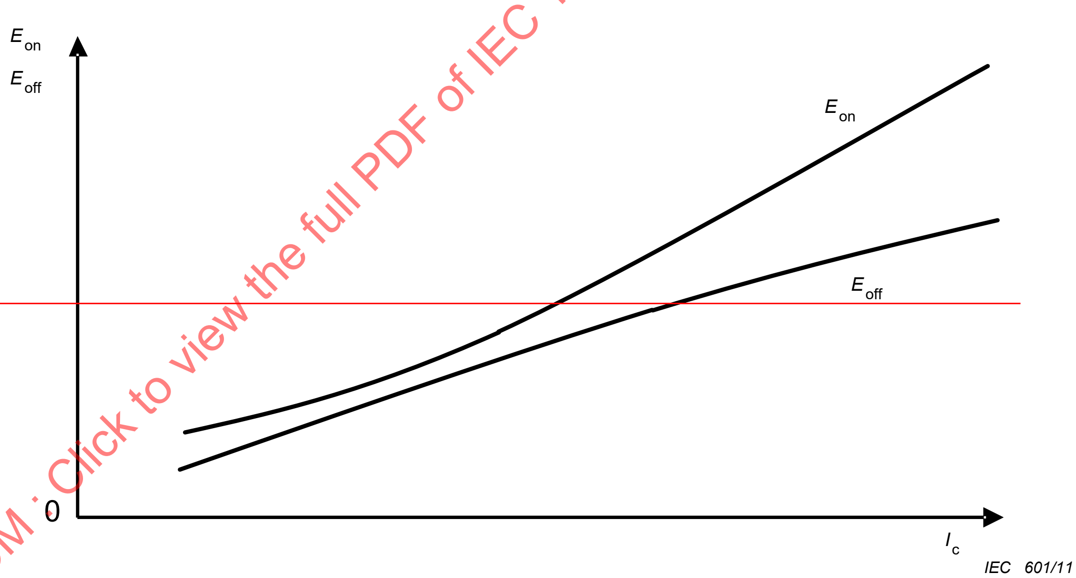


Figure B.3 – IGBT switching losses as a function of collector current

E_{on} and E_{off} are normally quoted by the IGBT manufacturer as a function of current, under certain idealised operating conditions with a simple design of gate drive and a fixed value of gate resistor. The gate resistor value influences the switching losses because it affects the charge and discharge times of the gate capacitance, and hence the switching speed.

Moreover, some designs of VSC, particularly in valves of the “switch” type, may use more advanced designs of gate drive which incorporate active voltage sharing algorithms or “active snubber” circuits. The IGBT gate drive circuit may also include an active overvoltage clamp algorithm to suppress the transient overvoltage which occurs across the IGBT after turn-off. These algorithms adjust the switching speed of each IGBT in order to prevent any individual

IGBT in the valve from experiencing a potentially harmful overvoltage, but as a consequence they may result in the switching losses being higher than stated by the IGBT manufacturer.

The VSC manufacturer should therefore justify in detail the values of E_{on} and E_{off} used in the loss calculation, based on the design of gate drive circuit and choice of gate resistor (where applicable).

Switching losses also depend on the d.c. link voltage (per IGBT) at the instant of switching, and to a lesser extent also on junction temperature. In 2-level and 3-level converters the mean d.c. link voltage per IGBT varies little from the nominal design value. However, for modular multi-level converters the d.c. link voltage (here provided by the submodule d.c. capacitor) can vary considerably from one switching instant to the next. Consequently the IGBT switching losses should be evaluated with care in such designs.

The total IGBT switching losses per valve are calculated by summing all the turn-on losses E_{on} and the turn-off losses E_{off} over one power-frequency cycle and multiplying the result by the a.c. system frequency f and the number of VSC valve levels in the valve:

$$P_{V6} = N_t . f . \sum_{cycle} (E_{on}(V,I) + E_{off}(V,I)) \tag{B.11}$$

B.5.3 Free-wheeling diode switching losses

For FWDs, the turn-on loss is normally negligible because the diode conducts as soon as it becomes forward biased. However, the turn-off (recovery) loss E_{rec} is not negligible. The recovery loss arises from the reverse recovered charge Q_{rr} which passes through the FWD shortly after the current crosses zero. The recovery loss increases with the current which had been flowing in the diode prior to the turn-off event, although the relationship between E_{rec} and current, as shown on Figure B.4, is non-linear. E_{rec} can be expressed as a piecewise-linear function of current (as for on-state voltage) or a power law relationship.

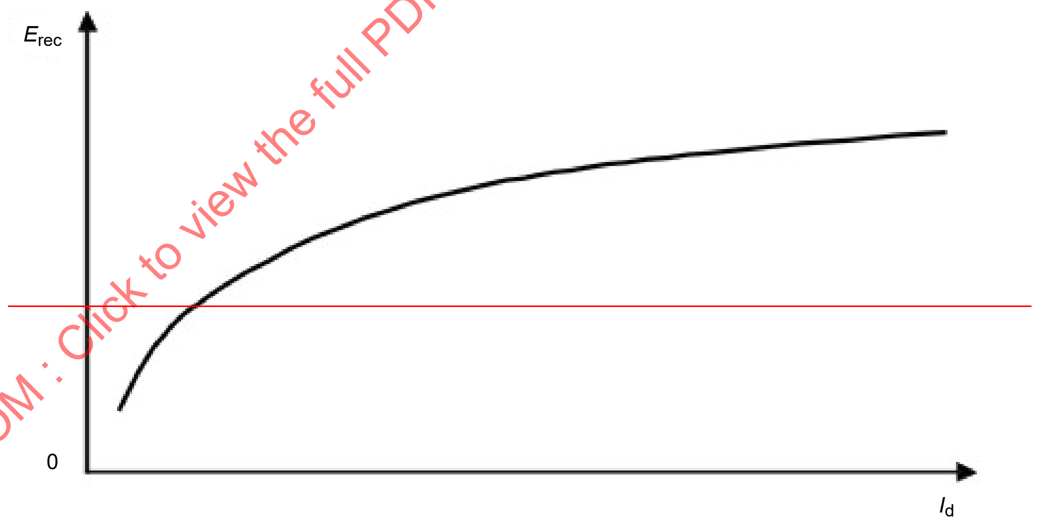


Figure B.4 – Free-wheeling diode recovery loss as a function of current

The total FWD switching losses per valve are then calculated by summing all the turn-off losses E_{rec} over one power-frequency cycle and multiplying the result by the a.c. system frequency f and the number of VSC valve levels in the valve:

$$P_{V7} = N_t \cdot f \cdot \sum_{cycle} E_{rec}(V, I)) \qquad (B.12)$$

B.6 Other losses

B.6.1 Snubber circuit losses

Some designs of VSC valve may use passive snubber circuits to reduce the turn-on or turn-off stresses on the IGBTs or, for valves of the "switch" type, to assist with voltage sharing.

NOTE 1 Resistive voltage sharing circuits are not considered as "snubber circuits", although they may contribute to voltage sharing.

NOTE 2 "Active snubber" circuits, where the IGBT gate drive adjusts the speed of switching of each IGBT in order to minimise any voltage distribution errors, are considered under "IGBT switching losses" in Subclause B.5.2.

Snubber circuits may be designed to assist with turn-on, or turn-off, or both. Each time a switching event takes place, the snubber circuit will incur an energy loss E_{sn_on} (for a turn-on snubber) or E_{sn_off} (for a turn-off snubber). Many different designs of snubber circuits are possible, but in principle the snubber losses are calculated by taking the energy dissipated in the snubber circuit multiplied by the frequency of occurrence of dissipative events in the valve:

$$P_{V8} = N_t \cdot f \cdot \sum_{cycle} (E_{sn\_on}(V, I) + E_{sn\_off}(V, I)) \qquad (B.13)$$

where

E_{sn_on} is the energy lost in the snubber circuit(s) of one VSC valve level each time the associated IGBT turns on.

E_{sn_off} is the energy lost in the snubber circuit(s) of one VSC valve level each time the associated IGBT turns off.

B.6.2 Losses in valve electronics

Each IGBT requires a local gate drive unit, or gate unit, to provide the required turn-on and turn-off signals to the gate terminal of the IGBT. Associated with the gate unit there may be other local auxiliary circuits for power supply, measurement, monitoring etc. The gate unit together with its associated auxiliary circuits is referred to as "valve electronics".

The total valve electronics losses per valve is calculated by multiplying the power loss per valve level by the number of valve levels per valve:

$$P_{V9} = P_{GU} \cdot N_t \qquad (B.14)$$

where

P_{GU} is the total power consumption of gate unit(s), power supply circuits and other auxiliary circuits in one VSC valve level.

NOTE Where the valve electronics derives its power from a passive snubber circuit, the power consumption of the valve electronics may already be counted in the losses of the snubber circuit as described in the previous sub-clause.

B.7 Total valve losses per station

The total losses per valve are calculated by summing the contributions P_{V1} to P_{V9}:

$$P_{VT} = \sum_{i=1}^{9} P_{Vi} \quad (B.15)$$

~~The total VSC valve losses per station are equal to the losses per valve, P_{VT} multiplied by the number of valves in the station.~~

~~NOTE Some multi-level converter topologies contain more than one type of valve, or valves with different operating duties. In such cases, the above procedure should be evaluated separately for each type of valve or operating duty.~~

Annex B
(informative)

Modulation strategies for 2-level converters

B.1 Carrier wave PWM

Figure B.1 a) shows the control signals (the carriers and the voltage references as sine wave) for a PWM VSC. Figure B.1 b) shows the resulting voltage V_{am} at the a.c. terminal a, with respect to a hypothetical midpoint m of the d.c. capacitor. In this example, the frequency of the carrier (triangular wave signal) is nine times the fundamental frequency.

The general harmonic form of the switched waveform of Figure 29 b) can be written as:

$$v_{am}(t) = \frac{U_d}{2} M \cos(\omega_1 t + \theta_1) + \sum_{m=1}^{\infty} \sum_{n=-\infty}^{\infty} C_{mn} \cos[m(\omega_c t + \theta_c) + n(\omega_1 t + \theta_1)]$$

where

M is the modulation index;

ω_1 is the fundamental frequency;

ω_c is the carrier frequency;

m is a multiple of the carrier frequency;

n is a multiple of the fundamental frequency;

θ_1 is an arbitrary phase offset of the fundamental waveform;

θ_c is an arbitrary phase offset of the carrier waveform.

