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BSI Standards Publication

Power losses in voltage sourced converter (VSC) valves for high-voltage direct current (HVDC) systems

Part 1: General requirements

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National foreword

This British Standard is the UK implementation of EN 62751-1:2014. It is identical to IEC 62751-1:2014.

The UK participation in its preparation was entrusted to Technical Committee PEL/22, Power electronics.

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Power losses in voltage sourced converter (VSC) valves for high-voltage direct current (HVDC) systems - Part 1: General requirements
(IEC 62751-1:2014)

Pertes de puissance dans les valves à convertisseur de source de tension (VSC) des systèmes en courant continu à haute tension (CCHT) - Partie 1: Exigences générales
(CEI 62751-1:2014)

Bestimmung der Leistungsverluste in Spannungszwischenkreis-Stromrichtern (VSC) für Hochspannungsgleichstrom(HGÜ)-Systeme - Teil 1: Allgemeine Anforderungen
(IEC 62751-1:2014)

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Europäisches Komitee für Elektrotechnische Normung

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Foreword

The text of document 22F/302/CDV, future edition 1 of IEC 62751-1, prepared by SC 22F "Power electronics for electrical transmission and distribution systems", of IEC/TC 22 "Power electronic systems and equipment" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 62751-1:2014.

The following dates are fixed:

– latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2015-07-01
– latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2017-10-01

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The text of the International Standard IEC 62751-1:2014 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following note has to be added for the standard indicated:

IEC 61803:1999	NOTE	Harmonised as EN 61803:1999.

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE 1 When an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cenelec.eu.

Publication	Year	Title	EN/HD	Year
IEC 60633	-	Terminology for high-voltage direct current (HVDC) transmission	EN 60633	-
IEC 60747-2	-	Semiconductor devices - Discrete devices and integrated circuits -- Part 2: Rectifier diodes	-	-
IEC 60747-9	2007	Semiconductor devices - Discrete devices - Part 9: Insulated-gate bipolar transistors (IGBTs)	-	-
IEC 62747	2014	Terminology for voltage-sourced converters (VSC) for high-voltage direct current (HVDC) systems	EN 62747	2014

CONTENTS

POWER LOSSES IN VOLTAGE SOURCED CONVERTER (VSC) VALVES FOR HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS –

Part 1: General requirements

1 Scope

This part of IEC 62751 sets out the general principles for calculating the power losses in the converter valves of a voltage sourced converter (VSC) for high-voltage direct current (HVDC) applications, independent of the converter topology. Clauses 6 and 8 and subclauses 9.1, 9.2 and A.2.12 of the standard can also be used for calculating the power losses in the dynamic braking valves (where used) and as guidance for calculating the power losses of the valves for a STATCOM installation.

Power losses in other items of equipment in the HVDC substation, apart from the converter valves, are excluded from the scope of this standard. Power losses in most equipment in a VSC substation can be calculated using similar procedures to those prescribed for HVDC systems with line-commutated converters (LCC) in IEC 61803. Annex A presents the main differences between LCC and VSC HVDC substations in so far as they influence the method for determining power losses of other equipment.

This standard does not apply to converter valves for line-commutated converter HVDC systems.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. 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 60747-2, *Semiconductor devices – Discrete devices and integrated circuits – Part 2: Rectifier diodes*

IEC 60747-9:2007, *Semiconductor devices – Discrete devices – Part 9: Insulated-gate bipolar transistors (IGBTs)*

IEC 62747:2014, *Terminology for voltage-sourced converters (VSC) for high-voltage direct current (HVDC) systems*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60633, IEC 62747, IEC 60747-2, IEC 60747-9 as well as the following apply.

NOTE 1 Related terms and definitions can also be found in IEC TR 62543, IEC 62751-2 and in the other relevant parts of the IEC 60747 series.

NOTE 2 Throughout this standard, the term "insulated gate bipolar transistor (IGBT)" is used to indicate a turn-off semiconductor device; however, the standard is equally applicable to other types of turn-off semiconductor devices such as the GTO, IGCT, ETO, IEGT, etc.

3.1 Converter types

3.1.1
2-level converter
converter in which the voltage between the a.c. terminals of the VSC unit and VSC unit midpoint is switched between two discrete d.c. voltage levels

Note 1 to entry: VSC unit midpoint is defined in 3.5.9.

3.1.2
multi-level converter
converter in which the voltage between the a.c. terminals of the VSC unit and VSC unit midpoint is switched between more than three discrete d.c. voltage levels

Note 1 to entry: VSC unit midpoint is defined in 3.5.9.

3.1.3
modular multi-level converter
MMC
multi-level converter in which each VSC valve consists of a number of MMC building blocks connected in series

Note 1 to entry: MMC building block is defined in 3.5.4.

Note 2 to entry: This note applies to the French language only.

3.1.4
cascaded two-level converter
CTL
modular multi-level converter in which each switch position consists of more than one IGBT-diode pair connected in series

Note 1 to entry: IGBT-diode pair is defined in 3.2.4.

Note 2 to entry: This note applies to the French language only.

3.2 Semiconductor devices

3.2.1
turn-off semiconductor device
controllable semiconductor device which may be turned on and off by a control signal, for example an IGBT

3.2.2
insulated gate bipolar transistor
IGBT
turn-off semiconductor device with three terminals: a gate terminal (G) and two load terminals emitter (E) and collector (C)

Note 1 to entry: By applying appropriate gate to emitter voltages, current in one direction can be controlled, i.e. turned on and turned off.

Note 2 to entry: This note applies to the French language only.

3.2.3
free-wheeling diode
FWD
power semiconductor device with diode characteristic

Note 1 to entry: A FWD has two terminals: an anode (A) and a cathode (K). The current through FWDs is in opposite direction to the IGBT current. FWDs are characterized by the capability to cope with high rates of decrease of current caused by the switching behaviour of the IGBT.

Note 2 to entry: This note applies to the French language only.

3.2.4
IGBT-diode pair
arrangement of IGBT and FWD connected in inverse parallel

Note 1 to entry: An IGBT-diode pair is usually in one common package; however, it can include individual IGBTs and/or diodes packages connected in parallel.

