

INTERNATIONAL STANDARD



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

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INTERNATIONAL STANDARD



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

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**DETERMINATION OF POWER LOSSES IN HIGH-VOLTAGE
DIRECT CURRENT (HVDC) CONVERTER STATIONS WITH
LINE-COMMUTATED CONVERTERS**

FOREWORD

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International Standard 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.

This second edition cancels and replaces the first edition published in 1999, Amendment 1:2010 and Amendment 2:2016. This edition constitutes a technical revision.

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

- a) 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, and therefore the production records of thyristors can be used for the power losses calculation;
- b) 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:

CDV	Report on voting
22F/563/CDV	22F/580A/RVC

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

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

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

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- withdrawn,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

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DETERMINATION OF POWER LOSSES IN HIGH-VOLTAGE DIRECT CURRENT (HVDC) CONVERTER STATIONS WITH LINE-COMMUTATED CONVERTERS

1 Scope

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

In some applications, synchronous compensators or static var compensators (SVC) may be 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. ~~Typical HVDC equipment is shown in figure 1.~~ 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 affect the losses, ~~shall be~~ 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 60076-1:1993, *Power transformers – Part 1: General*

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

~~IEC 60289:1988, *Reactors*~~

~~IEC 60633:1998, *Terminology for high-voltage direct current (HVDC) transmission*~~

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

IEC 60700-1:1998/2015, *Thyristor valves for high voltage direct current (HVDC) power transmission – Part 1: Electrical testing*

~~IEC 60747-6:1983, *Semiconductor devices – Discrete devices – Part 6: Thyristors*~~

IEC 60871-1:1997, *Shunt capacitors for a.c. power systems having a rated voltage above 1 000 V – Part 1: General performance, testing and rating – Safety requirements – Guide for installation and operation*

3 Terms, definitions and symbols

~~For the purpose of this International Standard, the following definitions apply:~~

For the purposes of this document, the terms and definition given in IEC 60633 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

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

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 transformer and the number of AC filters and shunt reactive elements connected shall be consistent with operation at rated load, coincident with nominal conditions.

3.1.6

total station no-load operation losses

~~the total station loss is the sum of all operating or no-load operation losses and the corresponding auxiliary 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 will affect the conversion capability of the HVDC converter station (e.g. valve cooling), as well as load that shall remain working in case of complete loss of AC power supply (e.g. battery chargers, operating mechanisms)

3.2 Symbols

α	(trigger/firing) delay angle, in radians (rad)
μ	~~commutation~~ overlap angle, in radians (rad)
f	AC system frequency, in hertz (Hz)
I_d	~~direct current in the bridge d.c. connection~~ , in amperes (A)
I_n	harmonic RMS current of order n , in amperes (A)
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, and 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	harmonic order
N_t	number of series-connected thyristors per valve
P	power loss in an item of equipment, in watts (W)
Q_n	quality factor at harmonic order n
R	resistance value, in ohms ~~(W)~~ (Ω)
U_d	direct voltage, in volts (V)
U_n	harmonic RMS voltage of order n , in volts (V)
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)
X_n	inductive reactance at harmonic order n , in ohms (Ω)

4 Overview

4.1 General

~~4.1 Introduction~~

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 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 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. However, the AC source ~~must~~ shall also provide 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 document 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.

The calculation of harmonic currents and voltages in HVDC equipment is described in Annex A.

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 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. **Corresponding valve hall temperature may 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.

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 three categories, termed the no-load operation losses, operating losses and auxiliary losses.~~

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 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 and 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, 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 reactive power. 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.

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.

5 Determination of equipment losses

5.1 Thyristor valve losses

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 2. Individual valves are marked in the order of their conduction sequence.

A simplified equivalent circuit of a typical valve is shown in Figure 3. Symbol th combines together 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.

Figure 4 shows, as an example, current and voltage waveforms of valve 1 (according to Figure 2) operating in rectifier – Figure 4 a) – and inverter – Figure 4 b) – modes. In the example shown, the firing instants of the valves of the upper bridge are delayed by 30° with respect to the valves of the lower bridge due to the phase shift between the two secondaries. For each valve, the length of the conduction intervals is 130° ($2\pi/3 + \mu$). During commutations, the valve current is assumed, for this document, to be changing linearly whereas in reality the valve currents follow portions of sine waves. This simplification has negligible effect on the resulting losses, while the trapezoidal waveform significantly simplifies the calculations. The voltage blocked by the valve shows notches caused by commutations between individual valves.

5.1.2 Thyristor conduction loss per valve

A typical thyristor on-state characteristic is shown in Figure 5. This Thyristor conduction loss component is the product of the conduction current $i(t)$ – Figure 6 a) – and the corresponding ideal on-state voltage as shown in Figure 5 – and 6. Formula P_{V1a} shall be used provided that the DC bridge current is well smoothed. In the event that the root sum square value of the DC side harmonic currents, determined in accordance with Clause A.4 (annex A), exceeds 5 % of the DC component, formula P_{V1b} shall be used instead.

$$P_{V1a} = \frac{N_t \times I_d}{3} \left[U_0 + R_0 \times I_d \times \left(\frac{2\pi - \mu}{2\pi} \right) \right]$$

$$P_{V1b} = \frac{N_t \times I_d \times U_0}{3} + \frac{N_t \times R_0}{3} \left(I_d^2 + \sum_{n=12}^{n=48} I_n^2 \right) \left(\frac{2\pi - \mu}{2\pi} \right)$$

where

U_0 is the current-independent component of the on-state voltage of the average thyristor (see note below), in volts;

R_0 is the slope resistance of the on-state characteristic of the average thyristor (see note below), in ohms;

I_n is the calculated RMS value of the n^{th} harmonic current in the bridge DC connection according to Clause A.4, in amperes.

NOTE U_0 and R_0 (see Figure 5) are determined from the fully spread on-state voltage measured at the appropriate current and junction temperature. The average value of U_0 and R_0 is obtained from production records of the thyristors ~~manufactured for the specific project at 100 % and 50 % of nominal d.c. current~~. The temperature dependence of U_0 and R_0 is established from type tests or routine tests on a statistically significant number of the thyristors employed, and is used, where necessary, to correct U_0 and R_0 to the appropriate service junction temperature. If parallel connection of p thyristors is employed, the appropriate 100 % current is the nominal DC bridge current divided by p . The calculated result is then multiplied by p .

5.1.3 Thyristor spreading loss per valve

This loss component is an additional conduction loss of the thyristors arising from the delay in establishing full conduction of the silicon after the thyristor has been turned on. The additional loss is the product of the current and the voltage by which the thyristor voltage exceeds the ideal thyristor on-state voltage drop – see the hatched area in Figure 6 b).

$$P_{V2} = N_t \times f \times \int_0^{t_1} [u_B(t) - u_A(t)] \times i(t) dt$$

where

t_1 is the length of the conduction interval, in seconds, which is given by:

$$t_1 = \frac{\frac{2}{3} \pi + \mu}{2\pi f};$$

$u_B(t)$ is the instantaneous on-state voltage, in volts, of a thyristor whose fully spread on-state voltage is typical for the thyristors used; the instantaneous on-state voltage shall be determined for the appropriate junction temperature measured with a trapezoidal current pulse exhibiting the correct amplitude and commutation overlap periods (see Figure 5 and Figure 6);

$u_A(t)$ is the calculated instantaneous on-state voltage of the average thyristor at the same junction temperature for the same current pulse but with the conducting area fully established throughout the conduction, as derived from its on-state characteristic represented by U_0 and R_0 only (see Figure 6);

$i(t)$ is the instantaneous current in the thyristor, in amperes.

NOTE—Instantaneous on-state voltage data, including the effects of spreading, are usually not available from production records. Measurements of typical thyristor on-state voltage, including spreading, should therefore be obtained during the valve periodic firing and

extinction type test (IEC 60700-1:2015, Clause 9) or, alternatively, from a separate laboratory test on a statistically significant number of thyristors.

5.1.4 Other conduction losses per valve

These are the conduction losses in the main circuit of the valve due to components other than the thyristors.

$$P_{V3} = \frac{R_s \cdot I_d^2}{3} \left(\frac{2\pi - \mu}{2\pi} \right)$$

where

R_s is the DC resistance of the valve terminal-to-terminal circuit excluding the thyristors, in ohms (see Figure 3).

The value of R_s is determined by direct measurement on a representative valve section that includes all elements of the main circuit of a valve in the correct proportions, but in which the thyristors have been replaced by copper blocks of the appropriate dimensions and with contacts treated in the same way as for real thyristors. Alternatively, the resistance may be calculated, in which case the calculation methods shall be documented.

5.1.5 DC voltage-dependent loss per valve

This loss component is the loss in the shunt resistance R_{DC} of the valve (see Figure 3), arising from the voltage which appears between valve terminals during the non-conducting interval (see Figure 4). It includes losses due to thyristor off-state and reverse leakage, losses in DC grading resistors, other resistive circuits and elements connected in parallel with the thyristors, resistance of the coolant in coolant pipes, resistivity effects of the structure, fibre optics, etc.

$$P_{V4} = \frac{U_{V0}^2}{2\pi R_{DC}} \left\{ \frac{4}{3} \pi + \frac{\sqrt{3}}{4} [\cos(2\alpha) + \cos(2\alpha + 2\mu)] + \frac{6m^2 - 12m - 7}{8} [\sin(2\alpha) - \sin(2\alpha + 2\mu) + 2\mu] \right\}$$

where

R_{DC} is the effective off-state DC resistance of a complete valve determined by measuring the current drawn during the valve terminal-to-terminal DC voltage type test (according to IEC 60700-1:2015, 8.3.1) in ohms; if a type test is not performed on the thyristor valve, R_{DC} shall be determined by reference to a previous type test (see also ~~note 2~~ the paragraph after Note 1 below);

$m = L_1 / (L_1 + L_2)$;

L_1 is the inductance, in henrys, 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 (see Figure 7);

L_2 is the inductance, in henrys, referred to the valve winding, between the point of common coupling between star- and delta-connected windings, and the valve; L_2 shall include the saturated inductance of the valve reactors (see Figure 7).

The value of L_2 shall be the same for both secondaries ($L_{2\Delta} = L_{2Y}$) (see ~~notes 3 and 4~~ Note 2 and last paragraph below).

NOTE 1 The formula for P_{V4} is valid for $\mu < \pi/6$ (30°) only.

~~NOTE 2~~ — Since the thyristor resistive leakage current is usually much higher at operating temperatures than at the prevailing ambient air temperature, it is either necessary to heat the

thyristors of the valve to the correct operating temperature before the measurement of R_{DC} is taken or to make later corrections to the measured value using the average thyristor data obtained separately, to include the mentioned temperature effect (see also 5.1.11). The same pertains to the liquid coolant.

NOTE 3—2 The value of m quantifies the effects of inductive coupling between the two secondaries of the converter transformer. It determines the magnitude of the notches caused by the commutation in the other bridge (notches from 1' to 3' and from 4' to 6' in Figure 4). If $m = 0$, then there is no coupling between the two bridges and the notches from 1' to 3' and from 4' to 6' disappear altogether. The notches in Figure 4 correspond to $m = 0,2$.

NOTE 4— Values of L_1 and L_2 are obtained from the short-circuit impedance measurements on the converter transformers, and by adding any external inductances as required. The value of L_1 includes any external common inductance (such as power line carrier filters) between the point of common coupling and the commutation voltage source. In cases where no AC harmonic filters are connected, L_1 also includes the AC system impedance. When separate transformers supply the star and delta bridges and no additional line-side inductance is included, $L_1 = 0$, hence $m = 0$. When a three-winding transformer construction is employed, a common winding impedance and mutual coupling effects of the two secondary windings give non-zero values for L_1 , which may be either positive or negative. For more complicated transformer arrangements, such as filters connected to a tertiary winding, the values of L_1 and L_2 ~~must~~ shall be determined with care.

