IEC 61803

Edition 3.0 2026-05

INTERNATIONAL STANDARD

COMMENTED VERSION

Determination of power losses in high-voltage direct current (HVDC) converter stations

IEC 61803:2026-05 CMV(en)

ICS 29.200

ISBN 978-2-8327-1267-2

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

Determination of power losses in high-voltage direct current (HVDC) converter stations ~~with line-commutated converters~~ 1

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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This commented version (CMV) of the official standard IEC 61803:2026 edition 3.0 allows the user to identify the changes made to the previous IEC 61803:2020 edition 2.0. Furthermore, comments from IEC SC 22F experts are provided to explain the reasons of the most relevant changes, or to clarify any part of the content.

A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text. Experts' comments are identified by a blue-background number. Mouse over a number to display a pop-up note with the comment.

This publication contains the CMV and the official standard. The full list of comments is available at the end of the CMV.

IEC 61803 has been prepared by subcommittee 22F: Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment. It is an International Standard.

This third edition cancels and replaces the second edition published in 2020. This edition constitutes a technical revision.

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

a) HVDC stations with voltage-sourced converters (VSC) technology have been included;

b) to facilitate the application of this document and to ensure its quality remains consistent, 5.1.8 and 5.8 have been reviewed, taking into consideration that the present thyristor production technology provides considerably less thyristor parameters dispersion comparing with the situation in 1999 when the first edition of IEC 61803 was developed; therefore, the production records of thyristors can be used for the power losses calculation;

c) the calculation of the total station load losses (cases D1 and D2 in Annex C) has been corrected.

The text of this International Standard is based on the following documents:

Draft	Report on voting
22F/860/FDIS	22F/868/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

– reconfirmed,

– withdrawn, or

– revised.

1 Scope

This document applies to all ~~line-commutated~~ high-voltage direct current (HVDC) converter stations with line-commutated converters (LCC) as well with voltage-sourced converters (VSC) used for power exchange (power transmission or back-to-back installation) in utility systems. For line-commutated converters (LCC), this document presumes the use of 12-pulse thyristor converters but can, with due care, also be used for 6-pulse thyristor converters.

Where VSC is referred to in this document, it is assumed to be of the MMC-type or similar, with very low harmonic generation. It is important to treat other types of VSC as appropriate. 2

In some applications, synchronous compensators, static var compensators (SVC), or static synchronous compensator (STATCOM) ~~may be~~ are connected to the AC bus of the HVDC converter station. The loss determination procedures for such equipment are not included in this document.

This document presents a set of standard procedures for determining the total losses of an HVDC converter station, except for VSC valves which are covered by the IEC 62751 series 3. The procedures cover all parts, except as noted above, and address no-load operation and operating losses together with their methods of calculation which use, wherever possible, measured parameters.

Converter station designs employing novel components or circuit configurations compared to the typical design assumed in this document, or designs equipped with unusual auxiliary circuits that ~~could~~ can affect the losses, are assessed on their own merits.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60076-1, *Power transformers - Part 1: General*

IEC 60076-6, *Power transformers - Part 6: Reactors*

IEC 60633, *High-voltage direct current (HVDC) transmission - Vocabulary*

IEC 60700-1:2015, *Thyristor valves for high voltage direct current (HVDC) power transmission - Part 1: Electrical testing*
IEC 60700-1:2015/AMD1:2021

IEC 60871-1, *Shunt capacitors for a.c. power systems having a rated voltage above 1 000 V - Part 1: General*

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

3 Terms, definitions and symbols

For the purposes of this document, the terms and definition given in IEC 60633, IEC 62747 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

– IEC Electropedia: available at http://www.electropedia.org/

– ISO Online browsing platform: available at http://www.iso.org/obp

3.1 Terms and definitions

3.1.1
auxiliary losses
electric power required to feed the converter station auxiliary loads

Note 1 to entry: The auxiliary losses depend on the number of converter units used and whether the station is in no-load operation or carrying load, in which case the auxiliary losses depend on the load level.