3.3 Converter operating states

3.3.1
no-load operating state
condition in which the VSC substation is energized but the IGBTs are blocked and all substation service loads and auxiliary equipment are connected

3.3.2
idling operating state
condition in which the VSC substation is energized and the IGBTs are de-blocked but with no active or reactive power output at the point of common connection to the a.c. network

Note 1 to entry: The “idling operating” and “no-load” conditions are similar but from the no-load state several seconds may be needed before power can be transmitted, while from the idling operating state, power transmission may be commenced almost immediately (less than 3 power frequency cycles).

Note 2 to entry: In the idling operating state, the converter is capable of actively controlling the d.c. voltage, in contrast to the no-load state where the behaviour of the converter is essentially “passive”.

Note 3 to entry: Losses will generally be slightly lower in the no-load state than in the idling operating state, therefore this operating mode is preferred where the arrangement of the VSC system permits it.

3.3.3
operating state
condition in which the VSC substation is energized and the converters are de-blocked

Note 1 to entry: Unlike line-commutated converter, VSC can operate with zero active/reactive power output.

3.3.4
no-load power losses
power losses in the VSC valve in the no-load state

Note 1 to entry: In some converter designs, it may be necessary to make occasional switching operations for the purposes of balancing voltages between different parts of the converter. In such converters, the calculation of no-load losses shall take into account the switching frequency of such an operating mode.

3.3.5
idling operating losses
losses in the VSC valve in the idling operating state

3.3.6
operating losses
losses in the VSC valve in the operating state

3.4 Device characteristics

3.4.1
IGBT collector-emitter saturation voltage
$V_{\mathrm{CE(sat)}}$
collector-emitter voltage under conditions of gate-emitter voltage at which the collector current is essentially independent of the gate-emitter voltage

3.4.2
IGBT turn-on energy
E_{on}
energy dissipated inside the IGBT during the turn-on of a single collector current pulse

3.4.3
IGBT turn-off energy
E_{off}
energy dissipated inside the IGBT during the turn-off procedure of a single collector current pulse

3.4.4
diode forward voltage
V_{F}
voltage across the terminals of a diode which results from the flow of current in the forward direction

3.4.5
diode reverse recovery energy
E_{rec}
energy dissipated inside the diode during the turn-off procedure

3.5 Other definitions

3.5.1
VSC valve level
smallest indivisible functional unit of VSC valve

Note 1 to entry: For any VSC valve in which IGBTs are connected in series and operated simultaneously, one VSC valve level is one IGBT-diode pair including its auxiliaries. For MMC type valve, one valve level is one submodule together with its auxiliaries.

3.5.2
redundant levels
maximum number of series connected 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

Note 1 to entry: In valve designs such as the cascaded two level converter, which contain two or more conduction paths within each cell and have series-connected VSC valve levels in each path, redundant levels shall be counted only in one conduction path in each cell

3.5.3
valve electronics
electronic circuits at valve potential(s) which perform control and protection functions for one or more valve levels

3.5.4
MMC building block
self-contained, two-terminal controllable voltage source together with d.c. capacitor(s) and immediate auxiliaries, forming part of a MMC

3.5.5
switch position
semiconductor function which behaves as a single, indivisible switch

Note 1 to entry: A switch position may consist of a single IGBT-diode pair or, in the case of the cascaded two level converter, a series connection of multiple IGBT-diode pairs.

3.5.6
submodule
MMC building block where each switch position consists of only one IGBT-diode pair cell

3.5.7
cell
MMC building block where each switch position consists of more than one IGBT-diode pair connected in series

3.5.8
VSC unit
three VSC phase units, together with VSC unit control equipment, essential protective and switching devices, d.c. storage capacitors, phase reactors and auxiliaries, if any, used for conversion

3.5.9
VSC unit midpoint
point in a VSC unit whose electrical potential is equal to the average of the potentials of the positive and negative d.c. terminals of the VSC unit

Note 1 to entry: In some applications the VSC unit midpoint may exist only as a virtual point, not corresponding to a physical node in the circuit.

4 General conditions

4.1 General

Suppliers need to know in detail how and where losses are generated, since this affects component and equipment ratings. Purchasers are interested in a verifiable loss figure which allows equitable bid comparison and in a procedure after delivery which can objectively verify the guaranteed performance requirements of the supplier.

As a general principle, it would be desirable to determine the efficiency of an HVDC converter station by a direct measurement of its energy losses. However, attempts to determine the station losses by subtracting the measured output power from the measured input power should recognize that such measurements have an inherent inaccuracy, especially if performed at high voltage. The losses of an HVDC converter station at full load are generally of the order 1 % of the transmitted power. Therefore, the loss measured as a small difference between two large quantities is not likely to be a sufficiently accurate indication of the actual losses.

In some special circumstances it may be possible, for example, to arrange a temporary test connection in which two converters are operated from the same a.c. source and also connected together via their d.c. terminals. In this connection, the power drawn from the a.c. source equals the losses in the circuit. However, the a.c. source also provides var support and commutating voltage to the two converters. Once again, there are practical measurement difficulties. In order to avoid the problems described above, this standard standardizes a method of calculating the HVDC converter station losses by summing the losses calculated for each item of equipment. The standardized calculation method will help the purchaser to meaningfully compare the competing bids. It will also allow an easy generation of performance curves for the wide range of operating conditions in which the performance has to be known. In the absence of an inexpensive experimental method which could be employed for an objective verification of losses during type tests, the calculation method is the next best alternative as it uses, wherever possible, experimental data obtained from measurements on individual equipment and components under conditions equivalent to those encountered in real operation.

It is important to note that the power loss in each item of equipment will depend on the ambient conditions under which it operates, as well as on the operating conditions or duty cycles to which it is subjected. Therefore, the ambient and operating conditions shall be defined for each item of equipment, based on the ambient and operating conditions of the entire HVDC converter station.

4.2 Causes of power losses

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

For the controllable voltage source type converter, the VSC valve is a complete controllable voltage source assembly, which is generally connected between one a.c. terminal and one d.c. terminal.