5.1.6 Damping loss per valve (resistor-dependent term)

This loss component depends on the value of the resistive elements of those circuits that are AC coupled via series capacitors and on the voltage appearing between valve terminals during the non-conduction interval.

$$P_{V5} = 2\pi f^2 U_{V0}^2 C_{AC}^2 R_{AC} \left\{ \begin{aligned} &\left(\frac{4\pi}{3} - \frac{\sqrt{3}}{2} + \frac{3\sqrt{3}m^2}{8} + (6m^2 - 12m - 7) \frac{\mu}{4} + \left(\frac{7}{8} + \frac{9m}{4} - \frac{39m^2}{32} \right) \sin 2\alpha + \right. \\ &\left. \left(\frac{7}{8} + \frac{3m}{4} + \frac{3m^2}{32} \right) \sin(2\alpha + 2\mu) - \left(\frac{\sqrt{3}m}{16} + \frac{3\sqrt{3}m^2}{8} \right) \cos 2\alpha + \frac{\sqrt{3}m}{16} \cos(2\alpha + 2\mu) \right\} \end{aligned} \right.$$

where

- C_{AC} is the effective terminal-to-terminal value of valve damping capacitance, in farads (see Figure 3);
- R_{AC} is the effective terminal-to-terminal value of the associated series-connected damping resistance, in ohms (see Figure 3);
- C_{AC} shall be the design value of damping capacitance per level divided by the number of thyristor levels in a valve;
- R_{AC} shall be the design value of damping resistor per level multiplied by the number of thyristor levels in a valve.

If the valve employs more than one damping or grading network that incorporates series-connected R-C branches, then each branch shall be evaluated separately and the results summed.

If energy is extracted from the R-C grading network to energise the thyristor firing and/or monitoring circuits, then either it shall be demonstrated that the additional losses are negligible or the additional loss shall be calculated separately and added to the figure obtained from the formula P_{V5} .

NOTE Notes 1, 3 and 4 in 5.1.4 1 and 2 and the last paragraph of 5.1.5 also apply to P_{V5} .

5.1.7 Damping loss per valve (change of capacitor energy term)

This loss component arises from the change in stored energy in the valve capacitances as a result of the step changes (ΔU) in the voltage blocked by the valve. Each step change incurs energy loss which equals $\frac{1}{2}C \times \Delta U^2$. The following formula is derived from the sum of the energies lost due to the 12 voltage jumps which take place during one cycle of blocking voltage (Figure 4) multiplied by the system frequency:

$$P_{V6} = \frac{U_{V0}^2 \times f \times C_{HF} \times (7 + 6m^2)}{4} [\sin^2(\alpha) + \sin^2(\alpha + \mu)]$$

where

C_{HF} is the sum of the effective terminal-to-terminal capacitance of all capacitive grading network branches within the valve (whether incorporating series resistors or not), plus the total effective stray capacitance between valve terminals arising from externally connected equipment and the vicinity of the valve to ground and/or adjacent objects (see Note 3 below); $C_{HF} = C_{AC} + C_S$ (see Figure 3).

NOTE 1 Notes ~~1, 3 and 4~~ in 5.1.4 1 and 2 and the last paragraph of 5.1.5 also apply to P_{V6} .

NOTE 2 The formula for P_{V6} produces overly pessimistic results for commutation overlaps whose length is shorter than 3 time-constants of the R-C damping network.

NOTE 3 The external stray capacitance arises predominantly from the winding and bushings of the converter transformer (plus separate wall bushings if fitted), all of which can be measured at manufacture. Depending on the design, it is possible stray capacitance between the valve and the earth ~~may also~~ have to be included. Surge arresters, busbars and the valve structure contribute to the stray capacitance, but these contributions are small and ~~may be~~ are neglected. Since the effective stray capacitance is different for each row of valves, the average value is used for loss calculation.

5.1.8 Turn-off losses per valve

These are additional losses ~~generated in the thyristors and damping resistors~~ due to reverse current flow in the thyristors at turn-off (see Figure 8).

$$P_{V7} = Q_{rr} \times f \times \sqrt{2} \times U_{V0} \times \sin(\alpha + \mu + 2\pi \times f \times t_0)$$

where

Q_{rr} is the average value of thyristor stored charge, in coulombs;

t_0 is the time determined from the relationship

$$t_0 = \sqrt{\frac{Q_{rr}}{(di/dt)_{i=0}}}$$

where

$(di/dt)_{i=0}$ is the commutating di/dt measured at current zero, in amperes per second.

NOTE 1 The value of Q_{rr} used is the full integral of reverse current (see Figure 8), not an approximate triangulation such as that proposed in IEC 60747-6. Q_{rr} is determined from production measurements on a statistically significant number of thyristors or, alternatively, a mean value of Q_{rr} to be used if the thyristors are selected from a predefined Q_{rr} band, and, where necessary, is corrected to the junction temperature, $(di/dt)_{i=0}$ and reverse recovery voltage corresponding to the operating conditions for which the losses are being determined. It is important that the magnitude and the duration of the conduction current are large enough to achieve a full conduction of the thyristor junction.

NOTE 2 The most part of the thyristor turn-off losses resulting from this mechanism are dissipated within the thyristor itself, although part of the losses can be dissipated in other components such as the damping resistor and valve reactor.

5.1.9 Reactor loss per valve

Reactor loss consists of three components: resistive loss in the winding plus eddy current loss and hysteresis loss in the magnetic core. If an additional damping circuit is employed across the winding, it also incurs loss.

Reactor winding loss and the reactor core eddy current loss (and/or reactor damping resistor loss) are already accounted for in the formulae for P_{V3} and P_{V6} .

Hysteresis loss shall be calculated as follows. A DC magnetization curve for the core material(s) shall be determined for the loop of excitation that an HVDC valve reactor normally experiences. This curve shall be established from a magnetizing force arising from not less than 1,5 times the peak of the reverse current I_{rr} at turn-off (see Figure 8) in one polarity to well into the saturated region in the other, and back again. From the area enclosed by the loop, a characteristic hysteresis loss in joules per kilogram shall be determined and applied to the design of the reactor in question, i.e.

$$P_{V8} = n_L \times M \times k \times f$$

where

n_L is the number of reactor cores in a valve;

M is the mass of each core, in kilograms;

k is the characteristic loss, in joules/kilogram.

NOTE — If the saturation current level for the reactor is high in relation to the rated bridge current, and normal commutation di/dt is also high (corresponding to small overlap angles at rated conditions), then additional reactor core eddy current losses will be generated during the commutation periods. If this is the case, it should be demonstrated that these additional losses are either negligible or else within the allowance made in the loss declaration.

5.1.10 Total valve losses

Total operating losses per valve are given by the sum of the eight individual components specified in 5.1.2 to 5.1.9.

$$R_{VT} = \sum_{i=1}^{i=8} R_{Vi}$$

The total operating converter losses are equal to the losses per valve multiplied by the number of valves in the converter.

5.1.11 Temperature effects

All valve components have electrical characteristics that are temperature sensitive. However, it is a common occurrence that the only component with temperature-sensitive characteristics that can substantially affect valve losses is the thyristor itself.

Thyristor junction temperature T_j is determined as

$$T_j = T_c + P_j \times R_{\theta JC}$$

where

T_c is the temperature of the coolant calculated as the mean of the valve inlet and valve outlet temperatures;

P_j is the total power loss per thyristor, calculated as the sum of its individual components due to conduction, spreading, blocking and turn-off;

$R_{\theta JC}$ is the thermal resistance from the thyristor junction to the coolant.

5.1.12 No-load operation loss per valve

The no-load operation loss per valve is the sum of losses caused by the currents which are driven by the voltage blocked by the valve through the resistances of the valve. It consists of two terms. The first quantifies the loss in the resistances which are connected in parallel with the blocking thyristors, the second determines the loss in the resistances which are capacitively coupled. In no-load operation mode, the valve blocks the sinusoidal waveform of the line to neutral voltage. Consequently:

$$R_{VSB} = \frac{U_{v0}^2}{3} \left(\frac{1}{R_{DC}} + \frac{R_{AC}}{Z_{AC}^2} \right)$$

where

$$Z_{AC} = \sqrt{R_{AC}^2 + \left(\frac{1}{2\pi \times f \times C_{AC}} \right)^2}$$

If the valve employs more than one grading network branch that incorporates series-connected R and C , then each branch shall be evaluated separately and the results summed.

If energy is extracted from the R-C grading network to energise the thyristor firing and/or monitoring circuits, then either it shall be demonstrated that the additional losses are negligible or the additional loss shall be calculated separately and added to the figure obtained from the formula P_{VSB} .

The total converter no-load operation losses are the no-load operation loss per valve multiplied by the number of valves in the converter.

5.2 Converter transformer losses

5.2.1 General

The current flowing through the windings of converter transformers contains harmonics whose magnitudes depend on the operating parameters of the converter station. The current-dependent load losses in the transformer due to the non-sinusoidal current waveshapes are greater than those that would occur with a sinusoidal current of the same RMS value at fundamental frequency.

5.2.2 No-load operation losses

In no-load operation mode, with the transformer energised and the valves blocked, the transformer losses are the no-load losses. The no-load losses (core losses) shall be determined according to IEC 60076-1.

The transformer tap-changer position shall be as defined in 4.3.

5.2.3 Operating losses

In the operating mode, the transformer operating losses shall be taken as the sum of the magnetizing losses (core losses) and the current-dependent (load) losses.

Under load-carrying conditions, harmonic voltages are imposed on the transformer. The core losses under load shall be considered equal to the no-load losses at the tap position corresponding to the load level considered, with nominal AC system voltage applied. The effect of the harmonic voltages on the magnetizing current of the transformer, relative to the effect of the fundamental frequency component of the voltage, is negligible.

The load losses of the transformer shall take into account both the fundamental frequency and the harmonic components of the current and shall be determined according to the following procedure.

- a) Measure the load losses P_1 at fundamental frequency f_1 (50 Hz or 60 Hz) according to IEC 60076-1.
- b) Calculate $P_{WE1} + P_{SE1} = P_1 - P_R$.
- c) Measure the load losses P_m at a higher frequency f_m equal to or greater than 150 Hz.

NOTE — A voltage source used for induced voltage tests is normally available. An acceptable accuracy is reached for currents as low as 10 % to 20 % of the rated current provided that stray flux distribution among metallic parts has been taken care of in the transformer design. If a reduced current is used, and the current is less than 10 %, P_m shall be recalculated to rated current.

- d) Calculate P_{WE1} and P_{SE1} based on the measurements at fundamental frequency and the higher frequency by solving

$$P_1 = P_R + P_{WE1} + P_{SE1}$$

$$P_m = P_R + P_{WE1} \times (f_m/f_1)^2 + P_{SE1} \times (f_m/f_1)^{0,8}.$$

- e) The total service load losses shall be calculated for each valve winding as follows:

$$P = P_R + P_{WE1} \times \sum_{n=1}^{n=49} (I_n/I_N)^2 \times (f_n/f_1)^2 + P_{SE1} \times \sum_{n=1}^{n=49} (I_n/I_N)^2 \times (f_n/f_1)^{0,8}$$

where

P_1 represents the total load losses at fundamental frequency (50 Hz or 60 Hz);

I_N is the rated current;

I_n is the RMS current at harmonic n ;

P_R represents the ohmic losses at rated current;

P_{SE1} represents the stray losses in structural parts (excluding windings) at fundamental frequency;

P_{WE1} represents the eddy losses in windings at fundamental frequency;

P_m represents the total load losses at frequency m ;

n is the harmonic order.

- f) The operating losses are calculated as the sum of the no-load losses (see 5.2.2) and the total service load losses as defined in 5.2.3, e).