3.1.2
equipment no-load operation losses
losses produced in an item of equipment with the converter station energised but with the converters blocked and all station service loads and auxiliary equipment connected as required for immediate pick-up of load to specified minimum power

3.1.3
load level
~~direct current, direct voltage, firing angle, AC voltage, and converter transformer tap-changer position at which the converter station is operating~~

set of AC system and converter operating conditions at which the converter station is operating

Note 1 to entry: For LCC schemes, the load level is defined by the direct current, direct voltage, firing angle, AC system voltage and converter transformer tap-changer position.

Note 2 to entry: For VSC schemes, the load level is defined by the direct current, direct voltage, AC system voltage, interface transformer tap-changer position (where appropriate), converter AC voltage, converter AC current and the phase angle between converter AC voltage and current. 4

3.1.4
equipment operating losses
losses produced in an item of equipment at a given load level with the converter station energised and the converters operating

3.1.5
rated load
~~load related to operation at nominal values of DC current, DC voltage, AC voltage and converter firing angle~~

load corresponding to operation at nominal values of the operating conditions defined in 3.1.3

Note 1 to entry: The AC system shall be assumed to be at nominal frequency, and its 3-phase voltages are nominal and balanced. The position of the tap-changer of the converter/interface transformer and the number of AC filters and shunt reactive elements, if any connected, shall be consistent with operation at rated load, coincident with nominal conditions.

3.1.6
total station no-load operation losses
sum of all equipment no-load operation losses (3.1.2) and corresponding auxiliary losses (3.1.1)

3.1.7
total station operating losses
sum of all equipment operating losses (3.1.4) and corresponding auxiliary losses (3.1.1) at a particular load level

Note 1 to entry: An illustrative example using total station operating losses and corresponding loss evaluation is given in Annex C, case D1.

3.1.8
total station load losses
difference between total station operating losses (3.1.7) and total station no-load operation losses (3.1.6)

Note 1 to entry: Such calculated total station load losses are considered as being quantitatively equivalent to load losses as in conventional AC substation practice.

Note 2 to entry: It is recognized that some purchasers evaluate total station no-load operation losses (3.1.6) and total station load losses individually instead of the evaluating total station operating losses (3.1.7).

Note 3 to entry: An illustrative example to derive load losses, equivalent load losses and corresponding loss evaluation is given in Annex C, case D2.

3.1.9
station essential auxiliary load
load whose failure affects the conversion capability of the HVDC converter station (e.g. valve cooling), as well as load that ~~shall remain~~ remains working in case of complete loss of AC power supply (e.g. battery chargers, operating mechanisms)

3.2 Symbols

3.2.1 Common

f	AC system frequency, in hertz (Hz)
I_d	direct current, in amperes (A)
I_n	harmonic RMS current of order n, in amperes (A)
n	harmonic order
P	power loss in an item of equipment, in watts (W)
Q_n	quality factor of a reactor at harmonic order n
R	resistance value, in ohms (Ω)
U_d	direct voltage, in volts (V)
U_n	harmonic RMS voltage of order n, in volts (V)
X_n	inductive reactance at harmonic order n, in ohms (Ω)

3.2.2 Line-commutated converters

α	(trigger/firing) delay angle, in radians (rad)
γ	extinction angle, in radians (rad)
μ	overlap angle, in radians (rad)
L_1	inductance, in henrys (H), referred to the valve winding, between the commutating voltage source and the point of common coupling between star- and delta-connected windings; L_1 shall include any external inductance between the transformer line-winding terminals and the point of connection of the AC harmonic filters
L_2	inductance, in henrys (H), referred to the valve winding, between the point of common coupling between star- and delta-connected windings; the valve L_2 shall include the saturated inductance of the valve reactors

m electromagnetic notch coupling factor, $m = L_1/(L_1 + L_2)$

N_t number of series-connected thyristors per valve

U_{vo} RMS value of the phase-to-phase no-load voltage on the valve side of the converter transformer excluding harmonics, in volts (V)