The most effective approach to determine the harmonic coefficients C_{mn} is using double integral Fourier form as:

$$C_{mn} = \frac{1}{2\pi^2} \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} F(x,y) e^{j(mx+ny)} dxdy$$

where

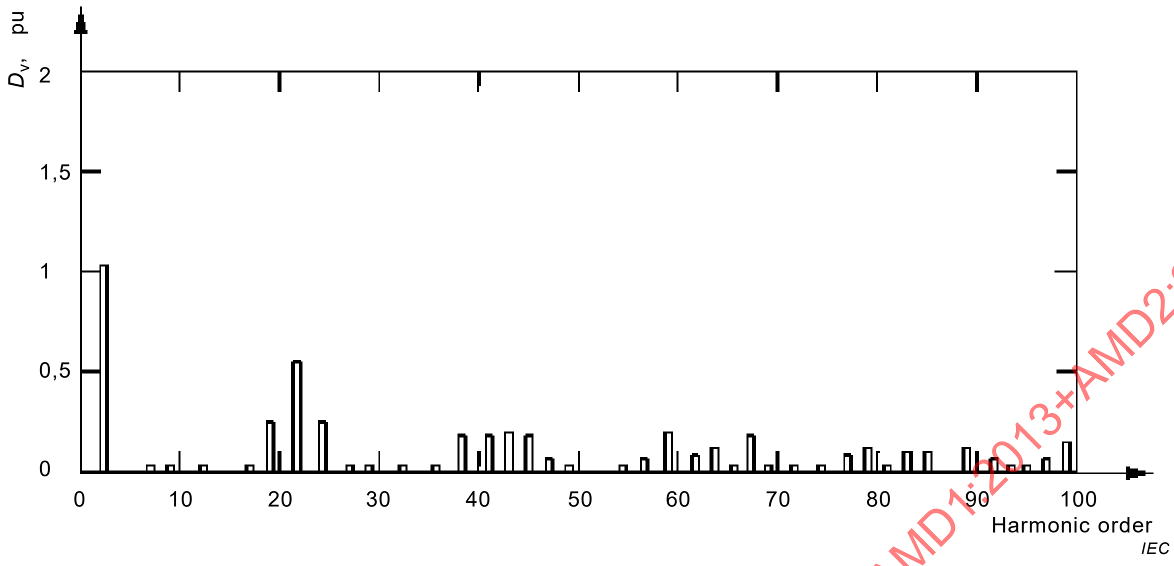
$F(x,y)$ is the switched waveform for one fundamental cycle;

x = $\omega_c t$;

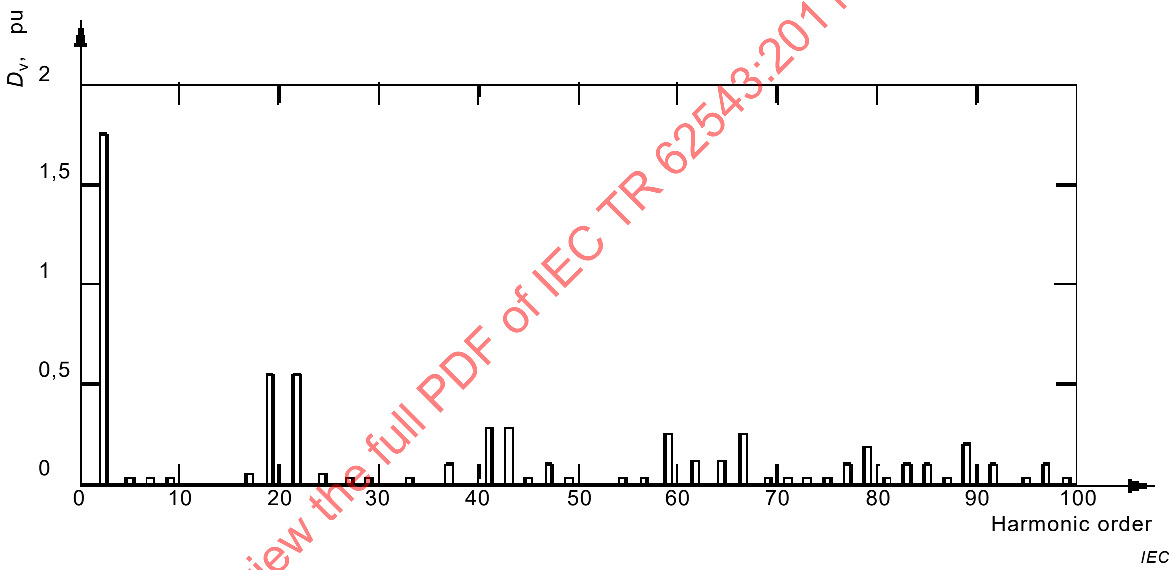
y = $\omega_1 t$.

The general harmonic form of the switched waveform defines carrier multiple harmonics (when $m \neq 0$ and $n = 0$) and sideband harmonics around the carrier multiples (when $m \neq 0$ and $n \neq 0$). Figure B.1 shows the typical harmonic spectra of the voltage waveforms for phase-to-floating neutral and phase-to-phase, respectively, for a 2-level VSC using PWM switched waveforms with a carrier-based control method using 21 times fundamental frequency and assuming infinite d.c. capacitance (i.e. no d.c. voltage ripple). These harmonic spectra would be changed under different specific operating conditions.

For a three-phase 2-level VSC, a balanced set of three-phase line-line output voltages is obtained if the phase leg references are displaced by 120°. In this case, the triplen sideband harmonics around each carrier multiple are cancelled in the line-line output voltages. It is important to note that the harmonic cancellation is a consequence of the triplen sideband harmonics. The carrier/fundamental ratio has no influence, and it can be odd, even or not integer.



B.1 a) Phase-to-floating neutral voltage amplitude versus harmonic order



B.1 b) Phase-to-phase voltage amplitude versus harmonic order

Figure B.1 – Voltage harmonics spectra of a 2-level VSC with carrier frequency at 21st harmonic

B.2 Selective harmonic elimination modulation

Selective harmonic elimination modulation (SHEM) is known as a modulation method to eliminate the undesirable low order harmonics. SHEM approach is an effective way to eliminate the selected most significant harmonics using lower switching frequency. Figure B.2 shows the waveform switched at predetermined angles. The switched waveform has odd half-wave symmetry and even quarter-wave symmetry. The K switching angles can be used to eliminate K-1 significant harmonic component and control the fundamental voltage.

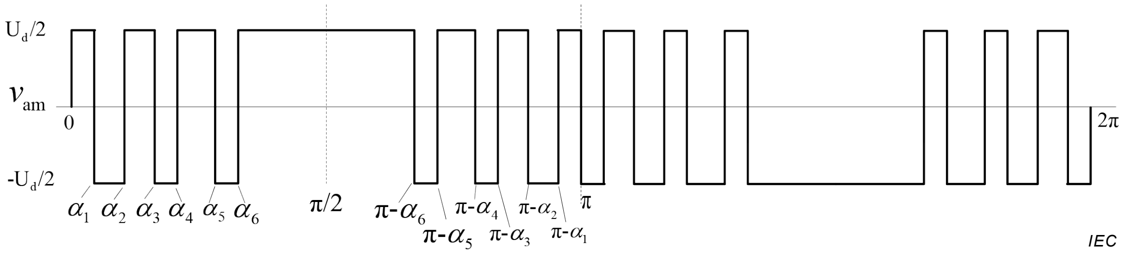


Figure B.2 – Phase output voltage for selective harmonic elimination modulation (SHEM)

The general Fourier series of the switched waveforms shown in Figure B.2 can be given as

$$v_{am}(t) = \sum_{n=1}^{\infty}(a_n \cos n\omega t + b_n \sin n\omega t)$$

For a waveform with quarter-wave symmetry, only the odd harmonics with sine component will be present. Therefore,

$$a_n = 0$$

$$b_n = \frac{4}{n\pi}\left[1 + 2\sum_{k=1}^{K}(-1)^k \cos n\alpha_k\right]$$

Note that K number of simultaneous equations are required to solve the K number of switching angles. The fundamental voltage can be controlled using one equation, and K-1 harmonics can be eliminated using the other K-1 equations. Usually, the lowest significant harmonics are to be eliminated. For a three-phase three-wire 2-level VSC, the triplen harmonics can be ignored if the phase references are displaced by 120°.

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Edition 1.2 2017-05

FINAL VERSION

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

IEC TR 62543:2011-03+AMD1:2013-07+AMD2:2017-05 CSV(en)

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

HIGH-VOLTAGE DIRECT CURRENT (HVDC) POWER TRANSMISSION USING VOLTAGE SOURCED CONVERTERS (VSC)

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This Consolidated version of IEC TR 62543 bears the edition number 1.2. It consists of the first edition (2011-03) [documents 22F/230/DTR and 22F/239A/RVC], its amendment 1 (2013-07) [documents 22F/300A/DTR and 22F/307/RVC] and its amendment 2 (2017-05) [documents 22F/440/DTR and 22F/450/RVDTR]. The technical content is identical to the base edition and its amendments.

Cette version Finale ne montre pas les modifications apportées au contenu technique par les amendements 1 et 2. Une version Redline montrant toutes les modifications est disponible dans cette publication.

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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.

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

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.

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

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HIGH-VOLTAGE DIRECT CURRENT (HVDC) POWER TRANSMISSION USING VOLTAGE SOURCED CONVERTERS (VSC)

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. 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.

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.

IEC 61975, *High-voltage direct current (HVDC) installations – System tests*

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*

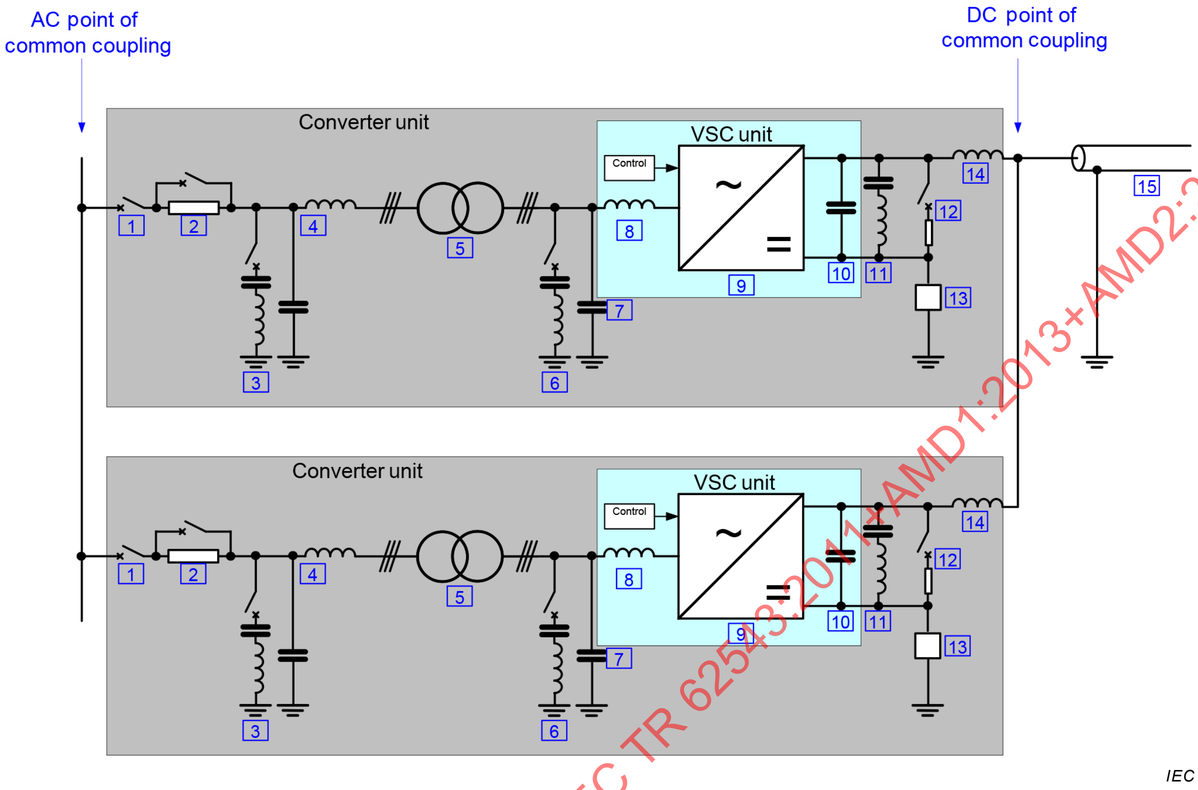
3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62747, IEC 62501 and the following apply.

3.1 General

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.



1	circuit breaker	9	VSC unit 3)
2	pre-Insertion Resistor	10	VSC d.c. capacitor 4)
3	line side harmonic filter1)	11	d.c. harmonic filter1)
4	line side high frequency filter6)	12	dynamic braking system7)
5	interface transformer	13	neutral point grounding branch 5)
6	converter side harmonic filter1)	14	d.c. reactor8)
7 + 8	converter side high frequency filter2)	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.

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.

3.5 VSC transmission

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

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

3.5.8
valve side harmonic filter
filters (if any) used to mitigate the HF stresses of the interface transformer

3.5.10
d.c. harmonic filter
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.

3.5.11
d.c. reactor
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.

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

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

3.11 Power losses

3.11.1
auxiliary losses
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.

3.11.2
no-load operating losses
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
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

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.