NOTE 1 — The formula for the total service load losses is valid for all harmonic numbers. However, the non-characteristic harmonics are small compared to the characteristic harmonics and should be neglected in the determination of the losses.

NOTE 2 — With the harmonic current spectrum specified in Clause A.1, the above method is valid for two-winding transformers or for three-winding transformers whose construction is such that the coupling between valve windings is negligible (for example where the line winding is split into two halves, one next to each valve winding). For other transformer

arrangements, a similar method may be used, with due care, but the harmonic current spectrum in the line windings may differ from that given in Clause A.1.

The calculation of harmonic currents and voltages in converter transformers is described in Clause A.1.

The measured values for P_R , P_{SE1} , and P_{WE1} are based on the reference temperature as given in IEC 60076-1. Values should be corrected to the operating temperature of the transformer.

5.2.4 Auxiliary power losses

The auxiliary power losses of the converter transformer shall be included in the auxiliary power energy consumption of the total converter station (see 5.8). They shall be measured ~~either separately during a factory test or during measurement of the converter station auxiliary power consumption~~ separately during factory test.

5.3 AC filter losses

5.3.1 General

The AC filters in an HVDC converter station provide a low-impedance shunt for the harmonic currents generated by the converter. The AC filters may comprise active filters, passive filters or a combination thereof.

The methods described in 5.3.2 to 5.3.5 assume that the AC filters are connected directly to the AC system busbar on the line side of the converter transformer. Where this is not the case, as for instance with filters connected to a tertiary winding of the converter transformer, the method is still valid but the harmonic currents in the filters shall be adjusted as required by the AC filter connection point.

For purposes of loss determination, the converter shall be modelled as a generator of harmonic currents and the AC system shall be assumed to be open-circuited so that all harmonic currents from the HVDC converters are considered to flow into the AC filters.

The harmonic current flowing in each filter branch shall be calculated from the total converter harmonic current and shall be used as a basis for determining the losses in each filter component. When active filters are used, the losses incurred by their presence shall be included and the calculation method documented by the supplier.

When the converter is operating, the determination of AC filter losses shall be based on the characteristic harmonic currents of the converter, which shall be calculated for each load level and with consistent operating parameters (see 4.3). For calculation of the converter harmonic currents, the first formula described in Clause A.2 shall be used.

In the no-load operation mode, AC filters are not usually connected to the AC system and, therefore, generate no losses. In the case where AC filters are energised while the converter is in no-load operation mode only, the fundamental frequency losses shall be considered.

For the calculation, it shall be assumed that the AC system operates at nominal frequency and the filter components are at their nominal values.

The calculation of harmonic currents and voltages in AC filters is described in Clause A.2.

5.3.2 AC filter capacitor losses

The fundamental frequency losses in the filter capacitors shall be determined in accordance with IEC 60871-1. The three-phase Mvar rating of the capacitor bank shall be calculated from

the capacitance value and the fundamental frequency voltage across the capacitor bank. The losses due to harmonic currents are very small and shall be neglected.

Losses in low voltage capacitors (for filters with 2 or more tuning frequencies) are very small and can be neglected.

5.3.3 AC filter reactor losses

The fundamental and harmonic currents in the filter reactors shall be considered. The impedance of the reactor at fundamental frequency and the quality factors at the fundamental and harmonic frequencies shall be measured at the factory and corrected to the ~~maximum~~ operating temperature of the winding. The reactor losses shall then be determined by the following formula:

$$P = \sum_{n=1}^{n=49} \frac{I_n^2 \times X_n}{Q_n}$$

where

n is the harmonic order;

I_n is the calculated RMS current through the reactor at the n^{th} harmonic, in amperes;

X_n is the reactor reactance at the n^{th} harmonic, $X_n = n \times 2\pi f \times L$, in ohms;

L is the reactor inductance, in henrys;

f is the AC system fundamental frequency;

Q_n is the average quality factor for all reactors of the same item measured at the n^{th} harmonic.

5.3.4 AC filter resistor losses

The losses in the filter resistors shall be calculated for the fundamental and harmonic currents together. The resistance value of the resistor shall be determined by factory measurements and corrected to the operating temperature of the resistor. The current of each harmonic through the filter resistor shall be calculated. The losses in each resistor are obtained by the following formula:

$$P = R \times \sum_{n=1}^{n=49} I_n^2$$

where

R is the resistor value, in ohms;

I_n is the RMS value of the n^{th} harmonic current through the resistor, in amperes.

5.3.5 Total AC filter losses

The total AC filter losses shall be obtained by summing the losses of all capacitors, reactors, and resistors for filters which are energised at the corresponding load level of the converters.

5.4 Shunt capacitor bank losses

Shunt capacitors are sometimes used in addition to harmonic filters to provide reactive support to the AC system. Power losses in shunt capacitor banks shall be determined for those load levels of the converter station at which such banks are connected to the AC bus.

The fundamental frequency losses in the shunt capacitor bank shall be determined in accordance with IEC 60871-1. The three-phase Mvar rating of the capacitor bank shall be

calculated from the capacitance value and the fundamental frequency voltage across the capacitor bank. The losses due to harmonic currents are very small and shall be neglected.

5.5 Shunt reactor losses

Shunt reactors may be connected to the AC bus of an HVDC converter station to compensate for capacitive currents from AC harmonic filters, particularly at light load. Their duty does not differ from conventional applications in AC transmission systems. Therefore, losses of shunt reactors in HVDC converter stations shall be measured during factory tests in accordance with ~~IEC 60289~~ IEC 60076-6 and corrected to the maximum winding temperature, excluding hot spots, calculated for the standard ambient conditions (see 4.3). For oil-insulated reactors, the standard winding temperature of 75 °C shall be used.

Shunt reactor losses shall be included in the total converter station losses for those load levels at which it is intended that shunt reactors will be connected to the AC bus.

If forced cooling is used, the cooling equipment power consumption shall be included in the auxiliary power consumption of the total converter station (see 5.8).

5.6 DC smoothing reactor losses

The current through the smoothing reactor is direct current with superimposed harmonics.

The DC side harmonic currents through the smoothing reactor are calculated by representing the converter with a voltage source with harmonic voltages in accordance with Clause A.3 (see Clause A.4).

During no-load operation conditions, the smoothing reactor current is zero. Therefore, losses do not occur.

The DC component of the smoothing reactor losses shall be established from factory tests according to ~~IEC 60289~~ IEC 60076-6 and IEC 60076-1.

The winding losses due to harmonic currents shall be determined by calculation. The calculation shall use the harmonic current amplitudes applicable to the appropriate load level and the corresponding harmonic resistance. The harmonic currents shall be calculated in accordance with Clause A.4. The harmonic resistance shall be measured.

If a tanked construction with an iron core is used, the magnetization losses shall be calculated as:

$$P_m = (0,125 \times k_h + 0,125 \times k_e) \times P_d$$

where

P_m represents the magnetization losses, in watts;

P_d represents the direct current losses, in watts;

$k_h = \sum_{n=12}^{n=48} k_{hn}$ is the hysteresis losses component;

$k_e = \sum_{n=12}^{n=48} k_{en}$ is the eddy current losses component;

$k_{hn} = (I_n/I_d) \times n$;

$k_{en} = (I_n/I_d)^2 \times n^{0,5}$.

The total operating losses shall be the sum of losses due to direct current, losses due to harmonic currents and, where applicable, core magnetizing losses.

Auxiliary power losses of the smoothing reactor shall be included, where applicable, in the auxiliary power consumption of the total converter station (see 5.8). ~~They may be measured separately during factory tests or during measurements of the converter station auxiliary power consumption.~~ They shall be measured separately during the factory test.

5.7 DC filter losses

5.7.1 General

The principal function of the DC filters, in conjunction with the DC smoothing reactor, is to provide a low-impedance shunt for the harmonic currents generated by the converter, thus reducing the level of harmonic currents on the DC line and preventing noise generation in adjacent open-wire communication systems. The DC filter may be configured either as a single branch or as several filter branches, depending on system requirements. The DC filters may comprise active filters, passive filters or a combination thereof.

DC filters are connected between the high- and low-voltage terminals of the converter. Under no-load operation conditions, the DC filter current and voltage are both zero; therefore, losses do not occur.

When the converter is operating, the DC filter losses shall be determined for normal operating parameters, at the appropriate load level, using factory loss measurements and calculated harmonic currents. The harmonic currents through the filters shall be calculated by representing the converter as a voltage source and an impedance. For calculation of the converter harmonic voltages, the formulae according to Clause A.3 shall be used. The smoothing reactors and the DC line/cable shall be represented with their actual impedances. For the calculation, it shall be assumed that the AC system operates at nominal frequency and the filter components are at their nominal values. When active filters are used, the losses incurred by their presence shall be included and the calculation method documented by the supplier.

The calculations of harmonic voltages on the DC side is described in Clause A.3.

5.7.2 DC filter capacitor losses

Losses in the DC filter capacitors comprise losses in the DC grading resistors and harmonic losses in the capacitors. Losses due to the harmonic current in the capacitor bank are very small because of the low power factor and shall be neglected.

The losses in the grading resistors shall be calculated by using the total resistance of the capacitor bank as determined from the mean value of all grading resistors per capacitor unit obtained from production tests, and the capacitor bank configuration, using

$$P = \frac{U^2}{R}$$

where

U is the operating capacitor bank DC voltage, in volts;

R is the total bank resistance, in ohms.

5.7.3 DC filter reactor losses

The reactor losses shall be determined by calculating the harmonic currents in the reactor for the appropriate load level and corresponding operating parameters (see 4.3) and by

measuring the reactor reactance and quality factor at the harmonic frequencies during factory tests, and corrected to the ~~maximum~~ operating temperature of the winding. The reactor losses are given by the formula

$$P = \sum_{n=12}^{n=48} \frac{I_n^2 \times X_n}{Q_n}$$

where

n is the harmonic order;

I_n is the calculated RMS current through the reactor at the n^{th} harmonic, in amperes;

X_n is the reactor reactance at the n^{th} harmonic, in ohms;

Q_n is the quality factor measured at the n^{th} harmonic.

5.7.4 DC filter resistor losses

The resistor losses shall be calculated considering all harmonic currents together. The resistance value of the resistor R shall be determined by factory measurements.

The RMS value of the current of each harmonic through the resistor shall be calculated for the appropriate load level of the converter station and corresponding operating parameters (see 4.3). The losses in each resistor are obtained by the formula

$$P_R = R \times \sum_{n=12}^{n=48} I_n^2$$

where

R is the resistance value, in ohms;

I_n is the calculated RMS current through the resistor at the n^{th} harmonic, in amperes.

5.7.5 Total DC filter losses

The total DC filter losses shall be obtained by summing the losses of all capacitors, reactors, resistors and active devices, where applicable, that make up the DC filters.

5.8 Auxiliaries and station service losses

The auxiliary power consumed by the HVDC converter station depends on station service facilities, operating requirements and ambient conditions. Moreover, it is subject to variation with time as intermittent loads such as heating, cooling, lighting and maintenance equipment are utilized. The purchaser shall define the extent of the auxiliary services to be included in the loss evaluation **if losses other than station essential auxiliary loads are required to be considered.**

The total station auxiliary losses shall be determined **on an averaged basis** for no-load operation mode and for the appropriate load level(s) of the station. The losses shall be determined ~~under~~ **for** normal steady-state operating conditions by **calculation or direct measurements** on the main feeder(s) at each source.

NOTE Purpose is to determine the average loss during normal operation but not to determine the maximum losses.

Station service auxiliaries used only under special circumstances, for example during maintenance outages, short-time overload or transient disturbances, shall not be considered in the evaluation of auxiliary losses.

If auxiliaries and station service losses are determined by measurement, the following procedures shall be considered.

To account for load variations with time due, for example, to intermittent operation of cooling pumps or fans or to heating and lighting loads which are required only at certain times of the day, a series of measurements shall be taken over a defined time interval and the results averaged.