4 Overview

4.1 General

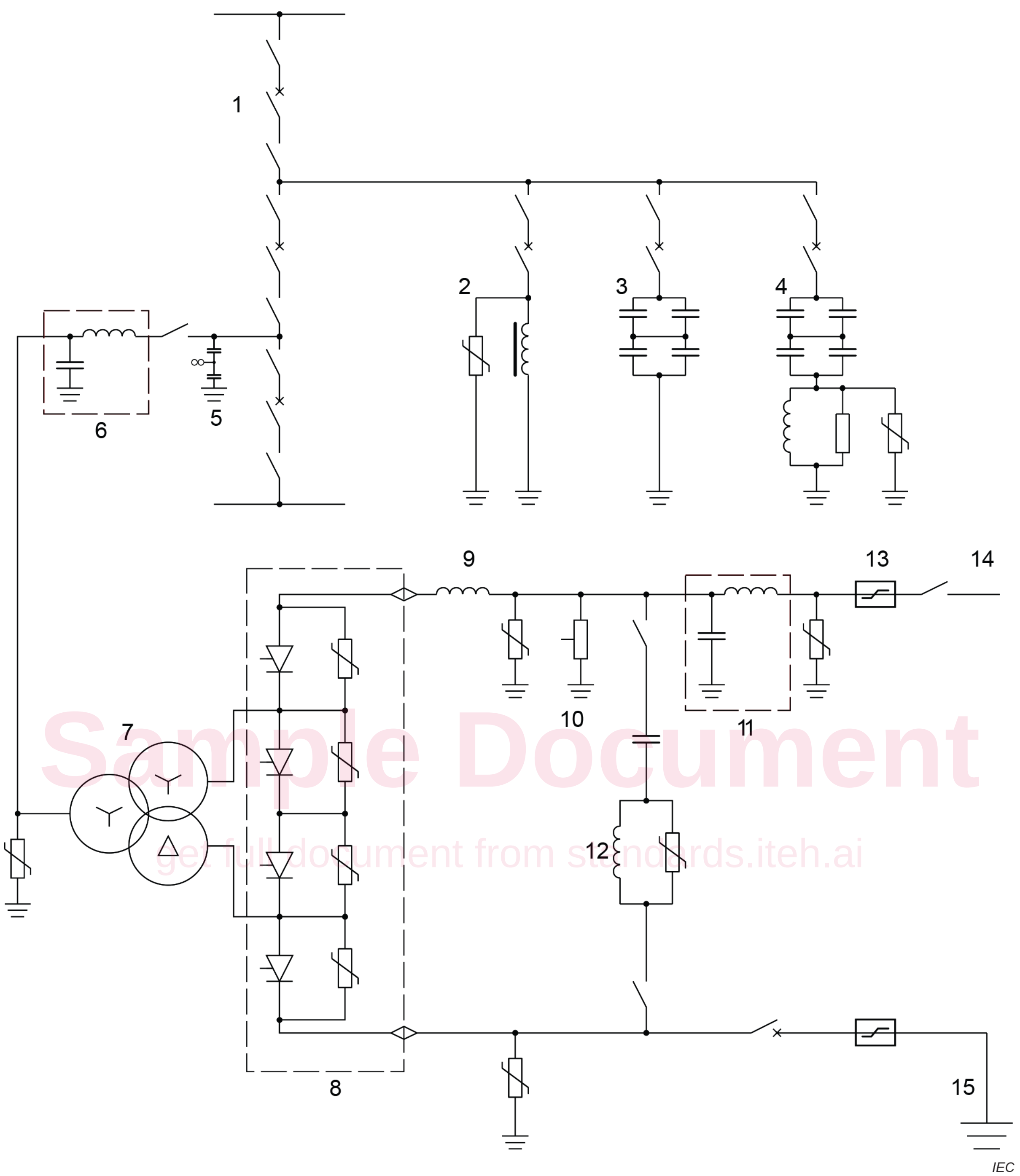
It is important for suppliers to know in detail how and where losses are generated, since this affects component and equipment ratings. Purchasers are interested in a verifiable loss figure which allows equitable bid comparison and in a procedure which can objectively verify the guaranteed performance requirements of the supplier after delivery. The main purpose of this document is to serve the purchasers this specific interest.