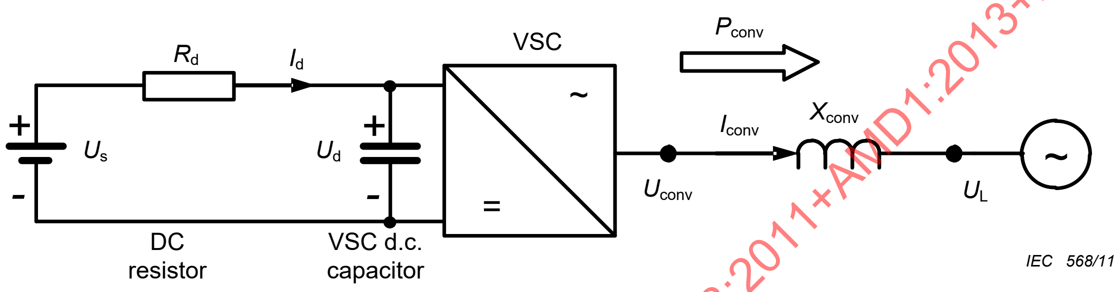


Figure 2 – Diagram of a generic voltage source converter (a.c. filters not shown)

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 ($\mathrm{Im}(U_L \cdot I_L) > 0$) , or inductively, absorbing reactive power from the a.c. network ($\mathrm{Im}(U_L \cdot I_L) < 0$). 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.

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:

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

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

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.

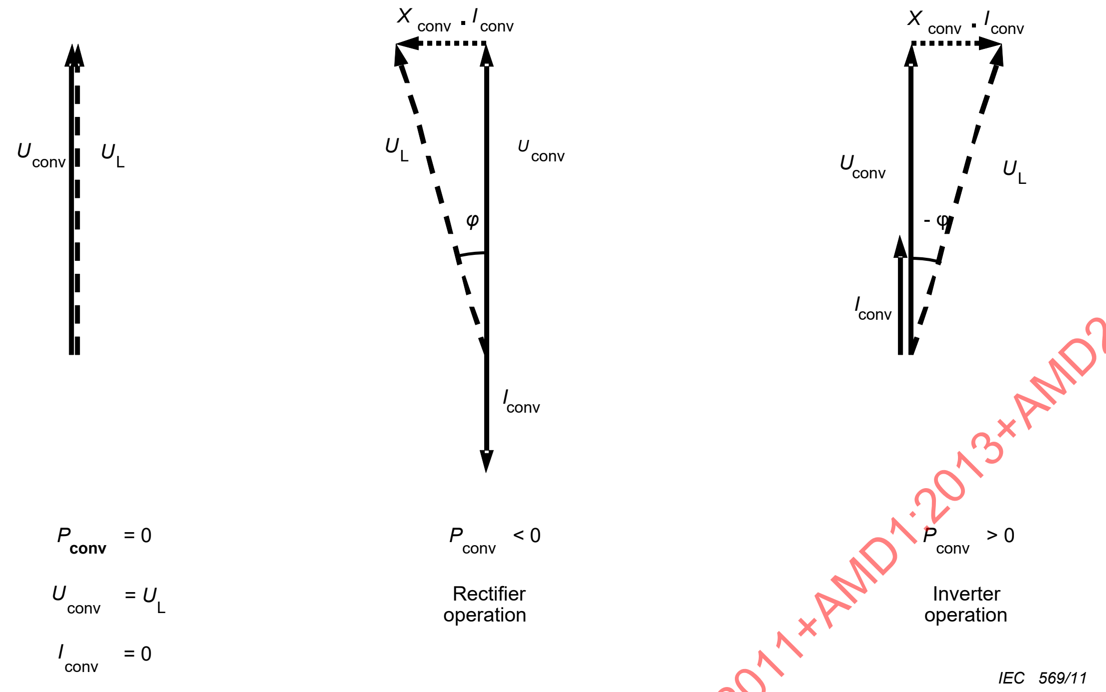


Figure 3 – The principle of active power control

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.

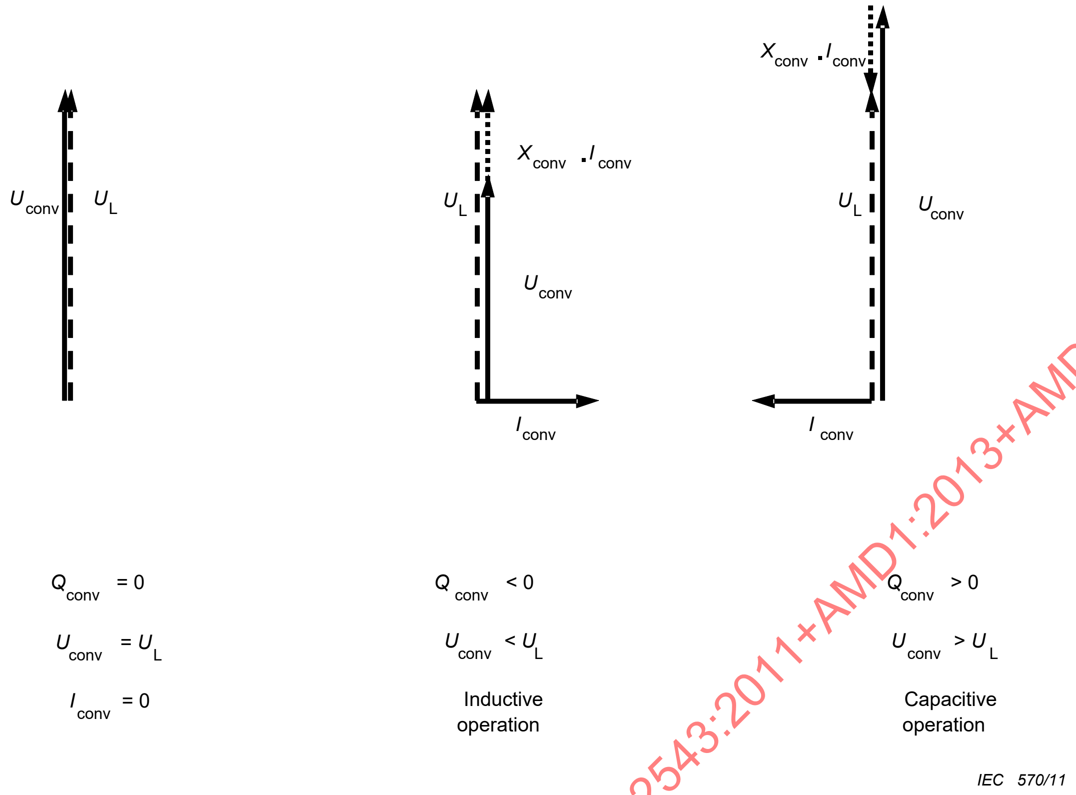


Figure 4 – The principle of reactive power control

4.1.3 Operating principles of a VSC transmission scheme

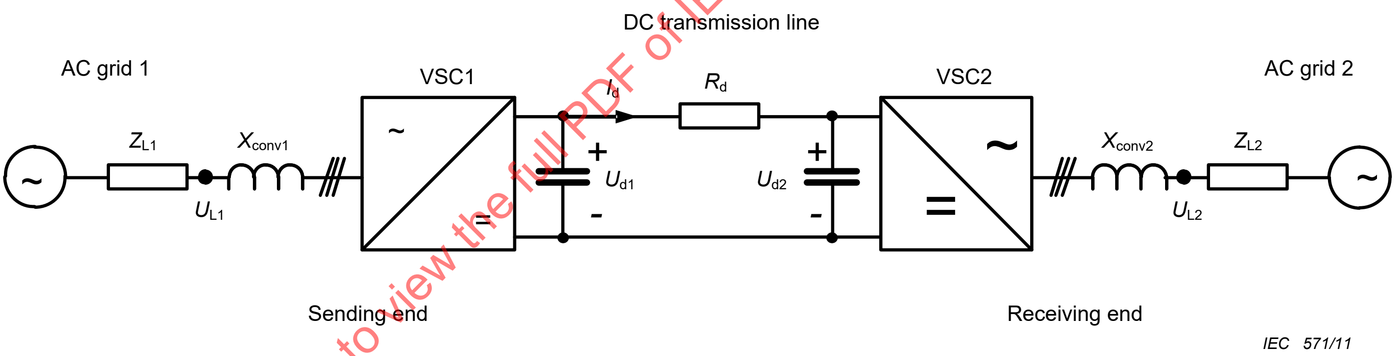


Figure 5 – A point-to-point VSC transmission scheme

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 $I_d = (U_{d1}-U_{d2})/R_d$.

For example, 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.
- In most cases, 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.

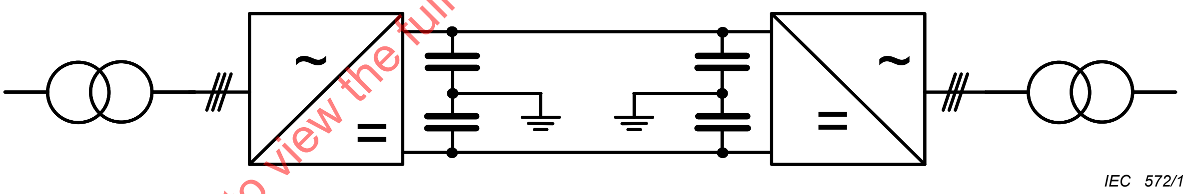


Figure 6 – VSC transmission with a symmetrical monopole

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.

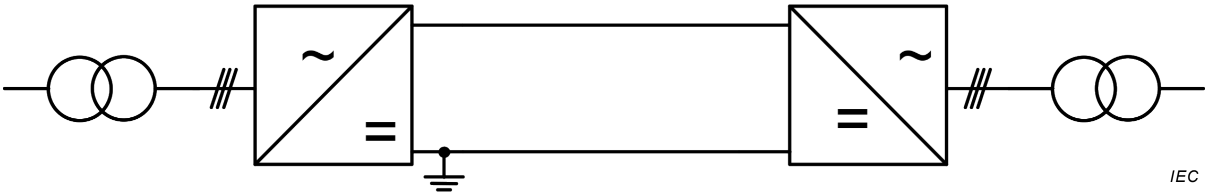


Figure 7 – VSC transmission with an asymmetrical monopole with metallic return

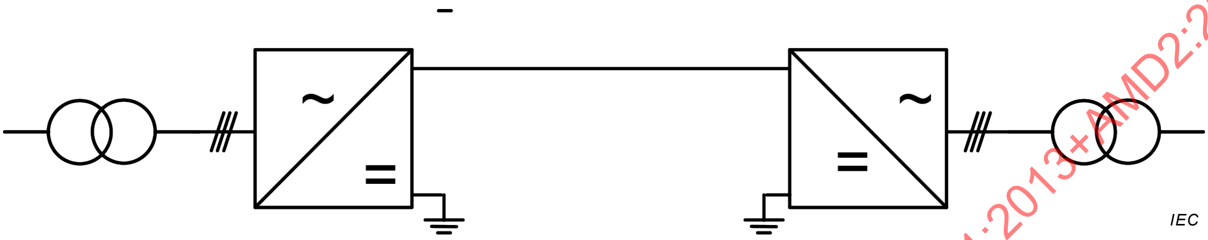


Figure 8 – VSC transmission with an asymmetrical monopole with earth return

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.