If it is not practical to perform the measurement on auxiliary power consumption at a constant ambient temperature of 20 °C, an appropriate adjustment shall be made to those loads (such as cooling equipment) which are sensitive to the ambient temperature. The calculation shall be documented.

In cases where the feeder(s) for the auxiliary systems also supply equipment which is not within the responsibility of the supplier, or not part of guaranteed losses, the load(s) of this equipment shall be measured separately and subtracted from the overall loss measurement for contractual purposes.

If the design of the auxiliary system is such that the total auxiliary power consumption cannot practically be determined by direct measurement, then an alternative calculation procedure may be agreed between purchaser and supplier. In this case, the calculation procedure shall be clearly documented.

5.9 Radio interference/PLC Series filter losses

In addition to the AC and DC harmonic filters normally required at an HVDC station, certain applications require further equipment to prevent radio interference (RI) or interference with power line carrier (PLC) systems. In other applications, series filters are used to prevent harmonic interaction with the interconnected AC systems or for other purposes.

Such equipment may consist of series reactors in the AC or DC connections (with or without tuning capacitors connected in parallel), shunt branches or a combination thereof.

Losses in shunt branches are small and shall be neglected.

For series filters, only the losses in the reactor shall be considered. The reactor losses shall be calculated in accordance with the following formulae:

$$P = \sum_{n=1}^{n=49} \frac{I_n^2 \times X_n}{Q_n}$$

for filters in the AC connections, or

~~$$P = I_d^2 \times R_{\text{PLC}} + \sum_{n=12}^{n=48} \frac{I_n^2 \times X_n}{Q_n}$$~~

$$P = I_d^2 \times R + \sum_{n=12}^{n=48} \frac{I_n^2 \times X_n}{Q_n}$$

for filters in the DC connections,

where

R_{PLC} is the DC resistance of the reactor, in ohms;

n is the harmonic order;

I_n is the calculated current through the reactor at the n^{th} harmonic, in amperes;

I_d is the direct current through reactor for operating condition, in amperes.

X_n is the reactor reactance at the n^{th} harmonic, in ohms;

Q_n is the quality factor measured at the n^{th} harmonic.

When AC series filters are located on the AC system side of the AC harmonic filters, only the fundamental frequency ($n = 1$) component of current shall be considered. Where AC series filters are located between the shunt AC harmonic filters and the converter transformers, or between the converter transformers and the valves, then both the fundamental frequency and characteristic harmonic (up to $n = 49$) components of current shall be considered.

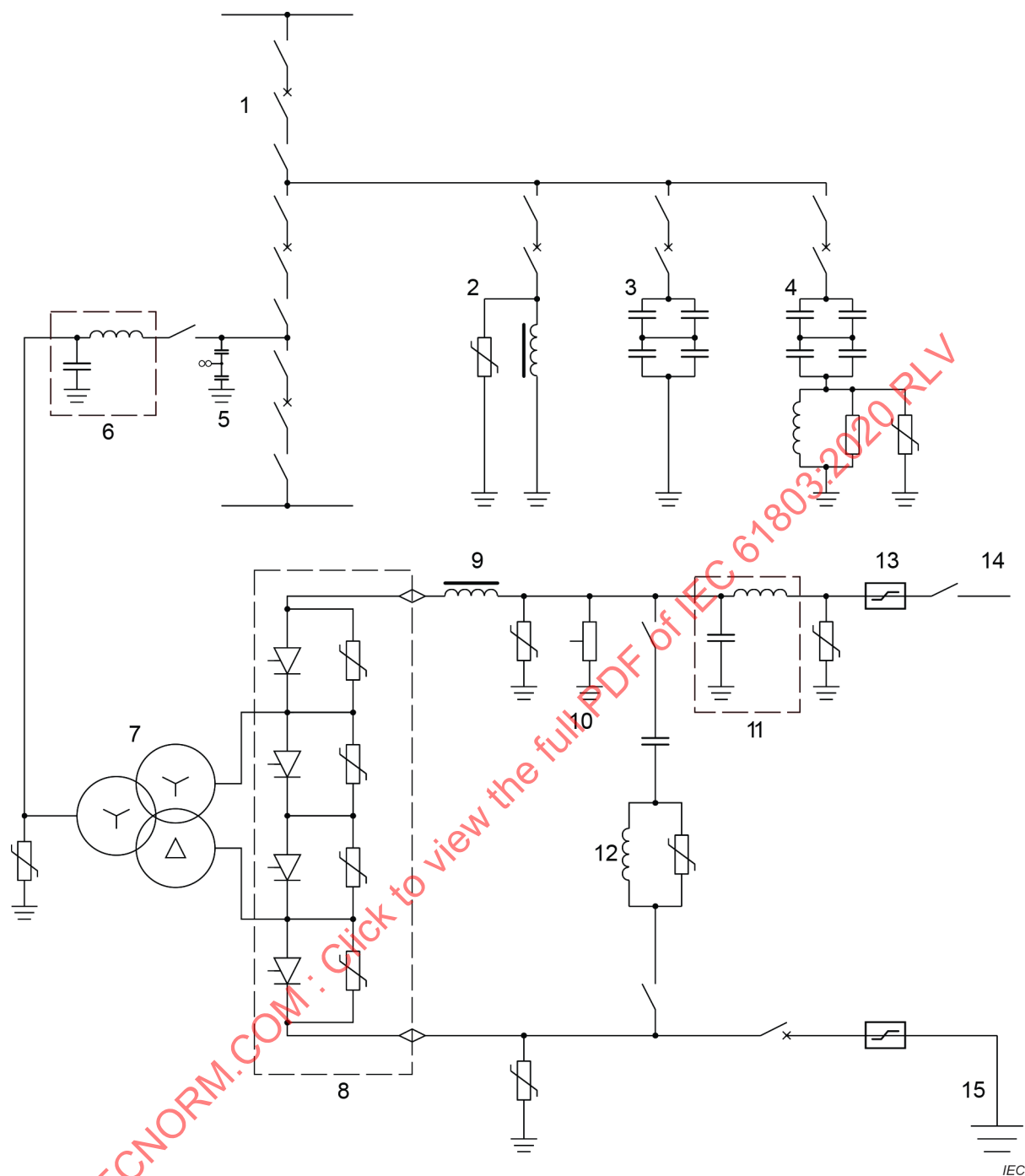
Harmonic currents shall be calculated in accordance with Clause A.1 and Clause A.2 or (for filters on the DC side) Clause A.4, as appropriate.

5.10 Other equipment losses

The losses caused by the remaining equipment, such as surge arresters, instrument transformers, switchgear, etc., shall be neglected. They are negligible in comparison with the main equipment losses discussed in 5.1 through 5.9, and neglecting them will not significantly affect the total converter station losses.

The losses of special equipment in a particular converter station, which are not included in the typical converter station considered in this document, shall be determined for each of the operating conditions of interest. The determination shall be based on the characteristics of the special equipment and sound engineering practice.

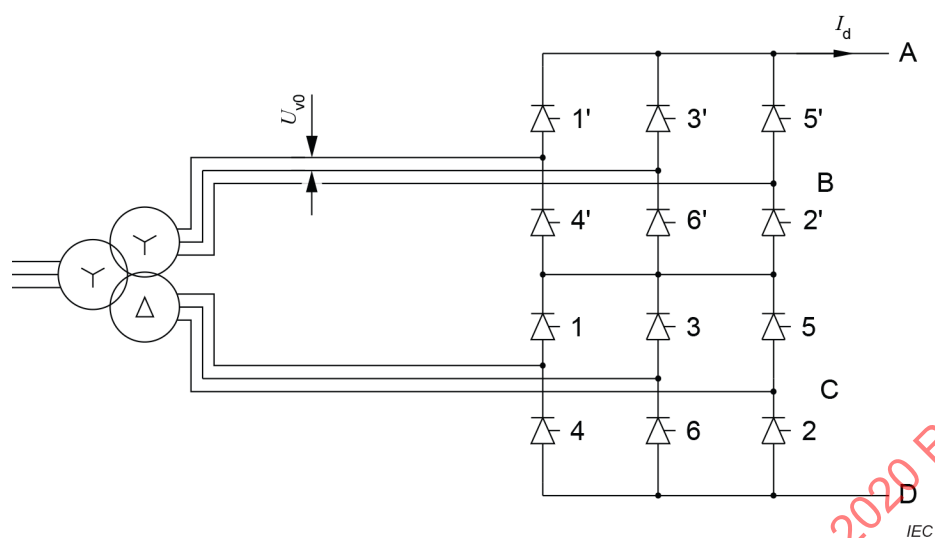
Typical values of losses in a HVDC substation are given in Annex B, and an illustration of a HVDC converter station loss evaluation is given in Annex C.



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 | | |

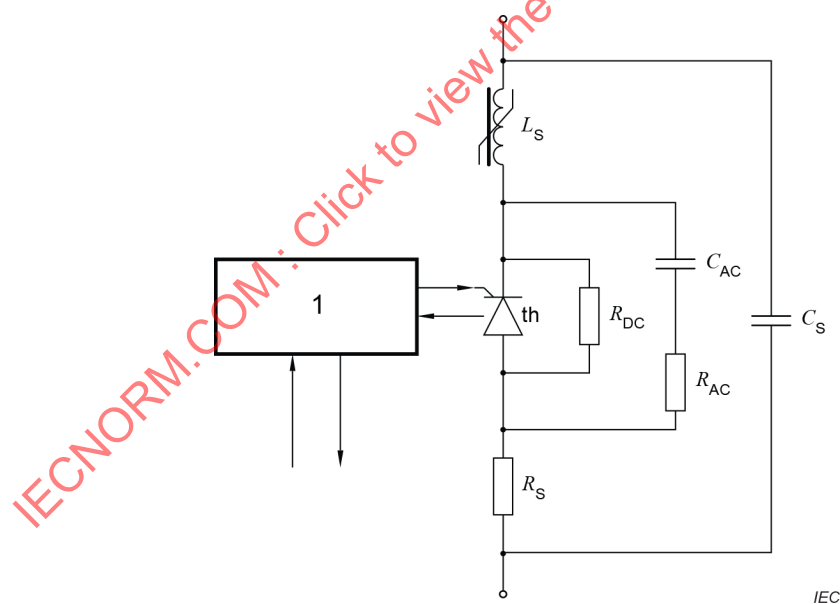
Figure 1 – Typical high-voltage direct current (HVDC) equipment for one pole (auxiliary equipment is not shown)

**Key**

A high-voltage DC terminal
B upper bridge

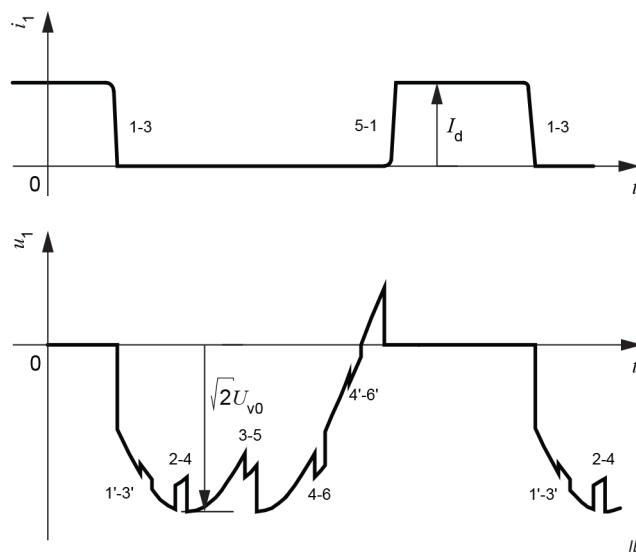
C lower bridge
D low voltage DC terminal

Figure 2 – Simplified three-phase diagram of an HVDC 12-pulse converter



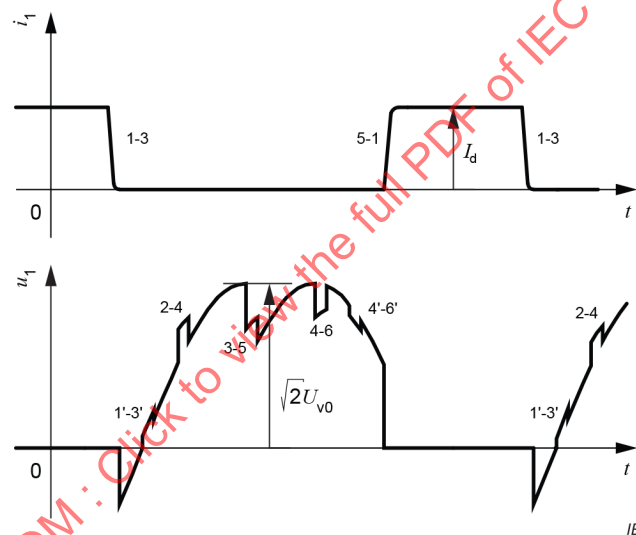
1 control and monitoring

Figure 3 – Simplified equivalent circuit of a typical thyristor valve



$$\alpha = 20^\circ \quad \mu = 10^\circ$$

a) – Rectifier operation



$$\gamma = 20^\circ \quad \mu = 10^\circ$$

b) – Inverter operation

NOTE Commutation overshoots are not shown.