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 less than 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~~ can be possible, for example, to arrange a temporary test connection in which two converters are operated from the same AC source and also connected together via their DC terminals. In this connection, the power drawn from the AC source equals the losses in the circuit though in most cases this does not represent a normal operating design mode. However, the AC source shall also provide var support and commutating voltage to the two converters. Once again, there are practical measurement difficulties, and it is still important that the losses are recalculated/corrected for nominal parameters and ambient/operating conditions. 5

In order to avoid the problems described above since these practical measurements are unreliable and also will depend on the type of HVDC solution, it is recommended to use this document which 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.

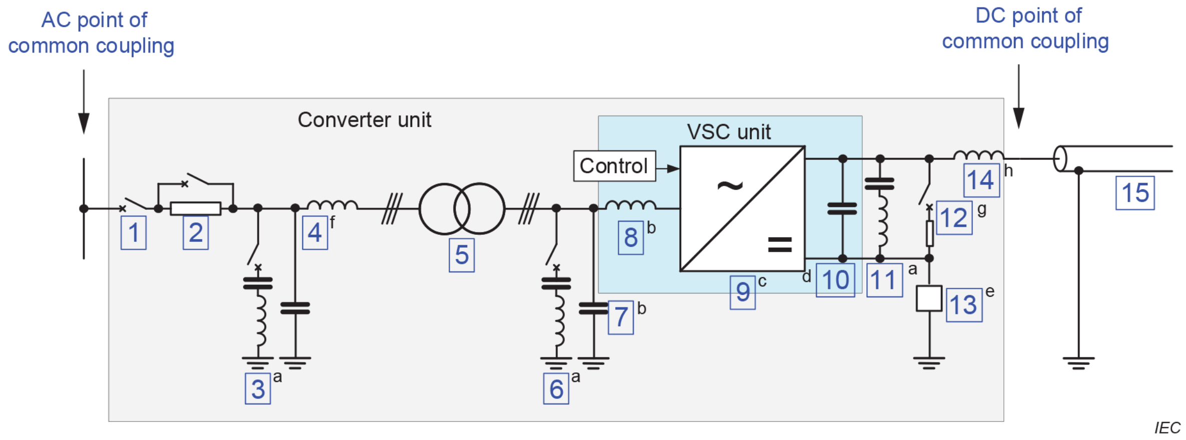
Typical high-voltage direct current (HVDC) equipment for one pole of an LCC HVDC substation is shown in Figure 1 and for one pole of a VSC HVDC substation in Figure 2 6. The calculation of harmonic currents and voltages in HVDC equipment for line-commutated converter stations is described in Annex A.



Key

1	AC switchyard	9	DC smoothing reactor
2	shunt reactor bank	10	voltage divider
3	shunt capacitor bank	11	PLC filter
4	AC filter bank	12	DC filter
5	capacitor voltage transformer	13	DC current measuring device
6	PLC filter	14	pole line
7	converter transformer	15	ground electrode
8	valve hall		

Figure 1 – Typical high-voltage direct current (HVDC) equipment for one pole of an LCC scheme



Key

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

[a] In some designs of VSC based on VSC switch type valves, the harmonic filters may not be required.

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

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

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

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

[f] In some designs of VSC, the interface transformer can fulfill part of the function of the line-side high frequency filter.

[g] Optional.

[h] Optional, if phase reactors or valve reactors are located on the DC side of the converter.