For the switch type converter, the VSC valve is an arrangement of IGBT-diode pairs connected in series and arranged to be switched simultaneously as a single functional unit.

Most of the power losses in VSC valves appear in IGBTs and diodes. In each case, two mechanisms are involved:

- conduction losses;
- switching losses.

There may, in addition, be small losses in d.c. submodule or cell capacitors, voltage divider and snubber circuits, valve electronics etc.

Since the technology of VSC transmission is developing rapidly with several quite different VSC topologies being used, a detailed procedure for calculating the power losses is not yet available for all possible converter topologies. As a result, the manufacturer of the VSC equipment shall present a detailed report of the VSC valve loss calculation, explaining the method used and justifying any assumptions made. This standard gives the general principles to be followed in calculating valve losses and provides guidance for the preparation and interpretation of such a report.

Due to the accuracy of d.c. metering systems (especially due to the poor accuracy of d.c. voltage measurement) the approach of the standard rests on calculations based on routine testing of devices (datasheet) together with some characterisation measurements.

4.3 Categories of valve losses

The various components of valve losses are subdivided into terms referred to as P_{V1} to P_{V9}:

- P_{V1}: IGBT conduction losses
- P_{V2}: diode conduction losses
- P_{V3}: other valve conduction losses
- P_{V4}: d.c. voltage-dependent losses
- P_{V5}: losses in d.c. capacitors of the valve

- P_{V6}: IGBT switching losses
- P_{V7}: diode turn-off losses
- P_{V8}: snubber losses
- P_{V9}: valve electronics power consumption

4.4 Operating conditions

4.4.1 General

Purchasers of HVDC systems may specify their own standard reference conditions for atmospheric pressure, ambient temperature, humidity, coolant temperature, power transmission level etc, at which the power losses are to be determined. Where the purchaser does not specify such reference conditions, losses shall be determined under the following default conditions.

4.4.2 Reference ambient conditions

The following default reference ambient conditions are applied:

- dry-bulb ambient temperature = 20 °C
- wet-bulb ambient temperature = 14 °C
- atmospheric pressure = 101,3 kPa.

4.4.3 Reference a.c. system conditions

The following default reference a.c. system conditions are applied:

- nominal a.c. system frequency,
- nominal a.c. network voltage,
- balanced a.c. conditions (i.e. no negative phase sequence).

4.4.4 Converter operating states

As a minimum, VSC valve losses shall be determined for the following operating states:

- no-load operation;
- idling operation;
- operation with 100 % rated power in each relevant direction of power transmission, with zero net reactive power exchange with the a.c. system, and with the d.c. voltage at the value as applicable to the power being transmitted.

In some VSC systems, the interface transformer includes a tap changer, the purpose of which is to adjust the valve-side a.c. voltage, in steady-state, to a value which allows the power losses to be optimised. The tap position has a large effect on the power losses of both the transformer and the converter and should therefore be correctly represented in all calculations. The tap position of the transformer tap changer (where fitted) is important in the determination of losses. The calculations of losses shall take into account the tap position corresponding to the operating point at which losses are to be determined and the control and protection strategies employed for the VSC system, including, for example, fault ride-through requirements. The manufacturer is responsible for defining and justifying the tap position for the loss calculation.

4.4.5 Treatment of redundancy

For the calculation of valve losses, all redundant VSC levels shall be assumed to be in operation.

NOTE This approach yields the highest total losses in the valve, although it does not give the highest losses per VSC valve level, which occur when redundant levels are shorted.

4.5 Use of real measured data

4.5.1 General

The characteristics of the IGBTs and diodes used in the valve shall be determined by a combination of routine tests performed under standardised conditions on 100 % of production, and more comprehensive characterisation tests performed on smaller samples under conditions that are more representative of the conditions encountered in the real converter valve.

The routine tests shall be used to derive a population average of all IGBTs and diodes supplied for the project, but under standardised operating conditions which may not necessarily be applicable to the project (for example, junction temperature). The characterisation tests shall then be used to derive correction factors applicable for the exact operating conditions of the project.

4.5.2 Routine testing

As a minimum, the following tests shall be performed in accordance with IEC Publications by the device manufacturer on all IGBTs (IEC 60747-9), and diodes (IEC 60747-2) used for the valve:

- IGBT on-state voltage $V_{\mathrm{CE(sat)}}$ and diode forward voltage V_{F} at one typical value of current and temperature;
- IGBT turn-on energy E_{on} and turn–off energy E_{off} at one typical commutating condition;
- diode recovery energy E_{rec} at one typical commutating condition.

This data shall be used to calculate the average device properties for calculation of the losses of the complete converter.

The conditions under which the routine tests are performed may not be fully representative of the conditions encountered in the VSC valve, in respect of temperature, stray inductance, gate drive behaviour, etc.

4.5.3 Characterisation testing

4.5.3.1 Characterisation testing of semiconductor devices

A minimum of 10 devices from at least 2 different production lots shall be subjected to a more comprehensive programme of characterisation tests to permit the routine test data obtained in 4.4.1 above to be adjusted to the correct operating conditions of the VSC valve. The following conditions shall be reproduced adequately.

Fixed values for a given design of VSC valve are as follows:

- stray inductance of commutating loop;
- other semiconductor devices affected by the commutation process;
- gate drive characteristics;
- snubber circuits (if any).

Operating variables are as follows:

- d.c capacitor or d.c. submodule capacitor voltage, scaled to one VSC level;
- device current (over the range from standby to operation at full power in either rectifier or inverter mode);

- junction temperature (over the range from standby to operation at full power in either rectifier or inverter mode).

The characterization tests shall be performed in accordance with IEC 60747-2 and IEC 60747-9.

4.5.3.2 Characterisation testing of other components

Characterization tests for components are as follows:

- R_{ESR} test;
- snubber turn-on and turn-off tests.

5 Conduction losses

5.1 General

When an IGBT or a diode 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 diodes and $V_{\mathrm{CE(sat)}}$ 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 on Figure 1.