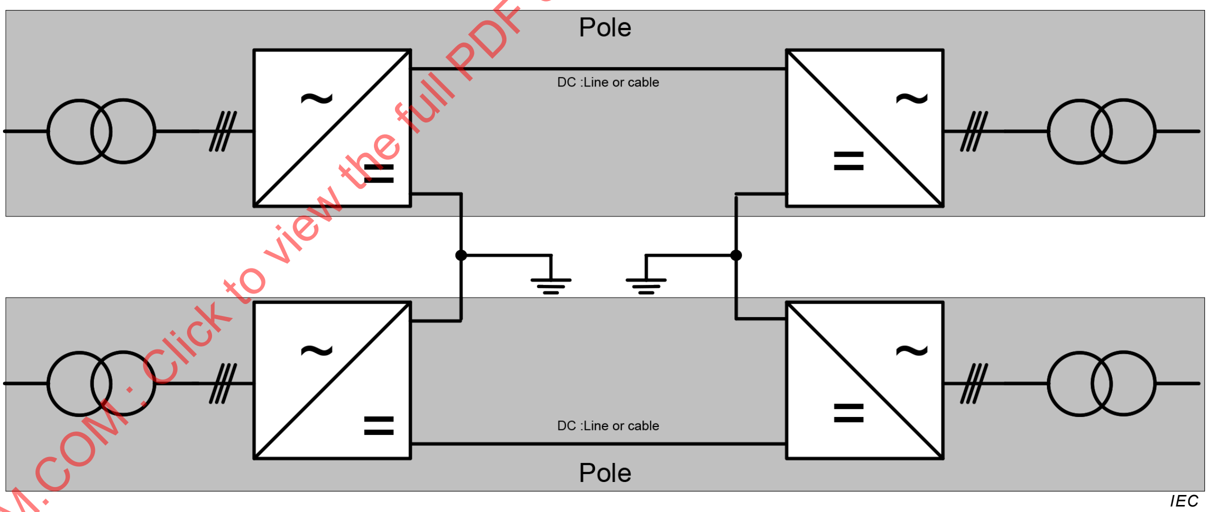


Figure 9 – VSC transmission in bipolar configuration

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.

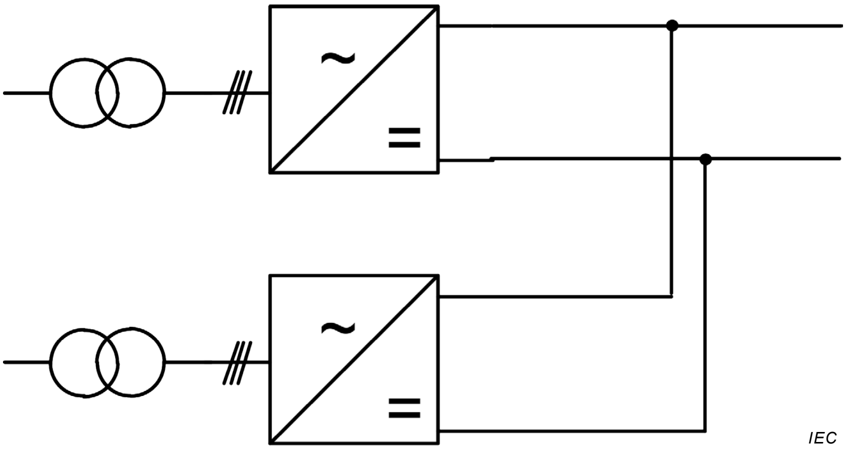


Figure 10 – Parallel connection of two converter units

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

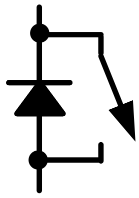
In principle, it is also possible to connect more than two converter units in parallel or in series. Connections of each converter units are either to separate windings of a common transformer or to separate transformers.

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 turn-off semiconductor device and a so called free-wheeling diode as shown in Figure 11.

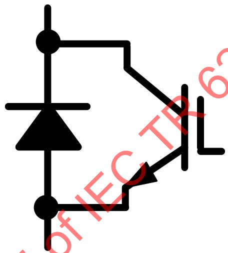


IEC 577/11

Figure 11 – Symbol of a turn-off semiconductor device and associated free-wheeling diode

Various different turn-off semiconductor devices 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 turn-off semiconductor devices 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.



IEC 1904/13

Figure 12 – Symbol of an IGBT and associated free-wheeling diode

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 kiloampers. 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 limits are not necessary in many cases. The gate drivers for IGBTs can be quite simple, since they have to deliver only a few watts of control power to the gate.

High power IGBTs are made up by a parallel connection of chips to achieve the required current capability. The chips are mounted in press packs or module housings. In most cases the FWD chips are included in the same housing.

Press pack housings are intended to be clamped between heat sinks; the paths for current and heat are the copper poles of collector and emitter of the devices that are separated by a ring of insulating material. For high voltage devices, this material is high strength porcelain in most cases, though glass fiber reinforced resin is also used.

Module IGBTs are designed for single sided cooling and are mounted on heat sinks by screws; spring loaded clamping is not necessary. The electrical terminals are on the top side of the module; the heat flows through the base plate of the module to the heat sink. Since the electrical part of the module is insulated to the base plate, it is possible to mount modules with different voltage potentials on a shared heat sink.

5 VSC transmission converter topologies

5.1 General

For a high power VSC transmission system, the key issue that determines the cost and operating losses of the overall system is the power circuit structure to construct the a.c. output voltage waveform. The output voltage waveform should approximate a sine-wave in order to eliminate or minimize the need for harmonic filtering. The switching converter considered for practical implementation is a voltage sourced converter operated with a fixed d.c. voltage. The converter is a combination of turn-off semiconductor devices that connect the d.c. input voltage periodically to the output for some intervals to produce the a.c. output voltage. The converters at each end of a VSC transmission system can be arranged in a number of different ways, with the configuration of the converter normally being referred to as its topology. A the time of writing, two different converter types have been used for commercial projects: those in which the converter valves act as controllable switches and those in which the converter valves act as controllable voltage sources. These two types are described in subclauses 5.2 and 5.3 respectively.

Some other converter topologies which share the characteristics of both the “controllable switch” and “controllable voltage source” types have been described in the literature. The reader is referred to CIGRÉ Technical Brochure No. 492 “Voltage Source Converter (VSC) HVDC for Power Transmission – Economic Aspects and Comparison with other AC and DC Technologies”, for details.

It is a fundamental criterion for any viable topology that it enables the functional requirements to be met. Different topologies have different technical characteristics, and therefore allow the overall scheme to be optimized in different ways. Manufacturers may have different preferred topologies and be able to best optimize their proposals around this preferred topology. It is recommended that customers do not stipulate the topology to be used for a VSC transmission system, unless there are compelling reasons for doing so.

It is possible to arrange the converters to have a single-, three- or multi-phase a.c. output/input. For the purpose of this report, only the three-phase arrangement will be discussed.

5.2 Converter topologies with VSC valves of “switch” type

5.2.1 General

The converter switches (normally called VSC valves) perform the function of connecting the a.c. bus to the d.c. terminals. If the connection is direct through two alternately operating switches, the a.c. bus voltage will change between the voltage levels at the two d.c. terminals. Such a converter is known as a 2-level converter. In the 2-level converter, each of the VSC valves has to withstand the voltage between the two d.c. terminals.

If the d.c. capacitor is subdivided, or additional d.c. capacitors are added, it is possible to arrange for the a.c. voltage to move not only to the voltage at the two d.c. terminals but also to intermediate levels. The number of voltage levels to which the a.c. bus voltage can be switched will depend on the number of valves and the number of d.c. capacitor subdivisions or additional d.c. capacitors. These arrangements are known as 3-level or multi-level converters, depending on the number of voltage levels that can be achieved. The term multilevel refers to a converter phase unit topology where the a.c. bus can be switched to attain more than three different voltage levels.

In 3-level or multi-level topologies, the VSC valves do not normally have to be designed for the full d.c. terminal-to-terminal voltage. For example, in normal operation each valve in a 3-level converter topology experiences only 50 % of the terminal-to-terminal d.c. voltage. Similarly, in normal operation each VSC valve in an *n*-level topology experiences only the terminal-to-terminal d.c. voltage of the phase unit divided by (*n*-1).

In the following paragraphs, converter topologies suitable for VSC transmission systems will be described in more detail. It should be noted that a considerable research and development effort is being invested in voltage sourced converter technology, so additional suitable topologies will likely become available subsequent to the issue of this report.

5.2.2 Operating principle

The basic operating mechanism of an ideal VSC is covered in this section. The description is initially limited to a 2-level VSC. The 2-level VSC is the simplest structure needed to convert a d.c. voltage into a.c. voltages. Although other types of multi-level VSCs are more complex, their basic operating principle does not differ from that of the 2-level VSC.

For the purpose of illustration, the VSC valves are described as ideal switches without any switching losses. A VSC valve in a real application consists of a large number of series-connected semiconductor devices, and is described in greater detail in Clause 5. The stray inductances are neglected here, and the d.c. capacitors have been assumed to have infinite capacitance—i.e., no d.c. voltage ripple is shown.

As explained in Subclause 4.1, the output of the VSC needs to be connected in series with a phase reactor. The phase reactor enables the VSC to control power flow in addition to smoothing the output current.

5.2.3 Topologies

5.2.3.1 Two-level converters

A 2-level converter is the simplest switching arrangement capable of producing a.c. output from a d.c. source in the form of a simple square-wave. A three-phase converter using three 2-level phase units is illustrated in Figure 13.

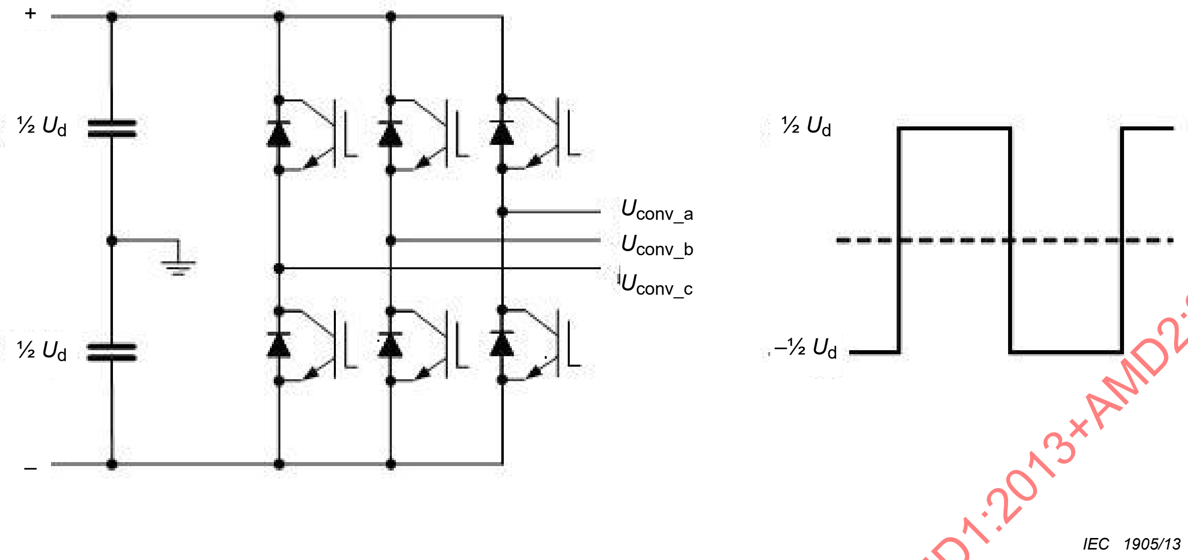


Figure 13 – Diagram of a three-phase 2-level converter and associated a.c. waveform for one phase

The a.c. waveform shown in the figure is the phase-to-neutral voltage. The neutral voltage is the voltage at the midpoint of the d.c. capacitor.

Since the square-wave output voltage shown in Figure 13 is not acceptable in a practical HVDC scheme, this converter type is normally operated with pulse width modulation (PWM) as described in Subclause 9.3.

A typical PWM-switched waveform, using a carrier based control method with a switching frequency of 21 times the fundamental, is given in Figure 14. For the purpose of this illustration, the d.c. capacitor has been assumed to have an infinite capacitance (i.e., no d.c. voltage ripple).