Figure 4 – Current and voltage waveforms of a valve operating in a 12-pulse converter (commutation overshoots are not shown)

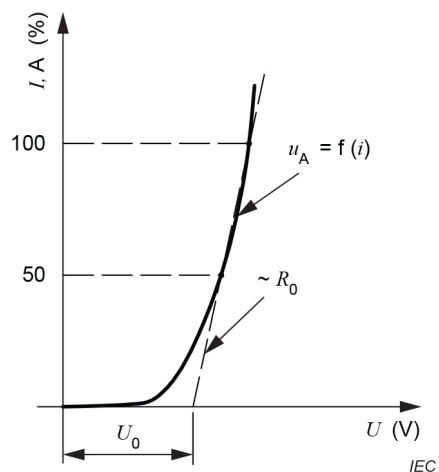
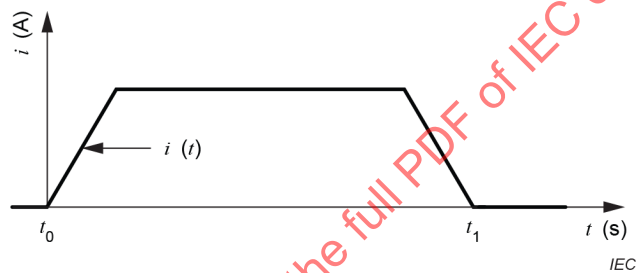
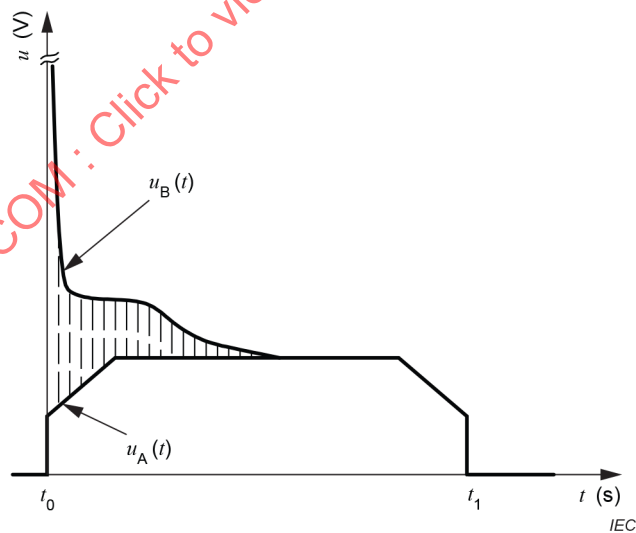


Figure 5 – Thyristor on-state characteristic



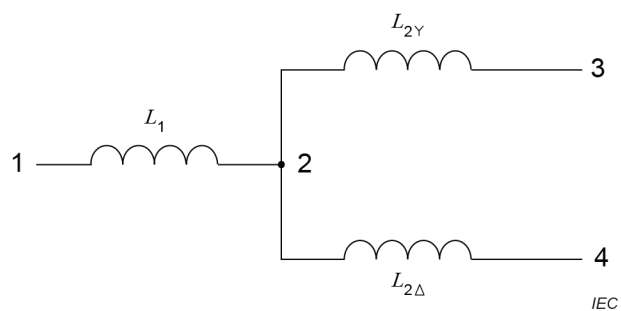
a) – Conduction current



b) – Voltage drop across an ideal thyristor A or a real thyristor B

In Figure 6 b), the ideal thyristor A is a thyristor with a conduction characteristic determined by U_0 and R_0 (as per Figure 5). The real thyristor B is a thyristor which displays the spreading effect.

Figure 6 – Conduction current and voltage drop



Key

- | | | | |
|---|--|---|---------------|
| 1 | from the source of the commutating voltage | 3 | to the valves |
| 2 | point of common coupling | 4 | to the valves |

Figure 7 – Distribution of commutating inductance between L_1 and L_2

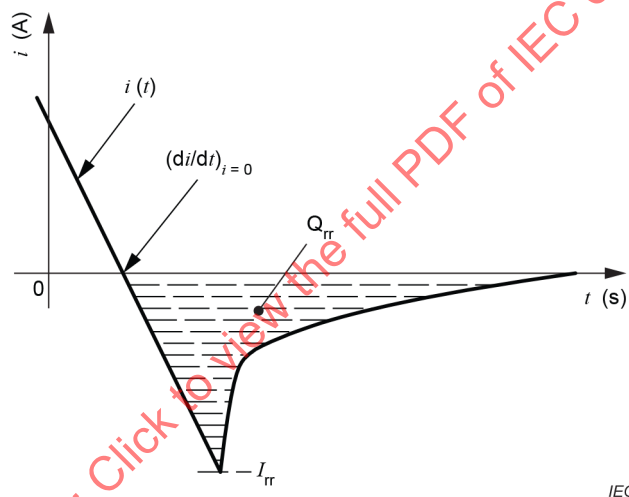


Figure 8 – Thyristor current during reverse recovery

Annex A

(~~normative~~ informative)

Calculation of harmonic currents and voltages

A.1 Harmonic currents in converter transformers

The RMS value of the six-pulse characteristic harmonic currents in each valve side terminal of the converter transformer is

$$I_n = \frac{\sqrt{6} \times I_d \times F_1}{\pi \times n}$$

where

n is the characteristic harmonic order, $n = k \times 6 \pm 1$, k being a positive integer in the range $1 \leq k \leq 8$;

$$F_1 = \frac{\left(k_1^2 + k_2^2 - 2k_1 \times k_2 \times \cos(2\alpha + \mu)\right)^{1/2}}{\cos\alpha - \cos(\alpha + \mu)}$$

where

$$k_1 = \frac{\sin\left((n-1) \times \frac{\mu}{2}\right)}{n-1};$$

$$k_2 = \frac{\sin\left((n+1) \times \frac{\mu}{2}\right)}{n+1}.$$

A.2 Harmonic currents in the AC filters

The RMS value of the 12-pulse characteristic harmonic currents on the line side of the converter transformer is

$$I_n = \frac{\sqrt{6} \times I_d \times F_1}{\pi \times n} \times \frac{U_v}{U_L} \times 2$$

where

n is the characteristic harmonic order, $n = k \times 12 \pm 1$, k being a positive integer in the range $1 \leq k \leq 4$;

U_v/U_L is the converter transformer voltage ratio, valve-side voltage divided by line-side voltage (including the actual tap position);

$$F_1 = \frac{\left(k_1^2 + k_2^2 - 2k_1 \times k_2 \times \cos(2\alpha + \mu)\right)^{1/2}}{\cos\alpha - \cos(\alpha + \mu)}$$

where

$$k_1 = \frac{\sin\left((n-1) \times \frac{\mu}{2}\right)}{n-1};$$

$$k_2 = \frac{\sin\left((n+1) \times \frac{\mu}{2}\right)}{n+1}.$$

A.3 Harmonic voltages on the DC side

The RMS value of the harmonic voltages from a 12-pulse bridge is

$$U_n = \frac{6\sqrt{2}}{\pi} \times U_{V0} \times F_2$$

where

n is the characteristic harmonic number, $n = k \times 12$, k being a positive integer in the range $1 \leq k \leq 4$;

$$F_2 = \frac{\left(k_3^2 + k_4^2 - 2k_3 \times k_4 \times \cos(2\alpha + \mu)\right)^{1/2}}{\sqrt{2}}$$

where

$$k_3 = \frac{\cos\left((n+1) \times \frac{\mu}{2}\right)}{n+1};$$

$$k_4 = \frac{\cos\left((n-1) \times \frac{\mu}{2}\right)}{n-1}.$$

If more than one 12-pulse converter is connected in series on the DC side, the harmonic voltage is U_n multiplied by the number of series-connected 12-pulse converters.

A.4 DC side harmonic currents in the smoothing reactor

The DC side harmonic currents through the smoothing reactor are calculated by representing the converter with a voltage source with harmonic voltages in accordance with Clause A.3. The converter impedance and the smoothing reactor, the DC filters and DC line/cable shall be represented by their actual impedances.

Annex B (informative)

Typical station losses

Typical values of losses are given in Table B.1 for information purposes.

Table B.1 – Typical values of losses

Item	Typical losses at nominal operating conditions %
Thyristor valves	~~25 — 45~~ 20 to 40
Converter transformers	40 to 55
AC filters	4 to 10
Shunt capacitors (if used)	0,5 to 3
Shunt reactors (if used)	2 to 5
Smoothing reactor	4 to 13
DC filters	0,1 to 1
Auxiliaries	3 to 10
Total	100

The total station no-load operation losses range from 10 % to 20 % of the total station operating losses at rated power under nominal operating conditions.

Annex C (informative)

HVDC converter station loss evaluation – An illustration

C.1 General

Annex C is included to provide an illustration only to describe the basic concept behind the loss evaluation of HVDC converter stations and is to be considered by readers as a guide only.

One of the purposes of HVDC converter station loss determination is to evaluate expected life time cost of associated electrical losses reasonably well; not the maximum losses at any time. This is also a mechanism to arrive at an optimum compromise between initial capital investment cost and life time operating cost associated with electrical losses. Actions which take very little time (for example, a few seconds when moving a tap changer) are basically irrelevant in this aspect of evaluating losses as the loss evaluation is to cover a very long period (such as 25 years). Similarly, events which last for a short duration should be disregarded for purpose of loss evaluation (e.g. maximum ambient temperature, instead of use of yearly average ambient temperature to be considered). Further, considering operating loss at full load only may not represent the losses corresponding to actual load curve of most HVDC systems. Hence, a realistic method is recommended to be considered by adopting suitable weighting factors to a few sets of load as per expected loading patterns of the particular HVDC transmission link over a long period.

Cost of losses CL is associated with average price per hour of electricity, the interest rate applicable and design life of the HVDC project. The following formula is an example:

$$CL = CE \times T \left\{ \frac{1 - (1 + R)^{-L}}{R} \right\}$$

where

CL is the cost of 1 kWh of losses (\$);

CE is the cost of 1 kWh of electric energy at the present value (\$);

T is the number of hours in a year that the HVDC equipment is expected to be in operation (hours);

R is the interest rate applicable to the investment in HVDC project (%/100);

L is the life expectancy of the HVDC project (years).