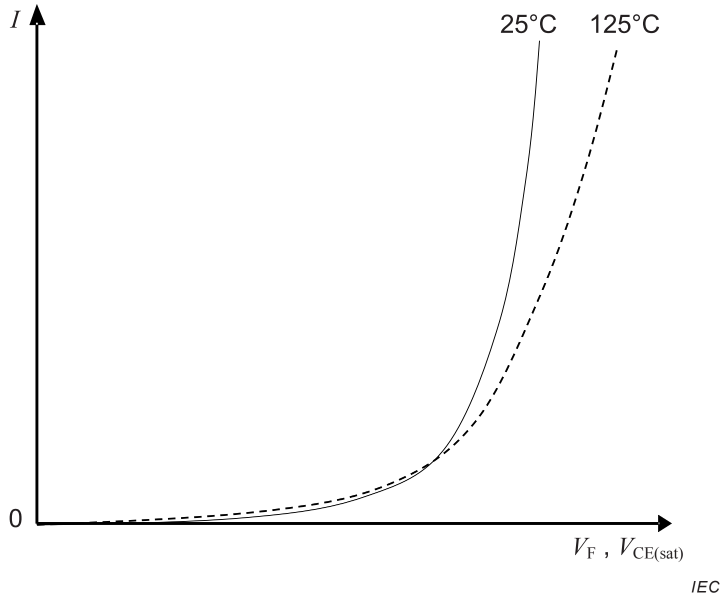


Figure 1 – On-state voltage of an IGBT or diode

NOTE 1 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}, little or 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 $V_{\mathrm{CE(sat)}}$ (the saturated value of V_{CE}) can be used for loss calculation.

NOTE 2 On some types of semiconductor device, the "crossover" current can be very low, such that for most practical values of current the on-state voltage always increases with temperature.

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:

$$P_{\mathrm{cond\_T}} = \frac{1}{2\pi} \cdot \int_0^{2\pi} I_{\mathrm{T}}(\omega t) \cdot V_{\mathrm{CE(sat)}}(I_{\mathrm{T}}) \cdot d(\omega t) \tag{1}$$

for an IGBT, or

$$P_{\mathrm{cond\_D}} = \frac{1}{2\pi} \cdot \int_0^{2\pi} I_{\mathrm{D}}(\omega t) \cdot V_{\mathrm{F}}(I_{\mathrm{D}}) \cdot d(\omega t) \tag{2}$$

for a diode.

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

To simplify this process, the on-state voltage shown in Figure 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 2.

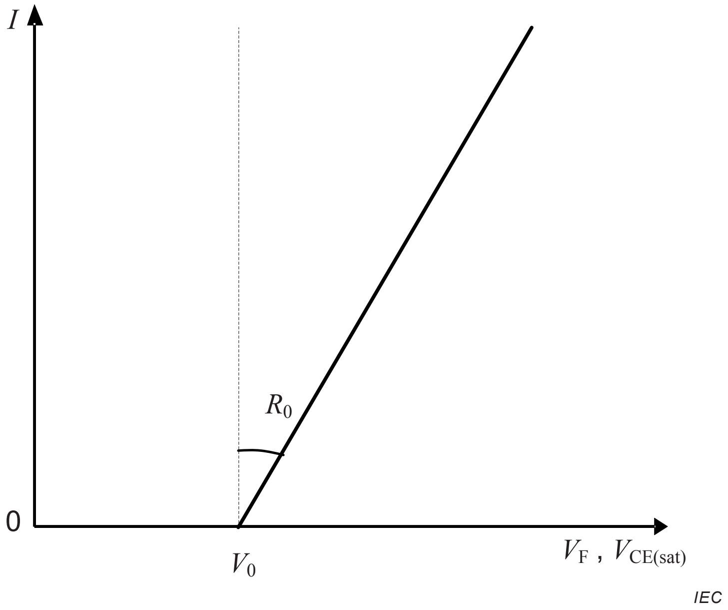


Figure 2 – Piecewise-linear representation of IGBT or diode on-state voltage

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

$$P_{\mathrm{cond}} = V_0 \cdot I_{\mathrm{av}} + R_0 \cdot I_{\mathrm{rms}}^{\ 2} \tag{3}$$

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.

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

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

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

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

It is possible to obtain greater accuracy by using a more exact model of the device on-state voltage (as per Figure 1) rather than the piecewise linear approximation, and then performing a direct numerical integration. However, the piecewise-linear approximation is preferred because it simplifies the calculation process, allows greater transparency and still permits good accuracy to be obtained, provided the measurements used to derive the piecewise-linear approximation are made at appropriate values of current. Therefore it is recommended that V_0 and R_0 are determined by measuring on-state voltage at 100 % and 33 % of the device rated current and performing a linear extrapolation.

5.2 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:

$$P_{\mathrm{V1}} = N_{\mathrm{t}} \cdot \left[V_{\mathrm{0T}} \cdot I_{\mathrm{Tav}} + R_{\mathrm{0T}} \cdot I_{\mathrm{Trms}}{}^2 \right] \tag{6}$$

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 rms 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 rms 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.

5.3 Diode conduction losses

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

$$P_{\mathrm{V2}} = N_{\mathrm{t}} \cdot \left[V_{\mathrm{0D}} \cdot I_{\mathrm{Dav}} + R_{\mathrm{0D}} \cdot I_{\mathrm{Drms}}{}^2 \right] \tag{7}$$

where

V_{0D} is the diode threshold voltage;

R_{0D} is the diode slope resistance;

I_{Dav} is the mean current in the diode;

I_{Drms} is the rms current in the diode.

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.

5.4 Other conduction losses

Conduction losses in components other than the semiconductors and submodule d.c. capacitor (for example, busbars) are normally small. However, they may not be negligible and should be included in the calculation of valve losses. Some designs of valve require inductance in series with each valve (valve reactor), either as a discrete component or distributed in the valve. Losses in the valve reactors for such valves shall be considered as part of the valve losses.

Calculation of such losses is relatively straightforward and depends only on the resistance of each conducting element and the rms 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:

$$P_{\mathrm{V3}} = I_{\mathrm{vrms}}^{2} \cdot R_{\mathrm{s}} \tag{8}$$

where

I_{vrms} is the rms current flowing in the valve;

R_{s} is the total resistance of all conducting elements in the valve, other than IGBTs and diodes.