Figure 2 – Typical high-voltage direct current (HVDC) equipment for one pole of a VSC scheme

Compared with LCCs, VSCs for HVDC systems generate a much less distorted AC side current waveform. Depending on the converter topology and the control methods employed for VSC, the network side voltage generated by the converter can approach a clean fundamental frequency sinusoid. The VSC converter can be considered as a harmonic voltage source behind an internal impedance, rather than a current source as for LCCs, as it is the generated harmonic voltage which remains independent of load. The harmonic levels can be extremely low compared to LCCs, but due to the adopted switching regime have a significant frequency range much higher than for LCCs, and can contain inter-harmonics, which are a result of the control strategy adopted. Refer to the IEC TR 62001-5 for harmonics generation of VSC converters. 7

NOTE In this document, where the term "harmonic" is used for VSC converters, it is considered to mean the "harmonic group" according to IEC 61000-4-7, which includes the integer harmonic and the spectral bins from h – 0,5 to h + 0,5, instead of "harmonic number n".

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.

It is recognized that, for AC and DC side filter equipment, the specified notional requirements do not represent the actual losses to be expected in service; however, the simplified approach specified in this document is considered acceptable to estimate losses and compare different bids.

4.2 Ambient conditions

4.2.1 General

A set of standard reference ambient conditions shall be used for determining the power losses in HVDC converter stations.

4.2.2 Outdoor standard reference temperature

An outdoor ambient dry bulb temperature of 20 °C shall be used as the standard reference temperature for determining the total converter station losses. The corresponding valve hall temperature ~~may~~ can be defined by the supplier if necessary. The equivalent wet-bulb temperature (where necessary) shall be defined by the purchaser.

If not defined, the wet-bulb temperature is recommended to be 14 °C, which corresponds to approximately 50 % RH at 20 °C dry bulb temperature.

4.2.3 Coolant standard reference temperature

Where forced cooling is used for equipment, the flow rate and temperature of the coolant can influence the temperature rise and associated losses of that equipment. Therefore, the coolant temperatures and flow rates established by the purchaser and the supplier shall be used as a basis for determining the losses.

4.2.4 Standard reference air pressure

The reference air pressure to be used for the evaluation of total converter station power losses shall be the standard atmospheric pressure (101,3 kPa) corrected to the altitude of the installation in question when station is located above 1 000 m above sea level.

4.3 Operating parameters

The losses of an HVDC converter station depend on its operating parameters.

The losses of HVDC converter stations are classified into two categories, referred to as operating losses (3.1.4 and 3.1.7) and no-load operation losses (3.1.2 and 3.1.6).

The operating losses and auxiliary losses are affected by the load level of the station because the numbers of certain types of energised equipment (for example harmonic filters and cooling equipment) ~~may~~ can depend upon the load level and because losses in individual items of equipment themselves vary with the load level.

HVDC converter station losses shall be determined for nominal (balanced) AC system voltage and frequency, symmetrical impedances of the ~~converter~~ transformer (between phases, and for LCC schemes, between the star and delta-connected bridges) and, for LCC schemes, symmetrical firing angles. The transformer tap-changer shall be assumed to be in the position corresponding to nominal AC system voltage or as decided by the control system for the defined operating condition.

The operating losses shall be determined for the load levels specified by the purchaser, or at rated load if no such conditions are specified. For each load level, ~~the valve-winding AC voltage, DC current, converter firing angle,~~ the converter operating conditions defined in 3.1.3, shunt compensation and harmonic filtering equipment shall be consistent with the respective load level and other specified performance requirements, relating, for example, to harmonic distortion and minimum reactive power exchange with the connected ac network. Cooling and other auxiliary equipment, as appropriate to the standard reference temperature (see 4.2.2 and 4.2.3), shall be assumed to be connected to support the respective load level. Unless specifically specified, reactive power shall be assumed zero for a VSC station.