Cost of losses may vary for example from 1 000 \$/kW to 5 000 \$/kW depending upon country, utility, project or other considerations. Different loss evaluation rates (\$/kW) are also used many times for no-load/standby losses and load/operating losses depending upon the evaluation (e.g. cost of lost opportunity of transmitting equivalent energy) perceived by the owner/utility. This means that the owner/utility profits from this evaluation in addition to the cost of lost energy. It may be noted that where a higher rate of loss evaluation rate is specified, it will lead to a higher initial capital investment cost which may not be optimum considering project utilisation.

The loss evaluation (also called "loss capitalisation") figures should be adapted to the application of the particular project considering necessary weighting factors depending upon the utilisation of the scheme/project and its expected cost of losses to the owner/utility. For a HVDC transmission scheme, the average time can be divided into:

a) energised and in standby (no-load);

- b) transmitting on average different powers for different time;
- c) not energised.

In some cases, it is necessary to keep the system energised in standby mode even when not transmitting power so that power can be transmitted without any delay and thus a concept of no-load and load loss is considered for loss evaluation (see case C and case D below).

In some other cases, it is not necessary to keep the system energised in standby mode when not transmitting power. In such a case, the concept of operating loss is to be considered for loss evaluation (see case A, case B and case C below).

Some typical scenarios are considered below:

- | | |
|--------|---|
| Case A | A 3 000 MW HVDC project is expected to be transmitting basically 100 % rated power 100 % of the time. |
| Case B | A 3 000 MW HVDC project is expected to be transmitting basically 100 % rated power for 9 months while not in operation for 3 months at all in a year. |
| Case C | A 3 000 MW HVDC project is expected to be transmitting basically 100 % rated power for 9 months on average while in remaining 3 months it has to be kept in standby mode so that power transmission can be started immediately whenever required. |
| Case D | <p>A 3 000 MW HVDC project is expected to be basically energised all the time and transmitting the following powers for the following periods</p> <p>0 % (0 MW) power but in standby – 10 % of the time</p> <p>10 % (300 MW) power – 10 % of the time</p> <p>50 % (1 500 MW) power – 60 % of the time</p> <p>100 % (3 000 MW) power – 20 % of the time</p> |

NOTE Above is just to illustrate a method of loss evaluation while the number of loading points to be selected will vary as per specific project requirement.

C.2 Loss evaluation under various cases

A typical loss evaluation rate of 3 000 \$/kW for total station no-load operation losses and 2 000 \$/kW for total station operating losses is considered in the following examples.

Case A:

In such a case, concept of operating loss is recommended to be adopted. If total station operating losses of whole station loss at rated power (3 000 MW) load are d kW, then loss evaluation would be $d \times 2\,000$ \$.

Case B:

In such a case, concept of operating loss is recommended to be adopted. If total station operating losses of whole station loss at rated power (3 000 MW) load are d kW, then loss evaluation would be $d \times 2\,000 \times (9/12)$ \$.

Case C:

In such a case, concepts of standby and operating loss are recommended to be adopted. If total station operating losses of whole station loss at rated power (3 000 MW) load are d kW and total station no-load operation losses are a kW, then loss evaluation would be $d \times 2\,000 \times (9/12) + a \times 3\,000 (3/12)$ \$.

Case D:

Some purchasers may use the approach to evaluate the total station no-load operation losses and the total station load losses separately (case D2 below), whereas others may evaluate only the total station operating losses (case D1 below).

Case D1:

It is assumed that standby losses (which are considered the same as total station no-load operation losses) is a kW, whereas total station operating losses at 10 %, 50 % and 100 % load are b kW, c kW and d kW respectively. It may be noted that losses a are calculated at different conditions, for example at a tap position which may be different than conditions for which losses b , or d are calculated. Losses in such case would be evaluated according to conditions shown in Table C.1.

Table C.1 – Conditions for calculation of losses in case D1

	Total station operating losses	Time factor
10 % load	b	0,10
50 % load	c	0,60
100 % load	d	0,20

Loss evaluation would be $\{(a \times 0,10) \times 3\,000\} + \{(b \times 0,10 + c \times 0,60 + d \times 0,20) \times 2\,000\}$ \$.

Case D2:

It is assumed that standby losses (which are considered the same as total station no-load operation losses) is a kW, whereas total station load losses at 10 %, 50 % and 100 % load are e kW, f kW and g kW respectively. It may be noted that losses a are calculated at different conditions, for example at a tap position which may be different than conditions for which losses e , f or g are calculated. Losses in such case would be evaluated according to conditions shown in Table C.2.

Table C.2 – Conditions for calculation of losses in case D2

	Total station load losses	Time factor
10 % load	$e = (b - a)$	0,10
50 % load	$f = (c - a)$	0,60
100 % load	$g = (d - a)$	0,20

The equivalent load losses can be calculated as $(e \times 0,10 + f \times 0,60 + g \times 0,20)$.

The loss evaluation would be $\{a \times 3\,000\} + \{(e \times 0,10 + f \times 0,60 + g \times 0,20) \times 2\,000\}$ \$.

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INTERNATIONAL STANDARD

NORME INTERNATIONALE

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

Détermination des pertes en puissance dans les postes de conversion en courant continu à haute tension (CCHT) munis de convertisseurs commutés par la ligne

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**DETERMINATION OF POWER LOSSES IN HIGH-VOLTAGE
DIRECT CURRENT (HVDC) CONVERTER STATIONS WITH
LINE-COMMUTATED CONVERTERS**

FOREWORD

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International Standard 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.

This second edition cancels and replaces the first edition published in 1999, Amendment 1:2010 and Amendment 2:2016. This edition constitutes a technical revision.

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

- a) 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, and therefore the production records of thyristors can be used for the power losses calculation;

- b) 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:

CDV	Report on voting
22F/563/CDV	22F/580A/RVC

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

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

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

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

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DETERMINATION OF POWER LOSSES IN HIGH-VOLTAGE DIRECT CURRENT (HVDC) CONVERTER STATIONS WITH LINE-COMMUTATED CONVERTERS

1 Scope

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

In some applications, synchronous compensators or static var compensators (SVC) may be 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. 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 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 60871-1, *Shunt capacitors for a.c. power systems having a rated voltage above 1 000 V – Part 1: General*

3 Terms, definitions and symbols

For the purposes of this document, the terms and definition given in IEC 60633 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

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

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 transformer and the number of AC filters and shunt reactive elements 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 will affect the conversion capability of the HVDC converter station (e.g. valve cooling), as well as load that shall remain working in case of complete loss of AC power supply (e.g. battery chargers, operating mechanisms)

3.2 Symbols

α	(trigger/firing) delay angle, in radians (rad)
μ	overlap angle, in radians (rad)
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)
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, and 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	harmonic order
N_t	number of series-connected thyristors per valve
P	power loss in an item of equipment, in watts (W)
Q_n	quality factor 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)
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)
X_n	inductive reactance at harmonic order n , in ohms (Ω)

4 Overview

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 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 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. However, the AC source shall also provide 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 document 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.

The calculation of harmonic currents and voltages in HVDC equipment is described in Annex A.

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 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. Corresponding valve hall temperature may 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.

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 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 and 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, 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 reactive power. 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.

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.

5 Determination of equipment losses

5.1 Thyristor valve losses

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 2. Individual valves are marked in the order of their conduction sequence.

A simplified equivalent circuit of a typical valve is shown in Figure 3. Symbol "th" combines together 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.

Figure 4 shows, as an example, current and voltage waveforms of valve 1 (according to Figure 2) operating in rectifier – Figure 4 a) – and inverter – Figure 4 b) – modes. In the example shown, the firing instants of the valves of the upper bridge are delayed by 30° with respect to the valves of the lower bridge due to the phase shift between the two secondaries. For each valve, the length of the conduction intervals is $130^\circ (2\pi/3 + \mu)$. During commutations, the valve current is assumed, for this document, to be changing linearly whereas in reality the valve currents follow portions of sine waves. This simplification has negligible effect on the resulting losses, while the trapezoidal waveform significantly simplifies the calculations. The voltage blocked by the valve shows notches caused by commutations between individual valves.

5.1.2 Thyristor conduction loss per valve

A typical thyristor on-state characteristic is shown in Figure 5. Thyristor conduction loss component is the product of the conduction current $i(t)$ – Figure 6 a) – and the corresponding ideal on-state voltage as shown in Figure 5. Formula P_{V1a} shall be used provided that the DC bridge current is well smoothed. In the event that the root sum square value of the DC side harmonic currents, determined in accordance with Clause A.4, exceeds 5 % of the DC component, formula P_{V1b} shall be used instead.

$$P_{V1a} = \frac{N_t \times I_d}{3} \left[U_0 + R_0 \times I_d \times \left(\frac{2\pi - \mu}{2\pi} \right) \right]$$

$$P_{V1b} = \frac{N_t \times I_d \times U_0}{3} + \frac{N_t \times R_0}{3} \left(I_d^2 + \sum_{n=12}^{n=48} I_n^2 \right) \left(\frac{2\pi - \mu}{2\pi} \right)$$

where

U_0 is the current-independent component of the on-state voltage of the average thyristor (see note below), in volts;

R_0 is the slope resistance of the on-state characteristic of the average thyristor (see note below), in ohms;

I_n is the calculated RMS value of the n^{th} harmonic current in the bridge DC connection according to Clause A.4, in amperes.

NOTE U_0 and R_0 (see Figure 5) are determined from the fully spread on-state voltage measured at the appropriate current and junction temperature. The average value of U_0 and R_0 is obtained from production records of the thyristors. The temperature dependence of U_0 and R_0 is established from type tests or routine tests on a statistically significant number of the thyristors employed, and is used, where necessary, to correct U_0 and R_0 to the appropriate service junction temperature. If parallel connection of p thyristors is employed, the appropriate 100 % current is the nominal DC bridge current divided by p . The calculated result is then multiplied by p .

5.1.3 Thyristor spreading loss per valve

This loss component is an additional conduction loss of the thyristors arising from the delay in establishing full conduction of the silicon after the thyristor has been turned on. The additional loss is the product of the current and the voltage by which the thyristor voltage exceeds the ideal thyristor on-state voltage drop – see the hatched area in Figure 6 b).

$$R_{V2} = N_t \times f \times \int_0^{t_1} [u_B(t) - u_A(t)] \times i(t) dt$$

where

t_1 is the length of the conduction interval, in seconds, which is given by:

$$t_1 = \frac{\frac{2}{3} \pi + \mu}{2\pi f};$$

$u_B(t)$ is the instantaneous on-state voltage, in volts, of a thyristor whose fully spread on-state voltage is typical for the thyristors used; the instantaneous on-state voltage shall be determined for the appropriate junction temperature measured with a trapezoidal current pulse exhibiting the correct amplitude and commutation overlap periods (see Figure 5 and Figure 6);

$u_A(t)$ is the calculated instantaneous on-state voltage of the average thyristor at the same junction temperature for the same current pulse but with the conducting area fully established throughout the conduction, as derived from its on-state characteristic represented by U_0 and R_0 only (see Figure 6);

$i(t)$ is the instantaneous current in the thyristor, in amperes.

Instantaneous on-state voltage data, including the effects of spreading, are usually not available from production records. Measurements of typical thyristor on-state voltage, including spreading, should therefore be obtained during the valve periodic firing and extinction type test (IEC 60700-1:2015, Clause 9) or, alternatively, from a separate laboratory test on a statistically significant number of thyristors.

5.1.4 Other conduction losses per valve

These are the conduction losses in the main circuit of the valve due to components other than the thyristors.

$$R_{V3} = \frac{R_s \cdot I_d^2}{3} \left(\frac{2\pi - \mu}{2\pi} \right)$$

where

R_s is the DC resistance of the valve terminal-to-terminal circuit excluding the thyristors, in ohms (see Figure 3).