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

6 D.C. voltage-dependent losses

D.C. voltage-dependent losses are losses caused by off-state leakage currents through IGBTs and diodes and shunt resistive components in parallel with the IGBTs and diodes. Shunt resistive components in parallel with the IGBTs and diodes 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;
- discharge resistors across d.c. capacitors.

These losses are calculated as follows:

$$P_{\mathrm{V4}} = V_{\mathrm{vrms}}^{2} / R_{\mathrm{DC}} \tag{9}$$

where

V_{vrms} is the rms value of voltage between the terminals of the valve;

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

NOTE Leakage currents in IGBTs and diodes are normally very low when the valve is in the no-load or idling operating states; however in the operating state, the leakage currents can be significant because of the high junction temperatures.

7 Losses in d.c. capacitors

Some types of VSC valve include in-built d.c. capacitors which 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, losses in d.c. capacitors can be divided into ohmic losses and dielectric losses.

Ohmic losses represent $I^2 \times R$ 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 realignment 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. capacitor losses per valve are then calculated as follows:

$$P_{\mathrm{V5}} = \sum_{j=1}^{N_c} I_{\mathrm{crms}\_j}{}^{2} \cdot R_{\mathrm{ESR}\_j} \tag{10}$$

where

N_{c} is the number of capacitors in the valve;

I_{crms_j} is the rms current flowing in the j^{th} d.c. capacitor of the valve;

R_{ESR_j} is the equivalent series resistance of the j^{th} d.c. capacitor in the valve.

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, cannot be negligible.

NOTE 2 There can 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 (equivalent series resistance) 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.

8 Switching losses

8.1 General

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

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. However, the manufacturer shall present, in the loss calculation report, a detailed justification of the method used.

8.2 IGBT switching losses

During turn-on and turn-off in an IGBT, the device is subjected to high current and high voltage simultaneously as 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 energy. IGBT switching energies are referred to as the turn-on energy E_{on} and the turn-off energy E_{off}. The switching losses of the IGBT E_on and E_off shall be provided according to the IEC 60747-9:2007 (6.3.11 and 6.3.12).

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 3.

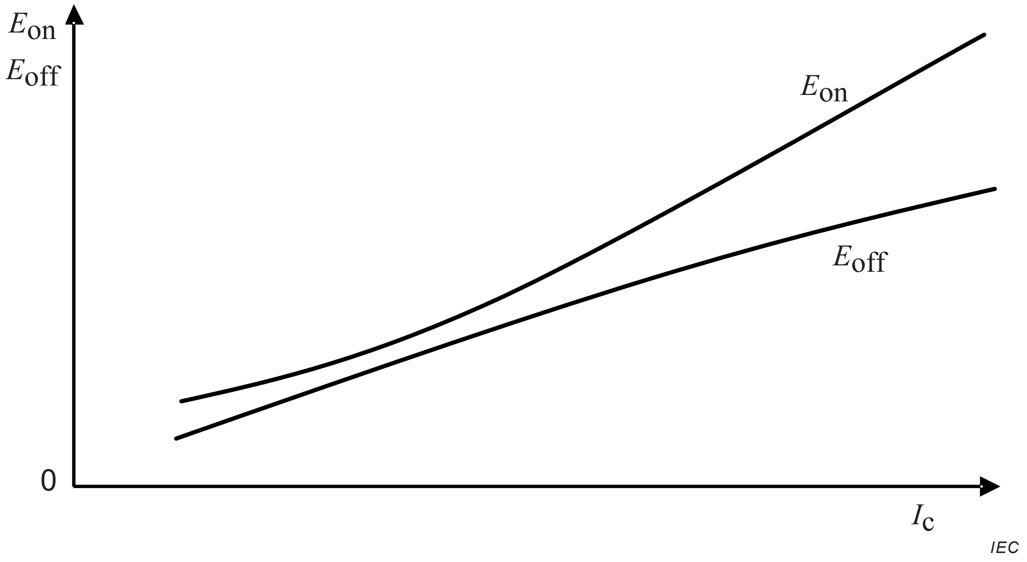


Figure 3 – IGBT switching energy as a function of collector current

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, the choice of gate resistor (where applicable) and the philosophy with regard to voltage grading where series connected IGBTs are used.

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 and the switching losses should be averaged over several cycles in order to obtain a meaningful result. An averaging period of one second is proposed in order to simplify the equation.

The total IGBT switching losses per valve are calculated by summing all the turn-on energies E_{on} and the turn-off energies E_{off} for all of the VSC valve levels in the valve, over a sampling period t_{s}, which is recommended to be one second:

$$P_{\text{V6}} = \frac{1}{t_s} \cdot \sum_{j=1}^{N_{\text{t}}} \sum_{k=1}^{N_{\text{s}}} (E_{\text{on}\_j,k}(V,I) + E_{\text{off}\_j,k}(V,I)) \tag{11}$$

where

t_{s} is the sampling time;

N_{s} is the average number of switching cycles (on+off) experienced by each VSC valve level during the sampling time t_{s};

$E_{\text{on}\_j,k}$ is the turn-on energy dissipated in the IGBT(s) of the j^{th} VSC valve level for the k^{th} turn-on event during the sampling time t_{s};

$E_{\text{off}\_j,k}$ is the turn-off energy dissipated in the IGBT(s) of the j^{th} VSC valve level for the k^{th} turn-off event during the sampling time t_{s}.

8.3 Diode switching losses

For diodes, the turn-on energy is normally negligible because the diode conducts as soon as it becomes forward biased. However, the turn-off (recovery) energy E_{rec} is not negligible. The recovery energy arises from the reverse recovered charge Q_{rr} which passes through the diode shortly after the current crosses zero. The recovery energy 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 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. The switching losses of the diode $E_{\_\text{rec}}$ shall be provided according to IEC 60747-2.