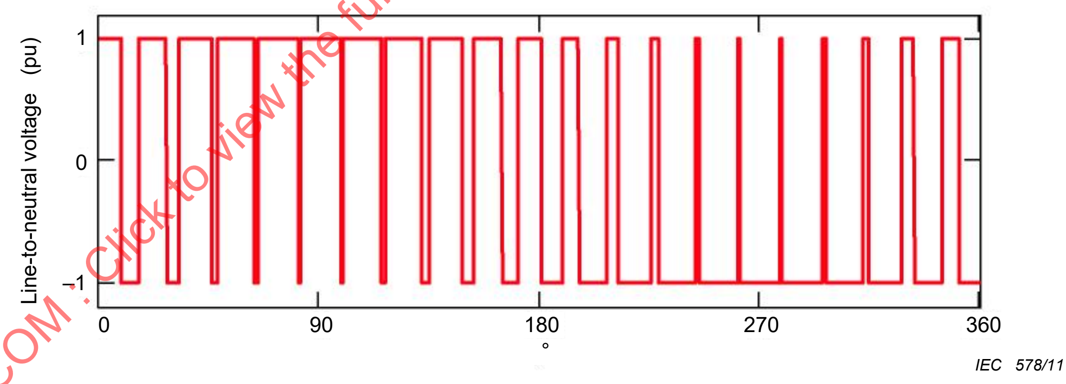


Figure 14 – Single-phase a.c. output for 2-level converter with PWM switching at 21 times fundamental frequency

Other PWM techniques are also available, such as optimised PWM (OPWM) or selective harmonic elimination method (SHEM). These aim to improve the compromise between power transfer capability, switching frequency and harmonic performance.

5.2.3.2 Three-level neutral-point clamped (NPC) converters

A three phase converter consisting of three 3-level phase units is illustrated in Figure 15. The converter has three d.c. terminals to connect to a split or centre-tapped d.c. source. As seen, there are more valves used than in the 2-level phase unit, and additional diodes or valves are required to connect to the d.c. supply centre-tap, which is the reference zero potential.

However, with identical valve terminal-to-terminal voltage rating, the total d.c. supply voltage can be doubled so that the output voltage per valve remains the same.

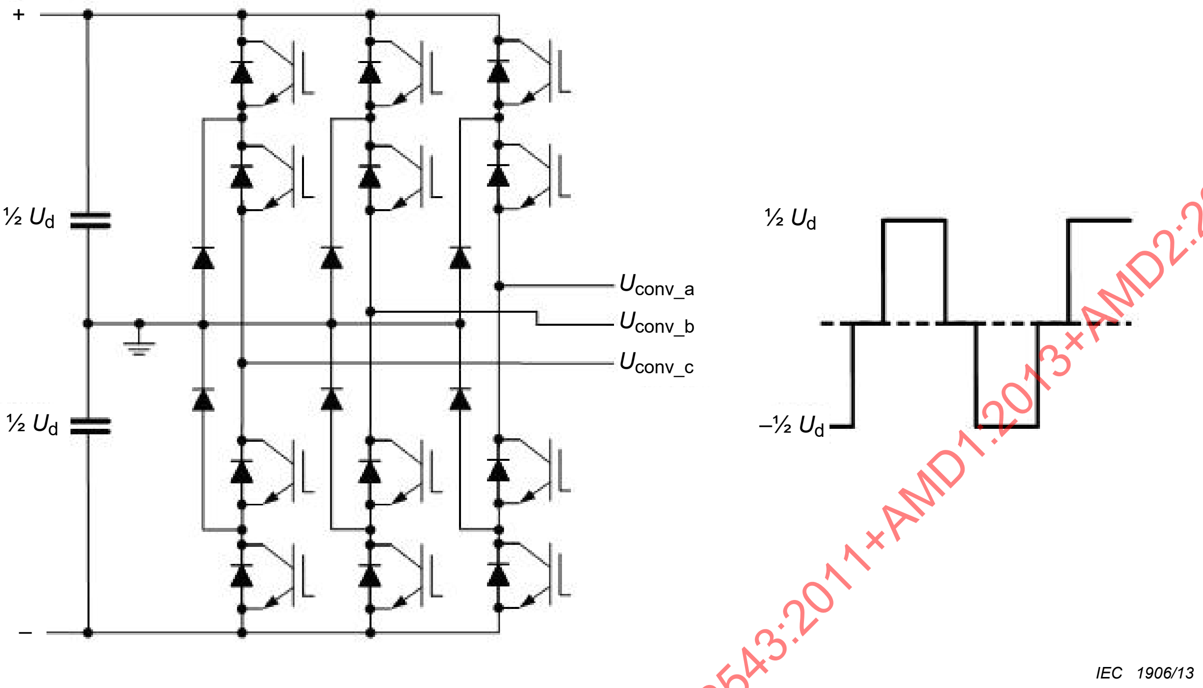


Figure 15 – Diagram of a three-phase 3-level NPC converter and associated a.c. waveform for one phase

NOTE The neutral-point clamping diodes shown in Figure 15 may be replaced by IGBTs in some applications.

The a.c. waveform shown in the figure is the phase-to-neutral voltage. The neutral voltage is the voltage at the midpoint of the d.c. capacitor. As illustrated in Figure 15, the output voltage of the 3-level phase unit can be positive, negative, or zero. Positive output is produced by gating on both upper valves in the phase unit, while negative output is produced by gating on both lower valves. Zero output is produced when the two middle valves, connecting the centre tap of the d.c. supply via the two diodes to the output, are gated on. At zero output, positive current is conducted by the upper-middle controllable device and the upper centre-tap diode, and negative current by the lower-middle controllable device and the lower centre-tap diode.

As indicated in Figure 15, the relative duration of the positive (and negative) output voltage with respect to the duration of the zero output is a function of control parameter α, which defines the conduction interval of the top upper, and the bottom lower valves. The magnitude of the fundamental frequency component of the output voltage produced by the phase unit is a function of parameter α. When α equals zero degrees it is maximum, while at α equals 90 degrees it is zero. Thus, one advantage of the 3-level phase unit is that it has an internal capability to control the magnitude of the output voltage without changing the number of valve switching events per cycle.

The operating advantages of the 3-level phase unit can only be fully realized with some increase in circuit complexity, as well as more rigorous requirements for managing the proper operation of the converter circuit.

An additional requirement is to accommodate the increased a.c. ripple current with a generally high triplen harmonic content flowing through the mid-point of the d.c. supply. This may necessitate the use of a larger d.c. storage capacitor or the employment of other means to minimize the fluctuation of the mid-point voltage. However, once these problems are solved, the 3-level phase unit provides a useful building block to structure high power converters, particularly when rapid a.c. voltage control is needed.

In common with the two-level converter, this converter is normally operated with PWM. A typical PWM switched waveform, using a carrier based control method with a frequency of 21 times fundamental frequency, is given in Figure 16. For the purpose of this illustration, the d.c. capacitor has been assumed to have an infinite capacitance (i.e., no d.c. voltage ripple).

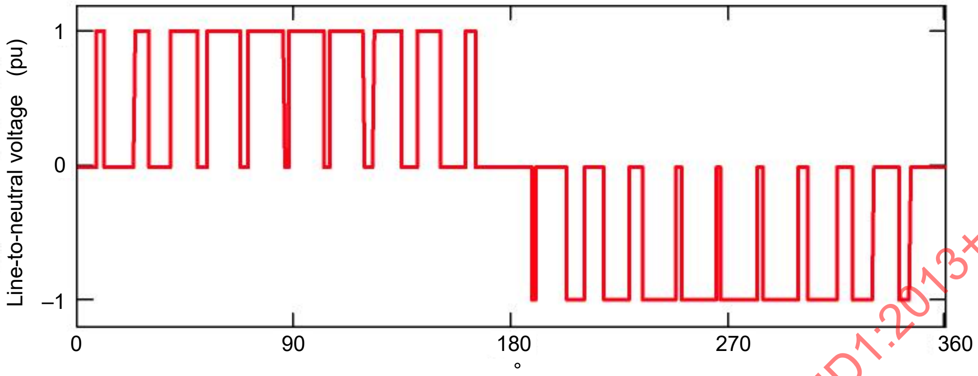


Figure 16 – Single-phase a.c. output for 3-level NPC converter with PWM switching at 21 times fundamental frequency

5.2.3.3 Other multi-level converter topologies

The neutral-point clamped circuit can be extended to higher numbers of output levels, for example 5 levels, but at the expense of disproportionately greater complexity. Another converter type which has been used in some power electronic applications is the "flying capacitor" or "floating capacitor" circuit, which can also exist in 3-level and 5-level forms but suffers the same disproportionately greater complexity as the number of output levels is increased. These and other possible multi-level converter topologies are described in CIGRÉ Technical Brochures 269 and 447.

5.3 Converter topologies with VSC valves of the "controllable voltage source" type

5.3.1 General

With valves of the "controllable voltage source" type, each VSC level is effectively a single-phase VSC in its own right, and contains power semiconductors and a capacitor for energy storage. Each level has two main terminals used for the series connection of the VSC levels within the valve. By appropriate control of the IGBTs within the valve level, either the voltage of the capacitor or zero volts can be applied to the main terminals of the VSC level.

By individual and appropriate control of the VSC valve levels, a desired voltage can be generated at the valve terminals. The valve voltage is the sum of those capacitor voltages, of which the voltage is applied to the main terminals of the VSC level. The VSC valve submodules or cells are controlled in that way so that the sum of the upper and lower arm of one phase unit equals to the d.c. voltage whereas the instantaneous voltage on the a.c. terminals is determined by the ratio of the voltages of the two converter phase arms of one phase unit.

Assuming infinite storage capacitances with equal voltages in the individual valve levels, n+1 different voltage steps can be applied to the terminals of a valve consisting of n valve levels. Assuming a high number of VSC levels per valve the topology can be approximated by electrical equivalent as shown in Figure 17. Each valve can be considered as a controllable voltage source.

The valve reactors contribute to both the phase reactance and the d.c. reactance, and are essential for the current control within the phase units. Furthermore they also limit the peak current and current gradients in case of severe faults, such as short circuit between the d.c. terminals.

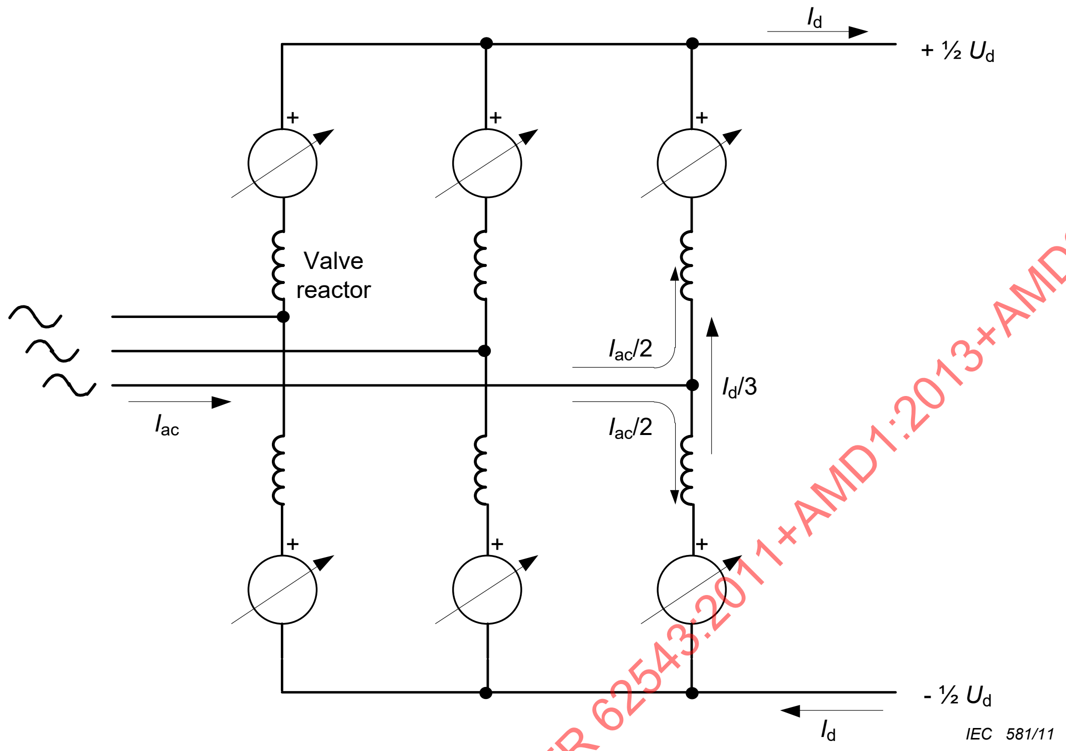


Figure 17 – Electrical equivalent for a converter with VSC valves acting like a controllable voltage source

Because of its modular design and the multi-level technology it is referred to as modular multi-level converter topology. For the design of the individual VSC levels different power building blocks can be used. At the time of writing, two different topologies are used:

- MMC with VSC levels in half-bridge topology;
- MMC with VSC levels in full-bridge topology.