The value of R_s is determined by direct measurement on a representative valve section that includes all elements of the main circuit of a valve in the correct proportions, but in which the thyristors have been replaced by copper blocks of the appropriate dimensions and with contacts treated in the same way as for real thyristors. Alternatively, the resistance may be calculated, in which case the calculation methods shall be documented.

5.1.5 DC voltage-dependent loss per valve

This loss component is the loss in the shunt resistance R_{DC} of the valve (see Figure 3), arising from the voltage which appears between valve terminals during the non-conducting interval (see Figure 4). It includes losses due to thyristor off-state and reverse leakage, losses in DC grading resistors, other resistive circuits and elements connected in parallel with the thyristors, resistance of the coolant in coolant pipes, resistivity effects of the structure, fibre optics, etc.

$$P_{V4} = \frac{U_{V0}^2}{2\pi R_{DC}} \left\{ \frac{4}{3}\pi + \frac{\sqrt{3}}{4} [\cos(2\alpha) + \cos(2\alpha + 2\mu)] + \frac{6m^2 - 12m - 7}{8} [\sin(2\alpha) - \sin(2\alpha + 2\mu) + 2\mu] \right\}$$

where

R_{DC} is the effective off-state DC resistance of a complete valve determined by measuring the current drawn during the valve terminal-to-terminal DC voltage type test (according to IEC 60700-1:2015, 8.3.1) in ohms; if a type test is not performed on the thyristor valve, R_{DC} shall be determined by reference to a previous type test (see also the paragraph after Note 1 below);

$m = L_1 / (L_1 + L_2)$;

L_1 is the inductance, in henrys, 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 (see Figure 7);

L_2 is the inductance, in henrys, referred to the valve winding, between the point of common coupling between star- and delta-connected windings, and the valve; L_2 shall include the saturated inductance of the valve reactors (see Figure 7).

The value of L_2 shall be the same for both secondaries ($L_{2\Delta} = L_{2Y}$) (see Note 2 and last paragraph below).

NOTE 1 The formula for P_{V4} is valid for $\mu \leq \pi/6$ (30°) only.

Since the thyristor resistive leakage current is usually much higher at operating temperatures than at the prevailing ambient air temperature, it is either necessary to heat the thyristors of the valve to the correct operating temperature before the measurement of R_{DC} is taken or to make later corrections to the measured value using the average thyristor data obtained separately, to include the mentioned temperature effect (see also 5.1.11). The same pertains to the liquid coolant.

NOTE 2 The value of m quantifies the effects of inductive coupling between the two secondaries of the converter transformer. It determines the magnitude of the notches caused by the commutation in the other bridge (notches from 1' to 3' and from 4' to 6' in Figure 4). If $m = 0$, then there is no coupling between the two bridges and the notches from 1' to 3' and from 4' to 6' disappear altogether. The notches in Figure 4 correspond to $m = 0,2$.

Values of L_1 and L_2 are obtained from the short-circuit impedance measurements on the converter transformers, and by adding any external inductances as required. The value of L_1 includes any external common inductance (such as power line carrier filters) between the point of common coupling and the commutation voltage source. In cases where no AC harmonic filters are connected, L_1 also includes the AC system impedance. When separate transformers supply the star and delta bridges and no additional line-side inductance is included, $L_1 = 0$, hence $m = 0$. When a three-winding transformer construction is employed, a common winding impedance and mutual coupling effects of the two secondary windings give non-zero values for L_1 , which may be either positive or negative. For more complicated transformer arrangements, such as filters connected to a tertiary winding, the values of L_1 and L_2 shall be determined with care.

5.1.6 Damping loss per valve (resistor-dependent term)

This loss component depends on the value of the resistive elements of those circuits that are AC coupled via series capacitors and on the voltage appearing between valve terminals during the non-conduction interval.

$$P_{V5} = 2\pi f^2 U_{V0}^2 C_{AC}^2 R_{AC} \left\{ \begin{aligned} &\left(\frac{4\pi}{3} - \frac{\sqrt{3}}{2} + \frac{3\sqrt{3}m^2}{8} + (6m^2 - 12m - 7) \frac{\mu}{4} + \left(\frac{7}{8} + \frac{9m}{4} - \frac{39m^2}{32} \right) \sin 2\alpha + \right. \\ &\left. \left(\frac{7}{8} + \frac{3m}{4} + \frac{3m^2}{32} \right) \sin(2\alpha + 2\mu) - \left(\frac{\sqrt{3}m}{16} + \frac{3\sqrt{3}m^2}{8} \right) \cos 2\alpha + \frac{\sqrt{3}m}{16} \cos(2\alpha + 2\mu) \right\} \end{aligned} \right.$$

where

C_{AC} is the effective terminal-to-terminal value of valve damping capacitance, in farads (see Figure 3);

R_{AC} is the effective terminal-to-terminal value of the associated series-connected damping resistance, in ohms (see Figure 3);

C_{AC} shall be the design value of damping capacitance per level divided by the number of thyristor levels in a valve;

R_{AC} shall be the design value of damping resistor per level multiplied by the number of thyristor levels in a valve.

If the valve employs more than one damping or grading network that incorporates series-connected R-C branches, then each branch shall be evaluated separately and the results summed.

If energy is extracted from the R-C grading network to energise the thyristor firing and/or monitoring circuits, then either it shall be demonstrated that the additional losses are negligible or the additional loss shall be calculated separately and added to the figure obtained from the formula P_{V5} .

NOTE Notes 1 and 2 and the last paragraph of 5.1.5 also apply to P_{V5} .

5.1.7 Damping loss per valve (change of capacitor energy term)

This loss component arises from the change in stored energy in the valve capacitances as a result of the step changes (ΔU) in the voltage blocked by the valve. Each step change incurs energy loss which equals $\frac{1}{2} C \times \Delta U^2$. The following formula is derived from the sum of the energies lost due to the 12 voltage jumps which take place during one cycle of blocking voltage (Figure 4) multiplied by the system frequency:

$$P_{V6} = \frac{U_{V0}^2 \times f \times C_{HF} \times (7 + 6m^2)}{4} \left[\sin^2(\alpha) + \sin^2(\alpha + \mu) \right]$$

where

C_{HF} is the sum of the effective terminal-to-terminal capacitance of all capacitive grading network branches within the valve (whether incorporating series resistors or not), plus the total effective stray capacitance between valve terminals arising from externally connected equipment and the vicinity of the valve to ground and/or adjacent objects (see Note 3 below); $C_{HF} = C_{AC} + C_S$ (see Figure 3).

NOTE 1 Notes 1 and 2 and the last paragraph of 5.1.5 also apply to P_{V6} .

NOTE 2 The formula for P_{V6} produces overly pessimistic results for commutation overlaps whose length is shorter than 3 time-constants of the R-C damping network.

NOTE 3 The external stray capacitance arises predominantly from the winding and bushings of the converter transformer (plus separate wall bushings if fitted), all of which can be measured at manufacture. Depending on the design, it is possible stray capacitance between the valve and the earth have to be included. Surge arresters, busbars and the valve structure contribute to the stray capacitance, but these contributions are small and are neglected. Since the effective stray capacitance is different for each row of valves, the average value is used for loss calculation.

5.1.8 Turn-off losses per valve

These are additional losses due to reverse current flow in the thyristors at turn-off (see Figure 8).

$$P_{V7} = Q_{rr} \times f \times \sqrt{2} \times U_{V0} \times \sin(\alpha + \mu + 2\pi \times f \times t_0)$$

where

Q_{rr} is the average value of thyristor stored charge, in coulombs;

t_0 is the time determined from the relationship

$$t_0 = \sqrt{\frac{Q_{rr}}{(di/dt)_{i=0}}}$$

where

$(di/dt)_{i=0}$ is the commutating di/dt measured at current zero, in amperes per second.

NOTE 1 The value of Q_{rr} used is the full integral of reverse current (see Figure 8), not an approximate triangulation such as that proposed in IEC 60747-6. Q_{rr} is determined from production measurements on a statistically significant number of thyristors or, alternatively, a mean value of Q_{rr} to be used if the thyristors are selected from a predefined Q_{rr} band, and, where necessary, is corrected to the junction temperature, $(di/dt)_{i=0}$ and reverse recovery voltage corresponding to the operating conditions for which the losses are being determined. It is important that the magnitude and the duration of the conduction current are large enough to achieve a full conduction of the thyristor junction.

NOTE 2 The most part of the thyristor turn-off losses resulting from this mechanism are dissipated within the thyristor itself, although part of the losses can be dissipated in other components such as the damping resistor and valve reactor.

5.1.9 Reactor loss per valve

Reactor loss consists of three components: resistive loss in the winding plus eddy current loss and hysteresis loss in the magnetic core. If an additional damping circuit is employed across the winding, it also incurs loss.

Reactor winding loss and the reactor core eddy current loss (and/or reactor damping resistor loss) are already accounted for in the formulae for P_{V3} and P_{V6} .

Hysteresis loss shall be calculated as follows. A DC magnetization curve for the core material(s) shall be determined for the loop of excitation that an HVDC valve reactor normally experiences. This curve shall be established from a magnetizing force arising from not less than 1,5 times the peak of the reverse current I_{rr} at turn-off (see Figure 8) in one polarity to well into the saturated region in the other, and back again. From the area enclosed by the loop, a characteristic hysteresis loss in joules per kilogram shall be determined and applied to the design of the reactor in question, i.e.

$$P_{V8} = n_L \times M \times k \times f$$

where

n_L is the number of reactor cores in a valve;

M is the mass of each core, in kilograms;

k is the characteristic loss, in joules/kilogram.

If the saturation current level for the reactor is high in relation to the rated bridge current, and normal commutation di/dt is also high (corresponding to small overlap angles at rated conditions), then additional reactor core eddy current losses will be generated during the commutation periods. If this is the case, it should be demonstrated that these additional losses are either negligible or else within the allowance made in the loss declaration.

5.1.10 Total valve losses

Total operating losses per valve are given by the sum of the eight individual components specified in 5.1.2 to 5.1.9.

$$P_{VT} = \sum_{i=1}^{i=8} P_{Vi}$$

The total operating converter losses are equal to the losses per valve multiplied by the number of valves in the converter.

5.1.11 Temperature effects

All valve components have electrical characteristics that are temperature sensitive. However, it is a common occurrence that the only component with temperature-sensitive characteristics that can substantially affect valve losses is the thyristor itself.

Thyristor junction temperature T_j is determined as

$$T_j = T_c + P_j \times R_{\theta JC}$$

where

T_c is the temperature of the coolant calculated as the mean of the valve inlet and valve outlet temperatures;

P_j is the total power loss per thyristor, calculated as the sum of its individual components due to conduction, spreading, blocking and turn-off;

$R_{\theta JC}$ is the thermal resistance from the thyristor junction to the coolant.

5.1.12 No-load operation loss per valve

The no-load operation loss per valve is the sum of losses caused by the currents which are driven by the voltage blocked by the valve through the resistances of the valve. It consists of two terms. The first quantifies the loss in the resistances which are connected in parallel with the blocking thyristors, the second determines the loss in the resistances which are capacitively coupled. In no-load operation mode, the valve blocks the sinusoidal waveform of the line to neutral voltage. Consequently:

$$P_{VSB} = \frac{U_{V0}^2}{3} \left(\frac{1}{R_{DC}} + \frac{R_{AC}}{Z_{AC}^2} \right)$$

where

$$Z_{AC} = \sqrt{R_{AC}^2 + \left(\frac{1}{2\pi \times f \times C_{AC}} \right)^2}$$

If the valve employs more than one grading network branch that incorporates series-connected R and C , then each branch shall be evaluated separately and the results summed.

If energy is extracted from the R-C grading network to energise the thyristor firing and/or monitoring circuits, then either it shall be demonstrated that the additional losses are negligible or the additional loss shall be calculated separately and added to the figure obtained from the formula P_{VSB} .

The total converter no-load operation losses are the no-load operation loss per valve multiplied by the number of valves in the converter.