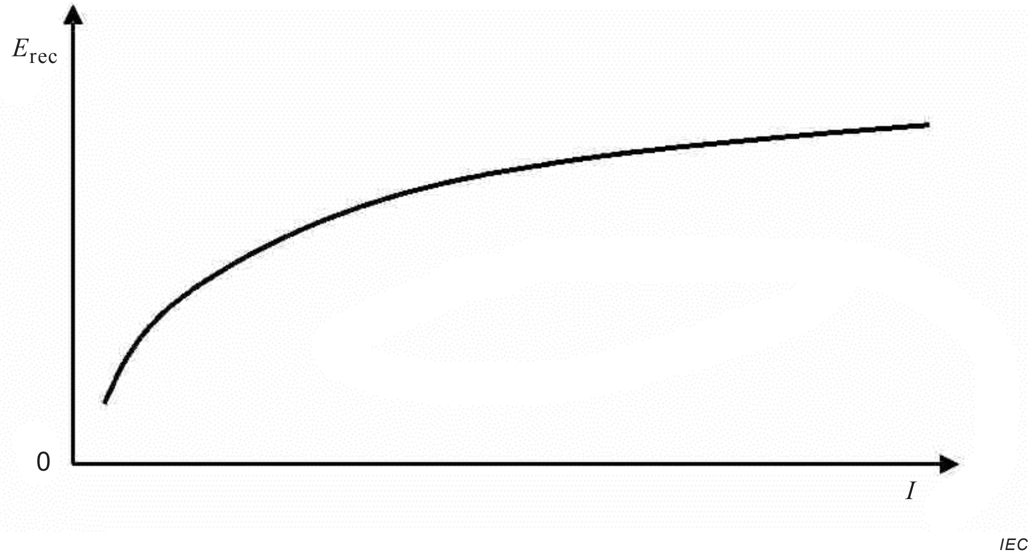


Figure 4 – Diode recovery energy as a function of current

The total diode switching losses per valve are then calculated by summing all the recovery energies E_{rec} for all of the valve levels in the valve, over a defined sampling period t_{s}:

$$P_{V7} = \frac{1}{t_s} \cdot \sum_{j=1}^{N_t} \sum_{k=1}^{N_s} E_{rec\_j,k}(V,I) \tag{12}$$

where

$E_{\mathrm{rec}\_j,k}$ is the diode recovery energy dissipated in the diode(s) of the j^{th} VSC valve level for the k^{th} diode turn-off event during the sampling time t_{s}.

9 Other losses

9.1 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 can contribute to voltage sharing. Losses in resistive voltage sharing circuits are covered by d.c. voltage dependent losses as described in Clause 6.

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 8.2.

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 dissipate an energy $E_{\mathrm{sn\_on}}$ (for a turn-on snubber) or $E_{\mathrm{sn\_off}}$ (for a turn-off snubber). Many different designs of snubber circuit 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 in a similar way to that used for IGBT and diode switching losses:

$$P_{\mathrm{V8}} = \frac{1}{t_{\mathrm{s}}} \cdot \sum_{j=1}^{N_{\mathrm{t}}} \sum_{k=1}^{N_{\mathrm{s}}} \left(E_{\mathrm{sn\_on}\_j,k}(V,I) + E_{\mathrm{sn\_off}\_j,k}(V,I)\right) \tag{13}$$

where

$E_{\mathrm{sn\_on}\_j,k}$ is the energy dissipated in the snubber circuit(s) of the j^{th} VSC valve level for the k^{th} turn-on event of the associated IGBT during the sampling time t_{s};

$E_{\mathrm{sn\_off}\_j,k}$ is the energy dissipated in the snubber circuit(s) of the j^{th} VSC valve level for the k^{th} turn-off event of the associated IGBT during the sampling time t_{s}.

The values of $E_{\mathrm{sn\_on}}$ and $E_{\mathrm{sn\_off}}$ should ideally be determined by direct measurement on a real snubber circuit, as part of the characterization testing; however, since the performance of the snubber is affected by the switching characteristics of the semiconductor devices and vice versa, the testing also needs to represent the semiconductor devices. It should be noted that, with this approach it is impossible to distinguish between measurements of snubber energies and semiconductor switching energies. Hence, where snubber losses are determined by measurement it may be necessary to consider the test as a combined test of snubber energy and switching energy, and subsequently to combine the calculation of P_{V8} with that of P_{V6} and P_{V7}.

9.2 Valve electronics power consumption

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

$$P_{\mathrm{V9}} = P_{\mathrm{GU}} \cdot N_{\mathrm{t}} \tag{14}$$

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 can already be counted in the losses of the snubber circuit as described in the previous subclause.

10 Total valve losses per converter substation

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

$$P_{VT} = \sum_{i=1}^{9} P_{Vi} \tag{15}$$

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

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 is evaluated separately for each type of valve or operating duty.

Table 1 contains a matrix indicating sources of data needed for calculation of various types of valve losses.

Table 1 – Matrix indicating the relationship of data needed for calculation of losses and the type of valve losses (*1 of 2*)

	Source			**Type of valve losses**								
Data needed as input for calculation of losses	**Routine testing**	**Characterising testing**	**Specified by VSC manufacturer**	**IGBT conduction losses (P_{V1})**	**Diode conduction losses (P_{V2})**	**Other conduction losses (P_{V3})**	**D.C. voltage-dependent losses (P_{V4})**	**Losses in d.c. capacitors (P_{V5})**	**IGBT switching losses (P_{V6})**	**Diode switching losses (P_{V7})**	**Snubber circuit losses (P_{V8})**	**Valve electronics power consumption (P_{V9})**
IGBT on-state voltage $V_{CE(sat)}$ under standardized reference conditions.	x			x								
IGBT on-state voltage $V_{CE(sat)}$ as a function of current and temperature.		x		x								
Diode forward voltage V_F under standardized reference conditions.	x				x							
Diode forward voltage V_F as a function of current and temperature		x			x							
Total resistance of all conducting elements in the valve R_s			x			x						
Effective d.c. resistance of a complete valve R_{DC}			x				x					
d.c. capacitor ESR as a function of frequency		x						x				
IGBT turn-on energy E_{on} under standardized reference conditions.	x								x			
IGBT turn-on energy E_{on} as a function of current, voltage, temperature, commutating inductance and gate drive parameters		x							x			
IGBT turn–off energy E_{off} under standardized reference conditions.	x								x			
IGBT turn–off energy E_{off} as a function of current, voltage, temperature, commutating inductance and gate drive parameters		x							x			