For the no-load operation mode, ~~converter~~ transformers shall be energised and the converters blocked. All filters and reactive power compensation equipment shall be assumed to be disconnected except for those which are required to sustain operation at zero load in order, for example, to meet the specified reactive power requirements. Station service loads and auxiliary equipment (e.g. cooling-water pumps) shall be assumed to be connected as required for immediate pick-up of load for the converter station (without waiting for tap changer movement) to specified minimum power.

NOTE For some MMC VSC valves, it can be impracticable to keep the converter blocked with AC circuit breaker closed for a while, due to a need for balancing the submodule capacitor voltages. The operating state generally known as "idling operating state" will also have an additional contribution of valve losses. However, for the purpose of guaranteeing loss calculation, it is sufficient to compare losses for no-load operation losses as defined in 3.1.2 at zero active and reactive power. 8

5 Determination of equipment losses

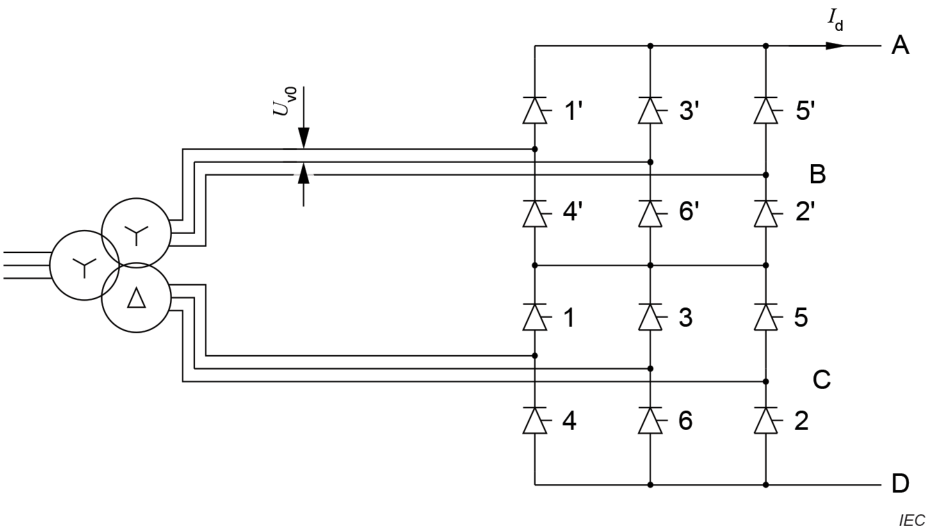
5.1 Thyristor valve losses (LCC only)

5.1.1 General

The loss production mechanisms applicable when the valves are blocked (no-load operation losses) are different from those applicable in normal operation (operating losses). Operating losses are dealt with in 5.1.2 to 5.1.11, and no-load operation losses are dealt with in 5.1.12. Auxiliary losses are dealt with in 5.8.

~~Typical high-voltage direct current (HVDC) equipment for one pole of a HVDC substation is shown in Figure 1.~~

A simplified three-phase diagram of an HVDC 12-pulse converter is shown in Figure 3. Individual valves are marked in the order of their conduction sequence.



Key

A high-voltage DC terminal

B upper bridge

C lower bridge

D low voltage DC terminal

Figure 3 – Simplified three-phase diagram of an HVDC 12-pulse converter (LCC)

A simplified equivalent circuit of a typical valve is shown in Figure 4, where symbol "th" combines the effects of N_t thyristors connected in series in the valve. C_{AC} and R_{AC} are the corresponding combined values of R-C damping circuits used for voltage sharing and overvoltage suppression. R_{DC} represents DC grading resistors and other resistive components which incur loss when the valve blocks voltage; it also includes the effects of the thyristor leakage current (see 5.1.5 and 5.1.12). C_s includes both stray capacitances and surge distribution capacitors (if used). L_s represents saturable reactors used to limit the di/dt stresses to safe values and to improve the distribution of fast rising voltages. R_s represents the resistances of the current conducting components of the valve such as the busbars, contact resistances, resistance of the windings of the saturable reactors, etc. Power losses in the valve surge arrester (not shown) shall be neglected.