Since the circuit is inherently modular, it is relatively straightforward to obtain high numbers of output levels, without requiring either PWM or series-connected IGBTs. Thus, a.c. filters can be omitted in many cases and considerations of voltage distribution amongst series-connected IGBTs do not arise.

This type of converter can also be realised with multiple IGBTs connected in series in each controllable switch, giving an output voltage waveform with fewer, larger, steps than the MMC. This configuration is referred to as the Cascaded Two Level (CTL) converter but is functionally identical to the MMC in every aspect apart from the harmonic performance which may be slightly poorer.

5.3.2 MMC topology with VSC levels in half-bridge topology

Each of the 6 variable voltage sources shown in Figure 17 is realised with a series connection of identical VSC valve levels with an electrical equivalent as shown in Figure 18. The VSC valve level is a two-terminal component with its own d.c. storage capacitor unit as shown in Figure 18. These VSC valve levels are individually controlled and can be switched between a state with full submodule voltage (voltage of the associated storage capacitor) and a state with zero submodule voltage for both current directions. If the submodule voltage is applied to the VSC valve level terminals, the capacitor can be charged and discharged dependent on the current direction of the converter phase arm.

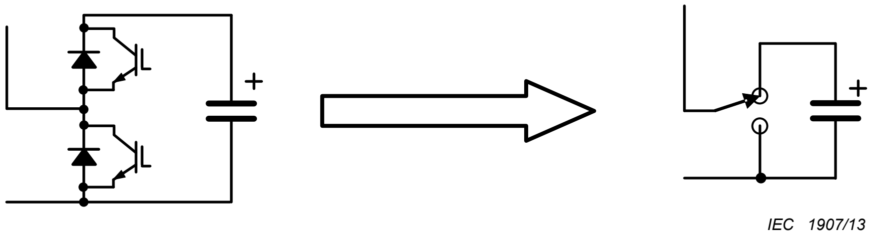


Figure 18 – VSC valve level arrangement and equivalent circuit in MMC topology in half-bridge topology

The electrical arrangement of VSC valve levels and valve reactors in a converter block is shown in Figure 19.

The VSC valve levels are controlled in that way that the sum of the upper and lower arm of one phase unit equals to the d.c. voltage whereas the instantaneous voltage on the a.c. terminals is determined by the ratio of the voltages of the two converter phase arms of one phase unit.

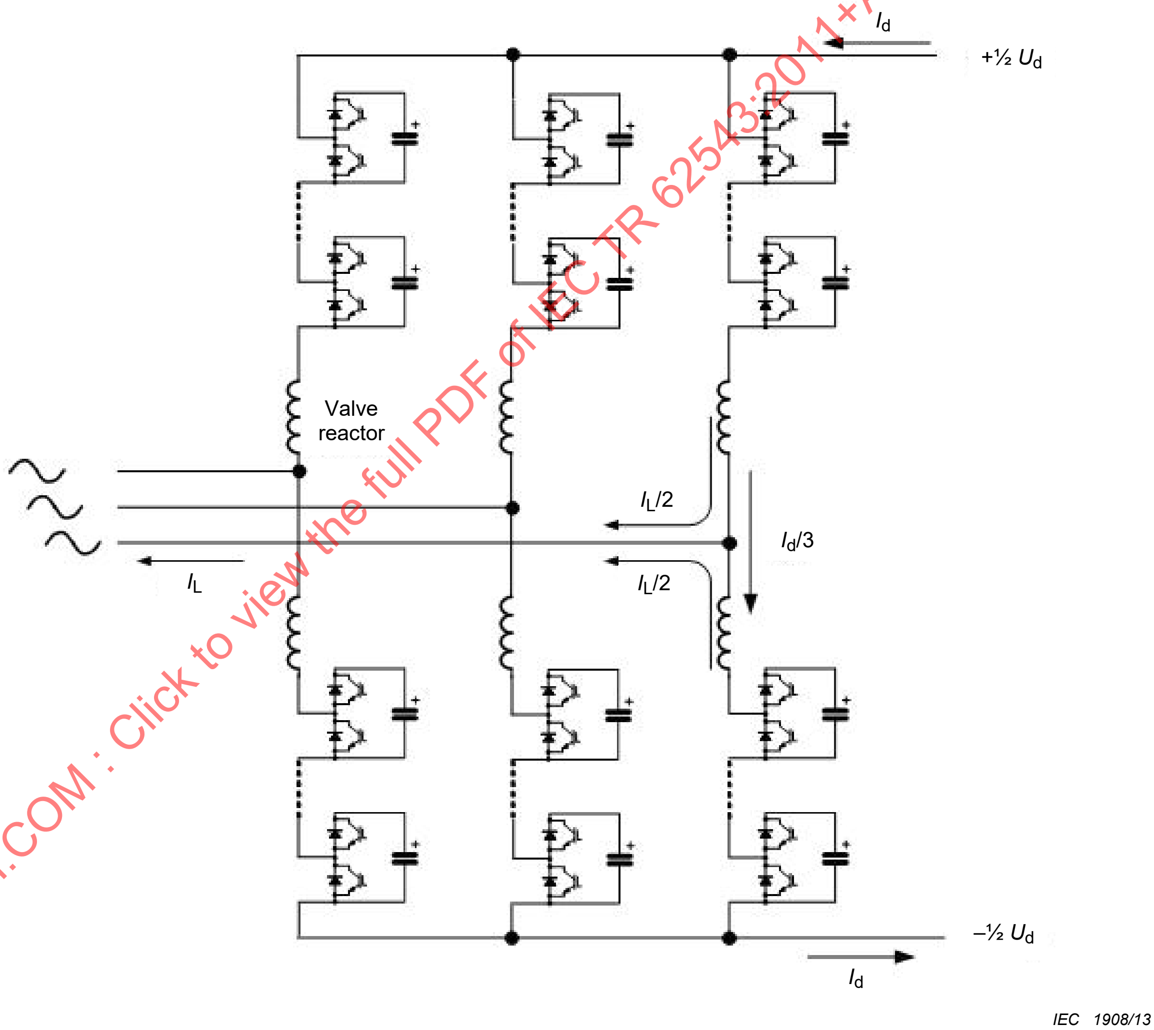


Figure 19 – Converter block arrangement with MMC topology in half-bridge topology

5.3.3 MMC topology with VSC levels in full-bridge topology

The MMC topology with “full-bridge” VSC levels operates on very similar principles to that based on half-bridge VSC levels. The principal difference is that each VSC level consists of one storage capacitor and four IGBTs in a bridge configuration as shown on Figure 20.

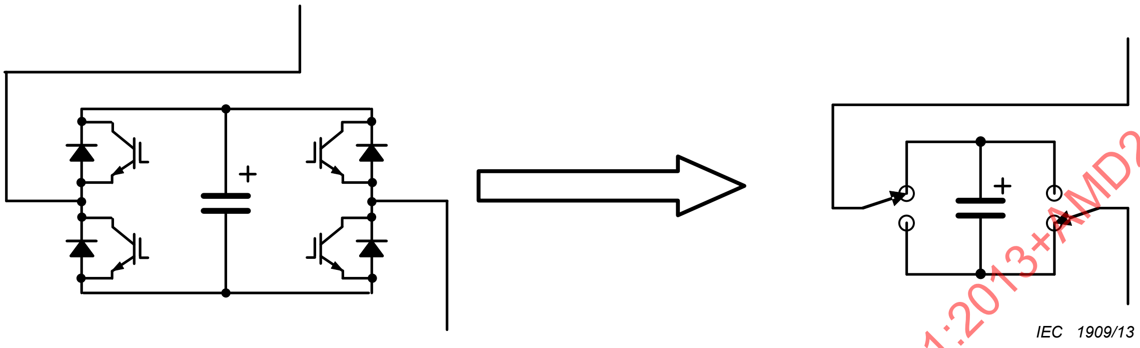


Figure 20 – VSC valve level arrangement and equivalent circuit in MMC topology with full-bridge topology

In common with the half-bridge sub-module configuration, each VSC level in the full-bridge configuration is capable of producing an output voltage of zero or a positive output voltage equal to the capacitor voltage. However, it can alternatively produce a negative output voltage equal to the capacitor voltage.

In contrast to the converter arrangements outlined in Subclauses 5.2 and 5.3.2, this converter arrangement is capable of producing a d.c. output voltage of either polarity, a feature which can be beneficial in applications where a VSC transmission station is connected as a tap onto an existing line commutated HVDC link.

A second advantage of the full-bridge circuit is that it permits faults on the d.c. side of the converter to be cleared by using only the power semiconductors in the valve, without requiring any additional switchgear.

On the other hand the full-bridge circuit requires, in principle, twice the number of IGBTs compared with the half-bridge circuit.

5.3.4 CTL topology with VSC cells in half-bridge topology

Each of the 6 variable voltage sources shown in Figure 17 is realized with a series connection of identical VSC valve cells. One VSC valve cell acts as a single-phase two-level converter and functions electrically equivalent to one level of the MMC described in Subclause 5.3.2, except that the voltage rating is higher. Instead of a single IGBT/diode level in one MMC level, multiple IGBT/diode levels are connected in series and synchronously controlled as one switch in one CTL cell.

The electrical arrangement of VSC valve cells and valve reactors in a converter block is similar to Figure 19. The IGBT/diode levels depicted in Figure 19 are substituted by valve cells in CTL topology.

The cell d.c. capacitor voltage in the CTL topology corresponds to one valve voltage step.

5.3.5 CTL topology with VSC cells in full-bridge topology

The CTL topology with “full-bridge” VSC cells functions similarly, in principle, to the MMC topology with VSC levels in full-bridge topology, in Subclause 5.3.3. The main difference between CTL topology with VSC cells in full-bridge topology and MMC topology with VSC levels in full-bridge topology is the number of IGBT/diode levels per CTL cell or MMC level.

Each CTL cell consists of multiple IGBT/diode levels in series connection and each MMC level is of one IGBT/diode level.

5.4 VSC valve design considerations

5.4.1 Reliability and failure mode

In addition to the number of series-connected valve levels that are needed to sustain the converter voltage rating, each single valve in a VSC transmission scheme shall include a few redundant valve levels. In case of failure of an individual valve level component, uninterrupted operation of the remaining healthy valve levels is mandatory. Therefore, a faulty valve level shall safely and controllably enter into a short-circuit mode and be capable of conducting current until it can be changed out, e.g., during a scheduled maintenance period.

This capability of short-circuit failure mode (SCFM) operation is very critical for series-connected valve levels, and shall be verified by appropriate tests under conditions that are relevant for a particular application. Some special designs of Presspack IGBT allow SCFM to be assured. Module IGBTs, however, do not exhibit this behaviour and a faulty Module IGBTs may result in an open circuit. Thus, additional components in parallel to the valve level terminals are required to ensure SCFM.

The operating voltage of the IGBT shall be selected to be low enough to achieve an adequately low failure-in-time (FIT) rate.