Table 1 (*2 of 2*)

	Source			**Type of valve losses**								
Data needed as input for calculation of losses	**Routine testing**	**Characterising testing**	**Specified by VSC manufacturer**	**IGBT conduction losses (P_{V1})**	**Diode conduction losses (P_{V2})**	**Other conduction losses (P_{V3})**	**D.C. voltage-dependent losses (P_{V4})**	**Losses in d.c. capacitors (P_{V5})**	**IGBT switching losses (P_{V6})**	**Diode switching losses (P_{V7})**	**Snubber circuit losses (P_{V8})**	**Valve electronics power consumption (P_{V9})**
Diode recovery energy E_{rec} under standardized reference conditions.	x									x		
Diode recovery energy E_{rec} as a function of current, voltage, temperature and commutating inductance		x								x		
Snubber turn-on energy $E_{\mathrm{sn\_on}}$			x								x	
Snubber turn-off energy $E_{\mathrm{sn\_off}}$			x								x	
Valve electronics power consumption		x										x

Annex A
(informative)

Determination of power losses in other HVDC substation equipment

A.1 General

For the majority of the equipment in a VSC HVDC substation, with the exception of the converter valves, it is possible to determine power losses in a similar way to that specified in IEC 61803 for an HVDC substation with line-commutated converters (LCC). Nevertheless there are some differences. Since there is currently no standard for calculating power losses in such equipment for a VSC HVDC substation, the purpose of this annex is to describe the main differences between the practice adopted in IEC 61803 for an LCC HVDC substation, and the method needed for a VSC HVDC substation. In general terms, the main differences arise from the different harmonic spectra emitted by LCC and VSC HVDC substations. Line-commutated converters produce very high amplitudes of relatively low-order characteristic harmonic currents on the a.c. side (11th, 13th, 23rd, 25th…) and harmonic voltages on the d.c. side (12th, 24th, 36th…). Voltage-sourced converters generally produce much smaller amounts of these low-order harmonics but may produce larger levels of higher-order harmonics.

When the converter valve is of the “switch” type (for example the 2-level and 3-level converters with Pulse-Width Modulation, PWM) the converter usually produces large amounts of harmonics at the PWM frequency, multiples and sidebands thereof. In such converters, the range of harmonics considered in IEC 61803 (fundamental to 49th on the a.c. side and 12th to 48th on the d.c. side) may not be wide enough and it may be necessary to extend the upper limit, for example to 100th harmonic.

Voltage sourced converters in which the converter valves are of the “controllable voltage source” type (for example the modular multi-level converter and cascaded two-level converter) generally produce only small amounts of harmonic distortion and in many cases require no filtering.

Figure A.1 illustrates a typical single-line diagram of a VSC HVDC substation. It should be emphasised that not all of the components shown on Figure A.1 will necessarily exist in all substations, and conversely some VSC substations may have a requirement for additional equipment not shown on Figure A.1.

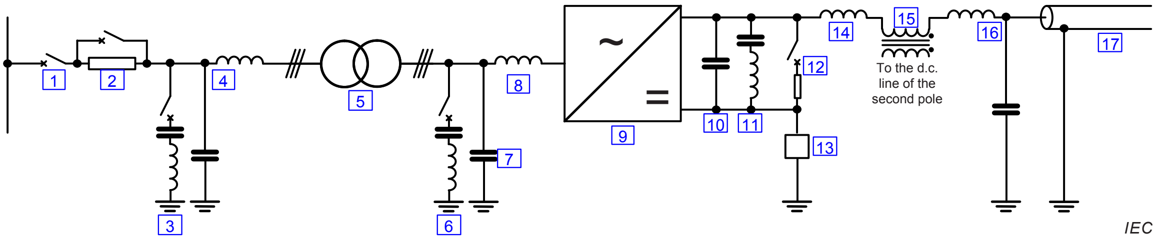
A.2 Guidance for calculating losses in each equipment

A.2.1 Circuit breaker

Power losses in the circuit breaker are normally neglected.

A.2.2 Pre-insertion resistor

Some VSC systems include a pre-insertion resistance in the a.c. connection to the converter, which is bypassed by a circuit breaker after the VSC d.c. capacitors and submodule/cell d.c. capacitors have been fully charged. However, this system does not contribute to steady-state losses and need not be considered in the loss evaluation.



Key

1	circuit breaker
2	pre-insertion resistor
3	line side harmonic filter
4	line side high frequency filter
5	interface transformer
6	converter side harmonic filter
7	converter side high frequency filter[a]
8	phase reactor [a]
9	VSC unit [b]
10	VSC d.c. capacitor [c]
11	d.c. harmonic filter
12	dynamic braking system
13	neutral point grounding branch [d]
14	d.c. reactor
15	common mode blocking reactor
16	d.c. side high frequency filter
17	d.c. cable or overhead transmission line

[a] In some designs of VSC, the phase reactor can fulfil part of the function of the converter-side high frequency filter.

[b] In some VSC topologies, each valve of the VSC unit can include a “valve reactor”, which can be built in to the valve or provided as a separate component.

[c] In some designs of VSC, the VSC d.c. capacitor can 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.

[d] The philosophy and location of the neutral point grounding branch can be different depending on the design of the VSC unit.

Figure A.1 – Major components that may be found in a VSC substation

A.2.3 Line side harmonic filter

Losses in the line side harmonic filter, where fitted, may be calculated by a similar process to the calculation of losses in the a.c. filters of an LCC HVDC substation, as described in 5.3 of IEC 61803:1999/AMD1:2010, . However, it should be noted that in comparison with the a.c. harmonic filters on an LCC HVDC substation, the a.c. filters in a VSC substation generally have much lower MVAr and consequently a smaller capacitor in relation to the tuning inductor(s) and damping resistor(s).

A.2.4 Line side high frequency filter

Losses in the line side high frequency filter, where fitted, may be calculated by a similar process to the calculation of losses in the a.c. series filters of an LCC HVDC substation, as described in 5.9 of IEC 61803:1999/AMD1:2010, but noting the possible need to extend the range of harmonic orders considered.