In selecting the operating voltage and current of the IGBT, due consideration should be given to the load cycling requirements for the VSC system.

5.4.2 Current rating

One of the important design bases of the semiconductor in the VSC valve is rated current. In addition, the valve should also be able to handle peak current, including ripple and transients, as well as margins for control and protection actions. The rated phase current gives the nominal stress on the component and shall be considered regarding power losses and junction temperature on the IGBT.

5.4.3 Transient current and voltage requirements

An important aspect of IGBTs is their capability to turn off current and voltage. This capability is defined in the switching safe operating area (SSOA) shown in Figure 21.

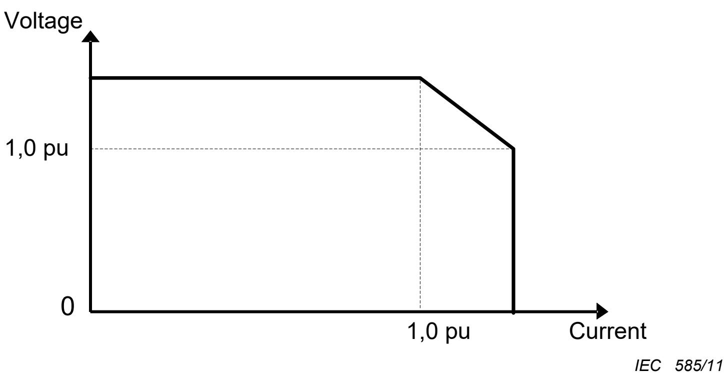


Figure 21 – Typical SSOA for the IGBT

During switching, the IGBT shall be able to turn-off the peak current, including ripple. Additionally, a margin is added to handle current control regulation and protection actions during transient conditions. The valve shall also be capable of turning off the current which results from a short circuit occurring close to the valve. The IGBT short circuit operation capability is defined by the SCSOA (short circuit safe operating area), which is slightly different from the SSOA under normal operation.

5.4.4 Diode requirements

In many converter topologies (including the 2-level and 3-level converters and the MMC with half-bridge topology), the free-wheeling diodes (FWD) in a VSC bridge act as an uncontrolled rectifier bridge. Thus they can be exposed to severe transient overcurrents, for example during d.c.-side short circuits or at energisation.

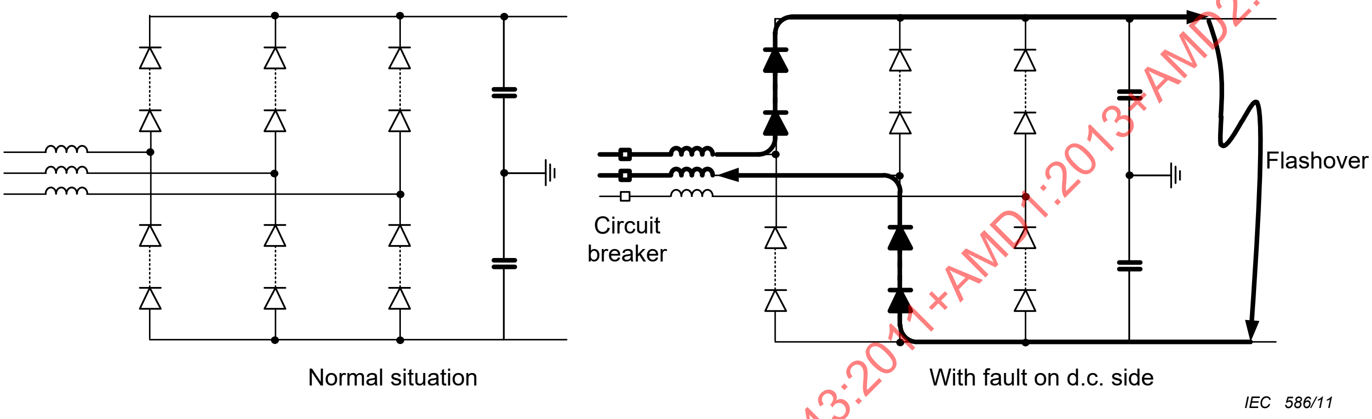


Figure 22 – A 2-level VSC bridge with the IGBTs turned off

In case of a d.c. side fault, as shown in Figure 22, a short circuit between the two d.c. terminals creates a fault current path through the diodes. The current in the a.c. phases in the VSC bridge is limited only by the short-circuit impedance of the a.c. network and the reactance in the converter, e.g., the phase or valve reactors and/or transformers. The fault current is detected by the protection system, which will open the breaker on the a.c. side and thereby eliminate the fault current. A normal protection and breaker scheme takes a time equivalent of three 50/60 Hz fundamental frequency cycles before the fault current is extinguished. If the d.c. system only consists of cables, a fault will be very unlikely. However, the consequences may not be acceptable if the system is not designed to handle the fault. The valve should be designed to handle the fault current with an asymmetrical offset as a worst case. Here, no reapplied voltage occurs since the breaker has disconnected the a.c. system.

Another transient that the diode may experience occurs if the VSC is energized through the a.c. breaker when there is either no voltage, or a low voltage, on the d.c. side. In this case, the converter experiences a surge inrush current and an overvoltage will occur on the d.c. bus. The valve shall be designed to handle the inrush current, or the current will have to be limited. The normal method for doing this is to include pre-insertion resistors.

5.4.5 Additional design details

Besides controlling the turn-off semiconductor device in regular operation, the gate unit should keep the switching device within the safe operating area in all other operational and short-circuit conditions. IGBTs have proven comparatively easy to handle in this respect, thereby facilitating precise control of switching waveforms. This, in turn, is necessary for achieving proper control and protection strategies for the converter.

The switching transients which appear when the IGBT turns on or off give stress to the IGBT and other components in the valve levels. The energy stored in stray inductances and capacitances will generate transient voltages and currents respectively.

Gate voltage control makes it possible to control the voltage between the main two terminals of the IGBT at its turn off process. Suppressing the speed of turn off makes the energy stored in the loop stray inductance dissipate in the IGBT itself. Applying the gate voltage control technology, the snubber circuit can be omitted from the circuit, although switching losses in the IGBT become larger.

For converter topologies with VSC valves of “switch” type it is possible to design the VSC valve such that it does not use traditional snubber circuits for protecting the individual IGBTs. In this case, the IGBTs shall themselves maintain sufficient voltage sharing, both during switching and blocked conditions, by means of gate control and d.c. grading resistors. This, in turn, requires a small spread in device data concerning characteristic switching times, switching transient properties, and leakage currents in the blocked state.

Converter topologies with VSC valves of the “controllable voltage source” type only require synchronized switching of individual valve levels when multiple IGBTs are connected in series in each switch position (as in the cascaded two level converter). Where no direct series connection of IGBTs is used, a coordination of IGBTs switching properties of individual valve levels is not required.

5.5 Other converter topologies

The technical field of VSC transmission is developing rapidly. Accordingly it is to be expected that other converter topologies in addition to those described above will emerge. Some existing known topologies are already described in CIGRÉ Technical Brochure 447.

Purchasers of VSC transmission schemes should consider such alternative converter topologies on their merits and not limit the permitted circuit topologies to those that have been described in Subclauses 5.2 and 5.3.

5.6 Other equipment for VSC transmission schemes

5.6.1 General

According to its principle of operation, only a few components are essential in a voltage sourced converter (VSC). These are

- a means to convert d.c. into a.c. voltages provided by a converter comprising VSC valves and controls;
- an a.c. side reactance provided by phase reactors/valve reactors, transformers, or a combination thereof;
- a d.c. voltage source provided by at least one VSC d.c. capacitor, submodule d.c. capacitor or cell d.c. capacitor.

In addition to these key components, a complete VSC substation may also need

- a.c. and d.c. filters;
- surge arresters;
- circuit breakers and switches;
- measuring equipment.

The above equipments are not always necessary in all converter topologies, but differ due to the real requirements because different components are stressed differently in the different topologies.

5.6.2 Power components of a VSC transmission scheme

Figure 1 shows the basic structure of a VSC substation and the location of the major power components. Depending on the design concept and the VSC substation topology, several components might occur more than once in a real structure, while others might not be needed. The functions and important design aspects of each component are briefly explained in the following paragraphs.

5.6.3 VSC substation circuit breaker

The VSC substation circuit breaker is located at the feeder from the a.c. transmission system to the VSC transmission scheme. Its main function is to connect and disconnect the VSC substation to and from the a.c. system. There are no special requirements compared to what is common practice for circuit breakers used for a.c. substation applications.

Depending on the start-up concept of the VSC transmission scheme, a circuit breaker can be equipped with a closing resistor, or a separate resistor, with either a circuit breaker or disconnector in parallel with it, may be provided in series with the main circuit breaker. The resistor reduces the charging currents of the d.c. circuit, resulting in smaller temporary a.c. system disturbances and lower stresses on the free-wheeling diodes during energization.

5.6.4 A.C. system side harmonic filters

Depending on the converter design and a.c. system conditions, filtering may be required to prevent VSC-generated harmonics from penetrating into the a.c. system or to prevent amplification of background harmonics on the a.c. system.

As a side effect, harmonic filters generate fundamental frequency reactive power which needs to be considered in the overall P-Q operating range of the VSC system. The design principles of system side harmonic filters and any associated circuit breakers do not differ from the design practice for HVDC systems with line-commutated converters (LCC) or flexible alternating current transmission systems (FACTS). High pass, single, double or triple tuned filters may be used as described in IEC/TR 62001.

5.6.5 Radio frequency interference filters

Radio frequency interference (RFI) filters reduce to acceptable limits the penetration of high frequency (HF) harmonics into the a.c. system.

HF harmonics generated require special attention during the design of a VSC substation. To calculate line-carried HF harmonics, a detailed representation of the VSC substation layout is necessary, including the structure and geometry of power components, busbars and grounding system. Additionally, the current and voltage waveforms experienced during the conversion process shall be known.

The design principles for the RFI filter do not differ from the design practice for LCC HVDC or FACTS.

5.6.6 Interface transformers and phase reactors

In many cases, the VSC substation design will include interface transformers. In general, they can fulfill the following tasks:

1) provide a reactance between the a.c. system and VSC unit;
2) adapt a standard a.c. system voltage to a value matching the VSC a.c. output voltage and allow optimal utilisation of VSC valve ratings;
3) connect several VSC units together on the a.c. side that have different d.c. voltage potentials;
4) prevent zero sequence currents from flowing between the a.c. system and VSC unit.

Depending on the design concept applied to the VSC substation, the reactance mentioned under point 1) can be provided by a phase reactor, a transformer, or a combination thereof.

The reactance is necessary to allow control of the a.c. output current of the VSC. Design criteria to determine the size of the reactance are

- the required dynamic behaviour of the system;
- the tolerable harmonic content of the converter a.c. current;
- constraints revealed from analysis of transient conditions and fault scenarios.

If points 2) to 4) do not apply under specific circumstances, the required reactance could be provided by phase reactors, which would eliminate the need for a transformer.

For the design of reactors or transformers, the following points have to be taken into account:

- DC voltage stress on converter winding insulation to ground, for the cases of asymmetrical monopole or bipole;
- stresses due to fundamental current;
- saturation characteristics with respect to possible a.c. harmonic and d.c. flux components;
- stresses due to harmonics in the lower and middle frequency range;
- dielectric stresses due to harmonics in the middle and upper frequency range, particularly for VSC valves of the “switch” type;
- dielectric stresses due to normal operating voltage and transient voltages occurring during fault scenarios.

Particularly in the case of high-voltage VSC valves of the “switch” type, the magnitudes of the harmonic voltages generated require detailed design studies to provide reliable information about the voltage and current profiles along windings. The interface transformer does not require a tap changer. However, if a tap changer is used, it is possible to optimise the VSC operation, e.g., to achieve reduced power losses or to increase power capability under low-voltage conditions.