A.2.5 Interface transformer

The interface transformer is analogous to the converter transformer in an LCC HVDC substation and is generally the second largest contributor to the losses of the entire substation, after the VSC valves.

Power losses in the interface transformer may be calculated in a similar way to the method given in 5.2 of IEC 61803:1999/AMD1:2010, but noting the possible need to extend the range of harmonic orders considered.

A.2.6 Converter side harmonic filter

Losses in the converter side harmonic filter, where fitted, may be calculated by a similar process to those outlined for the line side harmonic filter (A.2.3 above).

A.2.7 Converter side high frequency filter

Losses in the converter side high frequency filter, where fitted, may be calculated by a similar process to those outlined for the line side high frequency filter (A.2.4 above).

A.2.8 Phase reactor

The phase reactor used in some VSC substations has no direct equivalent in an LCC HVDC substation. It carries mainly fundamental frequency current but in converters based on valves of the “switch” type, is exposed to high levels of harmonic currents and voltages from the converter. In such cases the reactor may require a special design in order to eliminate problems of electromagnetic interference or heating caused by skin and proximity effects. The general principles outlined in IEC 61803:1999/AMD1:2010 (5.2, 5.3.3 and 5.6 being the most relevant) may be used for guidance but determination of losses in such reactors should be performed with care.

Where the converter is based on valves of the “controllable voltage source” type, the phase reactor may be of a more conventional design (usually air-cored) or may be omitted altogether. In such cases, the losses in the phase reactor may be calculated by a similar process to the calculation of losses in the a.c. filter reactors of an LCC HVDC substation, as described in 5.3.3 of IEC 61803:1999/AMD1:2010. In such designs, the harmonic content of the reactor current is normally very low.

A.2.9 VSC unit

The VSC unit consists of the VSC valves, which are covered by the body of this standard, and in some topologies the VSC unit also includes valve reactors. Losses in the valve reactors, where fitted, may be calculated by a similar process to the method for a.c. filter reactors given in 5.3.3 of IEC 61803:1999/AMD1:2010.

A.2.10 VSC d.c. capacitor

The VSC d.c. capacitor used in some VSC substations has no direct equivalent in an LCC HVDC substation, although it is analogous to the capacitive part of the d.c. filter. Its power losses may be calculated by a similar process to the calculation of losses in the d.c. filter capacitor of an LCC HVDC substation, as described in 5.7.2 of IEC 61803:1999.

NOTE The submodule d.c. capacitors fitted to some designs of valve are considered as part of the valve and are covered by the body of this standard.

A.2.11 D.C. harmonic filter

Power losses in the d.c. harmonic filter, where fitted, may be calculated in a similar way to the method given in 5.7 of IEC 61803:1999/AMD1:2010, but noting the possible need to extend the range of harmonic orders considered.

A.2.12 Dynamic braking system

Some VSC systems may include a dynamic braking system for active control of d.c. overvoltage, particularly during load-rejection events when importing power from an islanded a.c. generating system. The dynamic braking system generally consists of a power electronic valve (the dynamic braking valve) similar in construction to the main valves of the converter, and a large braking resistor. In some designs the braking resistor may be built in to the dynamic braking valve as opposed to being a separate item of equipment.

Losses in the dynamic braking system while it is operating to reduce the d.c. voltage do not need to be accounted for in the overall determination of losses, since such events are rare and of very short duration. However, the steady-state losses of the dynamic braking system should be accounted for.

In steady state, the losses in the resistive part of the dynamic braking system can generally be neglected. Similarly, conduction losses and d.c. capacitor losses in the dynamic braking valve may be neglected; however the dynamic braking valve will generally incur d.c. voltage-dependent losses (Clause 6) and the power consumption of the valve electronics (9.2). Some types of valve may also incur snubber losses (9.1) and switching losses (Clause 8).

Losses in the dynamic braking valve under steady-state conditions should be calculated using the relevant clauses of the body of this standard.

A.2.13 Neutral point grounding branch

The neutral-point grounding branch used in some VSC substations has no direct equivalent in an LCC HVDC substation. It is used in some symmetrical monopole VSC systems to provide a ground reference on the valve side of the interface transformer. It typically consists of a three-phase shunt reactor of relatively high impedance. Its losses may be calculated in a similar way to the method given for shunt reactors in 5.5 of IEC 61803:1999/AMD1:2010.

A.2.14 D.C. reactor

Power losses in the d.c. reactor, where fitted, may be calculated in a similar way to the method given in 5.6 of IEC 61803:1999/AMD1:2010, but noting the possible need to extend the range of harmonic orders considered.

However, it should be noted that the d.c. reactor in a VSC substation is usually somewhat smaller than its counterpart in an LCC substation and is usually air-cored in construction.

A.2.15 Common mode blocking reactor

The common-mode blocking reactor used in some VSC substations has no direct equivalent in an LCC HVDC substation. It is used in some VSC systems to introduce a low inductance for differential-mode currents but high inductance for common-mode currents caused, for example, by certain faults. It resembles a pair of d.c. reactors in a common structure so that there is a large mutual coupling between the two.

The losses in the common-mode blocking reactor may be calculated using the general principles outlined for the d.c reactor (A.2.16 below). For determination of losses, measurements should be based as far as possible on measurements taken with the currents in the two windings flowing in the normal (differential) mode rather than in common mode.

A.2.16 D.C. side high frequency filter

Losses in the d.c. side high frequency filter, where fitted, may be calculated by a similar process to the calculation of losses in the d.c. series filters of an LCC HVDC substation, as described in 5.9 of IEC 61803:1999/AMD1:2010, but noting the possible need to extend the range of harmonic orders considered.

A.2.17 D.C. cable or overhead transmission line

Power losses in the d.c. cable or overhead transmission line are out of the scope of this standard.

A.3 Auxiliaries and station service losses

Power losses in auxiliary and station service equipment may be calculated by the same process to the calculation of losses in the auxiliary and station service equipment of an LCC HVDC substation, as described in 5.8 of IEC 61803:1999/AMD1:2010. There are no significant differences between the VSC and LCC technologies in this respect.

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