5.6.7 Valve reactor

For valves of the “controllable voltage source” type, valve reactors are connected in series to the VSC valve levels as shown in Figure 17. These reactors have several different functions:

- the three phase units represent three d.c. voltage sources, connected in parallel. During operation, these voltages cannot be exactly equal, resulting in circulating currents between the three phase units. The valve reactors limit these circulating currents and enable to control them;
- the valve reactors limit the valve short circuit current;
- the valve reactors are a contribution to the interface impedance between the converter and the a.c. network;
- in some designs, the valve reactors may be combined with tuning capacitors and play a role in limiting circulating harmonic currents between phases.

NOTE The valve reactors can be placed in several locations, for example at the DC terminals, at the AC terminals, distributed amongst the valve submodules or integrated into the same tank as the interface transformer.

5.6.8 D.C. capacitors

5.6.8.1 VSC d.c. capacitor

5.6.8.1.1 General

The VSC d.c. capacitor, in conjunction with the d.c. cable (where used) provides the d.c. voltage necessary to operate the VSC. It is connected directly in parallel to the d.c. terminals of the VSC phase units. For the design of the VSC d.c. capacitor, the following aspects need to be considered.

5.6.8.1.2 Commutation circuit inductance

Switching the semiconductor devices of the VSC causes HF commutation current to flow through the commutation circuit formed by the switching valves, the VSC d.c. capacitor, and the connecting bus bars. Due to the stray inductance within the commutation circuit, these HF currents result in transient voltage stresses on the switching valves. To minimize these stresses, the inductance of the connection of the VSC d.c. capacitor to the valves should be as low as possible.

5.6.8.1.3 D.C. voltage ripple

VSC operation results in harmonic currents flowing in the d.c. circuit. These harmonic currents cause harmonic voltages (also known as d.c. voltage ripple). The following factors will influence the size of the d.c. voltage ripple:

- imbalances in the a.c. system and/or converter operation;
- pre-existing harmonics in the a.c. network;
- VSC valve switching strategy.

5.6.8.1.4 Capacitance of the VSC d.c. capacitor

The VSC d.c. capacitance shall be large enough to keep the d.c. voltage ripple within tolerable limits.

5.6.8.1.5 Control aspects

The d.c. voltage influences active and reactive power exchange with the a.c. system. To achieve stable operation of the transmission system, it is important to keep the d.c. voltage within tight limits. Changing power orders, a.c. system unbalances, or system transients change the operating conditions of the VSC and can cause d.c. voltage fluctuations or oscillations. Due to its energy storage capability, the VSC d.c. capacitor stabilises the operation of the VSC.

Important design parameters of the VSC d.c. capacitor are as follows:

- maximum d.c. voltage for continuous operation;
- maximum acceptable d.c. voltage variations under transient conditions, such as faults on the a.c. system.

5.6.8.1.6 Harmonic coupling of different VSC substations connected to one d.c. circuit

Harmonic currents generated by a VSC cause harmonic voltages not only on their own VSC d.c. capacitor, but also on the VSC d.c. capacitors in other VSC substations connected to the same d.c. circuit. As a result, the different VSC substations in a transmission scheme become mutually coupled via the d.c. circuit. To avoid unwanted interactions between the VSC substations, this coupling should be reduced to the largest extent possible. The capacitance of the VSC d.c. capacitor is an important factor influencing the coupling between the VSC substations.

5.6.8.2 Submodule/cell d.c. capacitor

5.6.8.2.1 General

In principle, the design and function of the submodule/cell capacitors for the MMC and CTL technologies are similar to that of the VSC d.c. capacitors.

However, due to their operation principle, the current stresses are different for d.c. submodule or cell capacitors. The individual submodules or cells can be individually switched "off" or "on" depending on output voltage generation. When the submodule is switched "off" the valve current does not pass through the d.c. submodule/cell capacitor and the capacitor current is zero. Conversely, when the submodule or cell is switched "on", the full valve current flows through the capacitor. In the "on" state, components of d.c. current and fundamental and low order currents have to be considered. The current flow in the "on" state results in a significant ripple voltage of the submodule/cell capacitors per power cycle. The average and RMS capacitor current stresses are calculated based on current contribution in the "on" state.

5.6.8.2.2 Commutation circuit inductance

Similar to the VSC d.c. capacitor, switching the semiconductor devices of the submodule causes HF commutation current to flow through the commutation circuit of the submodule. Due to the stray inductance within the commutation circuit, these HF currents result in transient voltage stresses on the submodule. To minimize these stresses, the inductance of the submodule should be as low as possible.

5.6.8.2.3 D.C. voltage ripple

a) Submodule capacitor voltage ripple

As mentioned before, the ratio of the voltage ripple to d.c. voltage of the submodule capacitor is larger than that of VSC d.c. capacitors.

b) D.C. link voltage ripple

The d.c. link voltage ripple of the MMC is much lower than that of the VSC d.c. capacitors of 2-level or NPC converters, because the MMC d.c. link voltage is almost the same as the sum of the output voltage of submodules in a phase leg. By shifting the output voltage pulse of the each submodule, the d.c. link voltage ripple of the MMC is small.

5.6.8.2.4 Capacitance of the MMC submodule capacitor

The MMC submodule capacitance shall be large enough to keep the voltage ripple of submodule capacitor within tolerable limits.

5.6.8.2.5 Control aspects

In addition to the control aspects of the VSC d.c. capacitors, the submodule capacitors have some control aspects described below.

- MMCs have many submodule capacitors, whose voltages may tend to become unbalanced. Therefore, a balancing control is required in order to ensure that any unbalance does not become excessive and result in equipment ratings being exceeded.
- Discharge of the MMC submodule capacitors caused by a d.c. fault can be prevented by blocking the converter.

5.6.8.2.6 Harmonic coupling of different MMC substations connected to one d.c. circuit

Between the submodule capacitors of different substations, there are some semiconductor devices. So harmonic coupling is less serious for the MMC VSC systems than that of 2-level or NPC VSC systems.

5.6.9 D.C. reactor

For long distance transmission, a d.c. reactor can be connected in series with a d.c. overhead transmission line or cable. Its main purpose is to reduce harmonic currents flowing in the d.c. line or cable.

The d.c. reactor also serves a secondary function in limiting short-circuit currents.

If a d.c. reactor is used in a VSC transmission system, its size can normally be considerably smaller than one used in an LCC HVDC scheme.

5.6.10 Common mode blocking reactor

A common mode blocking reactor consists of two magnetically-coupled windings having the same self impedance. Due to the winding arrangement, the reactor provides low impedance for differential mode currents but high impedance for common mode currents. The reactor, therefore, serves to block the common mode currents and leaves the differential mode currents largely undisturbed and, in consequence, does not affect the dynamic behaviour of the transmission system.

The design of the reactor depends largely on the system grounding arrangement, transmission line type, environmental conditions and electrical stresses associated to the project.

5.6.11 D.C. filter

Filtering of harmonics on the d.c. side is achieved by the VSC d.c. capacitor, d.c. reactor, common-mode blocking reactor and, in some cases, by a dedicated d.c. filter.

The design principles of the d.c. filters for VSC-based HVDC systems are similar to those for LCC HVDC systems, as described in CIGRE Technical Brochure 92.

5.6.12 Dynamic braking system

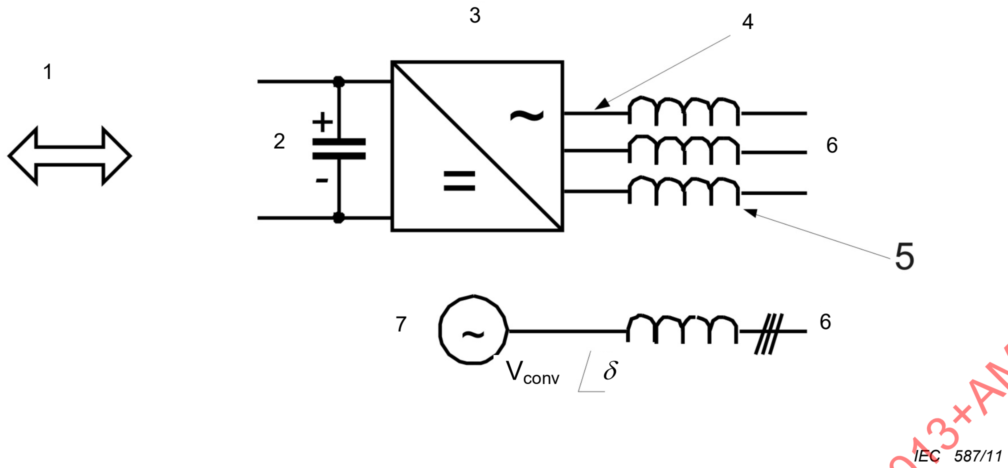
In some VSC HVDC schemes, but particularly where the HVDC system is exporting power from a small islanded a.c. system with little or no load (for example an offshore wind farm) the HVDC system may be required to include a dynamic braking system, for example as a chopper connected to the d.c. terminals of the VSC system. The function of the dynamic braking system is to absorb and dissipate the power generated in the islanded AC system during faults in the receiving-end AC system, typically for durations of 1 to 2 s.

There are several possible ways of implementing such a dynamic braking system but the valves in this system will, in general, be of similar design to the main VSC valves used for power transmission.

6 Overview of VSC controls

6.1 General

Although there are many configurations for voltage sourced converters (VSCs), they all can be considered to exhibit a common operating concept. All configurations possess a series inductive interface separating the switching valves from the a.c. system. The switching valves generate a fundamental frequency a.c. voltage from a d.c. voltage. The magnitude and phase of the fundamental frequency component of this a.c. voltage at the valve side of the series inductive interface can be controlled. The control of this voltage magnitude and phase is the essential controlling function common to all VSCs.



Key

1 active power
2 d.c. side
3 voltage sourced converter
4 point of phase and magnitude control of a.c. voltage
5 phase reactor and/or interface transformer
6 a.c. side
7 equivalent representation of a VSC as a voltage behind an inductance

Figure 23 – Representing a VSC unit as an a.c. voltage of magnitude *U* and phase angle *δ* behind reactance

Figure 23 shows that a VSC can be represented as an a.c. voltage source of magnitude U_{conv} and phase angle delta behind the reactance. If the per-unit voltage magnitude U_{conv} is higher than the per-unit line side voltage U_L, then reactive power will be transferred into the line side similarly to an overexcited synchronous machine. Conversely, if the magnitude U_{conv} is low and less than the line side volts, the VSC will be absorbing reactive power similarly to an under-excited synchronous machine.

The control of the phase angle δ is achieved by shifting the phase of the fundamental frequency a.c. voltage with respect to the phase locked loop normally synchronized to the a.c. side voltage. Regulating the phase angle δ causes active power to be transferred through the VSC, because a phase angle in fundamental frequency voltage is developed across the interface reactor so that power flows into or out of the VSC.

A VSC therefore has the capability of acting as a rectifier or as an inverter, and/or as a generator or an absorber of reactive power. It is the control of the magnitude and phase of the converter voltage U_{conv} that dictates the strategies for controlling voltage sourced converters.

6.2 Operational modes and operational options

The normal way of a.c. side voltage control is achieved by controlling the d.c. side capacitor voltage. In turn, the d.c. side capacitor voltage is varied by pumping power from the a.c. side into it or out of it. If power is pumped into the capacitor, its charge will increase and consequently so will its voltage. If power is taken from the capacitor, its voltage will decrease. Power can be taken from or fed into the a.c. side by varying the phase angle δ, as described above. In this way, d.c. voltage control is achieved by regulating a.c. phase angle δ.

Control of the magnitude and phase of the converter voltage U_{conv} for VSC transmission applications is usually achieved by means of vector control strategy. With vector control, three-phase currents are transformed to d and q axis quantities based on the conventional abc to dq transformation, synchronized to the a.c. side three-phase voltage through a phase locked loop (PLL). The d and q axis voltages generated by the vector controls are transformed to three-phase quantities and converted into line voltages by the VSC as shown in Figure 24.