5.2 Converter transformer losses

5.2.1 General

The current flowing through the windings of converter transformers contains harmonics whose magnitudes depend on the operating parameters of the converter station. The current-dependent load losses in the transformer due to the non-sinusoidal current waveshapes are greater than those that would occur with a sinusoidal current of the same RMS value at fundamental frequency.

5.2.2 No-load operation losses

In no-load operation mode, with the transformer energised and the valves blocked, the transformer losses are the no-load losses. The no-load losses (core losses) shall be determined according to IEC 60076-1.

The transformer tap-changer position shall be as defined in 4.3.

5.2.3 Operating losses

In the operating mode, the transformer operating losses shall be taken as the sum of the magnetizing losses (core losses) and the current-dependent (load) losses.

Under load-carrying conditions, harmonic voltages are imposed on the transformer. The core losses under load shall be considered equal to the no-load losses at the tap position corresponding to the load level considered, with nominal AC system voltage applied. The effect of the harmonic voltages on the magnetizing current of the transformer, relative to the effect of the fundamental frequency component of the voltage, is negligible.

The load losses of the transformer shall take into account both the fundamental frequency and the harmonic components of the current and shall be determined according to the following procedure.

- a) Measure the load losses P_1 at fundamental frequency f_1 (50 Hz or 60 Hz) according to IEC 60076-1.
- b) Calculate $P_{WE1} + P_{SE1} = P_1 - P_R$.

- c) Measure the load losses P_m at a higher frequency f_m equal to or greater than 150 Hz.

A voltage source used for induced voltage tests is normally available. An acceptable accuracy is reached for currents as low as 10 % to 20 % of the rated current provided that stray flux distribution among metallic parts has been taken care of in the transformer design. If a reduced current is used, and the current is less than 10 %, P_m shall be recalculated to rated current.

- d) Calculate P_{WE1} and P_{SE1} based on the measurements at fundamental frequency and the higher frequency by solving

$$P_1 = P_R + P_{WE1} + P_{SE1}$$

$$P_m = P_R + P_{WE1} \times (f_m/f_1)^2 + P_{SE1} \times (f_m/f_1)^{0,8}.$$

- e) The total service load losses shall be calculated for each valve winding as follows:

$$P = P_R + P_{WE1} \times \sum_{n=1}^{n=49} (I_n/I_N)^2 \times (f_n/f_1)^2 + P_{SE1} \times \sum_{n=1}^{n=49} (I_n/I_N)^2 \times (f_n/f_1)^{0,8}$$

where

P_1 represents the total load losses at fundamental frequency (50 Hz or 60 Hz);

I_N is the rated current;

I_n is the RMS current at harmonic n ;

P_R represents the ohmic losses at rated current;

P_{SE1} represents the stray losses in structural parts (excluding windings) at fundamental frequency;

P_{WE1} represents the eddy losses in windings at fundamental frequency;

P_m represents the total load losses at frequency m ;

n is the harmonic order.

- f) The operating losses are calculated as the sum of the no-load losses (see 5.2.2) and the total service load losses as defined in 5.2.3, e).

The formula for the total service load losses is valid for all harmonic numbers. However, the non-characteristic harmonics are small compared to the characteristic harmonics and should be neglected in the determination of the losses.

With the harmonic current spectrum specified in Clause A.1, the above method is valid for two-winding transformers or for three-winding transformers whose construction is such that the coupling between valve windings is negligible (for example where the line winding is split into two halves, one next to each valve winding). For other transformer arrangements, a similar method may be used, with due care, but the harmonic current spectrum in the line windings may differ from that given in Clause A.1.

The calculation of harmonic currents and voltages in converter transformers is described in Clause A.1.

The measured values for P_R , P_{SE1} , and P_{WE1} are based on the reference temperature as given in IEC 60076-1. Values should be corrected to the operating temperature of the transformer.

5.2.4 Auxiliary power losses

The auxiliary power losses of the converter transformer shall be included in the auxiliary power energy consumption of the total converter station (see 5.8). They shall be measured separately during factory test.

5.3 AC filter losses

5.3.1 General

The AC filters in an HVDC converter station provide a low-impedance shunt for the harmonic currents generated by the converter. The AC filters may comprise active filters, passive filters or a combination thereof.

The methods described in 5.3.2 to 5.3.5 assume that the AC filters are connected directly to the AC system busbar on the line side of the converter transformer. Where this is not the case, as for instance with filters connected to a tertiary winding of the converter transformer, the method is still valid but the harmonic currents in the filters shall be adjusted as required by the AC filter connection point.

For purposes of loss determination, the converter shall be modelled as a generator of harmonic currents and the AC system shall be assumed to be open-circuited so that all harmonic currents from the HVDC converters are considered to flow into the AC filters.

The harmonic current flowing in each filter branch shall be calculated from the total converter harmonic current and shall be used as a basis for determining the losses in each filter component. When active filters are used, the losses incurred by their presence shall be included and the calculation method documented by the supplier.

When the converter is operating, the determination of AC filter losses shall be based on the characteristic harmonic currents of the converter, which shall be calculated for each load level and with consistent operating parameters (see 4.3). For calculation of the converter harmonic currents, the first formula described in Clause A.2 shall be used.

In the no-load operation mode, AC filters are not usually connected to the AC system and, therefore, generate no losses. In the case where AC filters are energised while the converter is in no-load operation mode only, the fundamental frequency losses shall be considered.

For the calculation, it shall be assumed that the AC system operates at nominal frequency and the filter components are at their nominal values.

The calculation of harmonic currents and voltages in AC filters is described in Clause A.2.

5.3.2 AC filter capacitor losses

The fundamental frequency losses in the filter capacitors shall be determined in accordance with IEC 60871-1. The three-phase Mvar rating of the capacitor bank shall be calculated from the capacitance value and the fundamental frequency voltage across the capacitor bank. The losses due to harmonic currents are very small and shall be neglected.

Losses in low voltage capacitors (for filters with 2 or more tuning frequencies) are very small and can be neglected.

5.3.3 AC filter reactor losses

The fundamental and harmonic currents in the filter reactors shall be considered. The impedance of the reactor at fundamental frequency and the quality factors at the fundamental and harmonic frequencies shall be measured at the factory and corrected to the operating temperature of the winding. The reactor losses shall then be determined by the following formula:

$$P = \sum_{n=1}^{n=49} \frac{I_n^2 \times X_n}{Q_n}$$

where

n is the harmonic order;

I_n is the calculated RMS current through the reactor at the n^{th} harmonic, in amperes;

X_n is the reactor reactance at the n^{th} harmonic, $X_n = n \times 2\pi f \times L$, in ohms;

L is the reactor inductance, in henrys;

f is the AC system fundamental frequency;

Q_n is the average quality factor for all reactors of the same item measured at the n^{th} harmonic.

5.3.4 AC filter resistor losses

The losses in the filter resistors shall be calculated for the fundamental and harmonic currents together. The resistance value of the resistor shall be determined by factory measurements and corrected to the operating temperature of the resistor. The current of each harmonic through the filter resistor shall be calculated. The losses in each resistor are obtained by the following formula:

$$P = R \times \sum_{n=1}^{n=49} I_n^2$$

where

R is the resistor value, in ohms;

I_n is the RMS value of the n^{th} harmonic current through the resistor, in amperes.

5.3.5 Total AC filter losses

The total AC filter losses shall be obtained by summing the losses of all capacitors, reactors, and resistors for filters which are energised at the corresponding load level of the converters.

5.4 Shunt capacitor bank losses

Shunt capacitors are sometimes used in addition to harmonic filters to provide reactive support to the AC system. Power losses in shunt capacitor banks shall be determined for those load levels of the converter station at which such banks are connected to the AC bus.

The fundamental frequency losses in the shunt capacitor bank shall be determined in accordance with IEC 60871-1. The three-phase Mvar rating of the capacitor bank shall be calculated from the capacitance value and the fundamental frequency voltage across the capacitor bank. The losses due to harmonic currents are very small and shall be neglected.

5.5 Shunt reactor losses

Shunt reactors may be connected to the AC bus of an HVDC converter station to compensate for capacitive currents from AC harmonic filters, particularly at light load. Their duty does not differ from conventional applications in AC transmission systems. Therefore, losses of shunt reactors in HVDC converter stations shall be measured during factory tests in accordance with IEC 60076-6 and corrected to the maximum winding temperature, excluding hot spots, calculated for the standard ambient conditions (see 4.3). For oil-insulated reactors, the standard winding temperature of 75 °C shall be used.

Shunt reactor losses shall be included in the total converter station losses for those load levels at which it is intended that shunt reactors will be connected to the AC bus.

If forced cooling is used, the cooling equipment power consumption shall be included in the auxiliary power consumption of the total converter station (see 5.8).

5.6 DC smoothing reactor losses

The current through the smoothing reactor is direct current with superimposed harmonics.

The DC side harmonic currents through the smoothing reactor are calculated by representing the converter with a voltage source with harmonic voltages in accordance with Clause A.3 (see Clause A.4).

During no-load operation conditions, the smoothing reactor current is zero. Therefore, losses do not occur.

The DC component of the smoothing reactor losses shall be established from factory tests according to IEC 60076-6 and IEC 60076-1.

The winding losses due to harmonic currents shall be determined by calculation. The calculation shall use the harmonic current amplitudes applicable to the appropriate load level and the corresponding harmonic resistance. The harmonic currents shall be calculated in accordance with Clause A.4. The harmonic resistance shall be measured.

If a tanked construction with an iron core is used, the magnetization losses shall be calculated as:

$$P_m = (0,125 \times k_h + 0,125 \times k_e) \times P_d$$

where

P_m represents the magnetization losses, in watts;

P_d represents the direct current losses, in watts;

$k_h = \sum_{n=12}^{n=48} k_{hn}$ is the hysteresis losses component;

$k_e = \sum_{n=12}^{n=48} k_{en}$ is the eddy current losses component;

$k_{hn} = (I_n/I_d) \times n$;

$k_{en} = (I_n/I_d)^2 \times n^{0,5}$.

The total operating losses shall be the sum of losses due to direct current, losses due to harmonic currents and, where applicable, core magnetizing losses.

Auxiliary power losses of the smoothing reactor shall be included, where applicable, in the auxiliary power consumption of the total converter station (see 5.8). They shall be measured separately during the factory test.

5.7 DC filter losses

5.7.1 General

The principal function of the DC filters, in conjunction with the DC smoothing reactor, is to provide a low-impedance shunt for the harmonic currents generated by the converter, thus reducing the level of harmonic currents on the DC line and preventing noise generation in adjacent open-wire communication systems. The DC filter may be configured either as a single branch or as several filter branches, depending on system requirements. The DC filters may comprise active filters, passive filters or a combination thereof.

DC filters are connected between the high- and low-voltage terminals of the converter. Under no-load operation conditions, the DC filter current and voltage are both zero; therefore, losses do not occur.

When the converter is operating, the DC filter losses shall be determined for normal operating parameters, at the appropriate load level, using factory loss measurements and calculated harmonic currents. The harmonic currents through the filters shall be calculated by representing the converter as a voltage source and an impedance. For calculation of the converter harmonic voltages, the formulae according to Clause A.3 shall be used. The smoothing reactors and the DC line/cable shall be represented with their actual impedances. For the calculation, it shall be assumed that the AC system operates at nominal frequency and the filter components are at their nominal values. When active filters are used, the losses incurred by their presence shall be included and the calculation method documented by the supplier.

The calculations of harmonic voltages on the DC side is described in Clause A.3.

5.7.2 DC filter capacitor losses

Losses in the DC filter capacitors comprise losses in the DC grading resistors and harmonic losses in the capacitors. Losses due to the harmonic current in the capacitor bank are very small because of the low power factor and shall be neglected.

The losses in the grading resistors shall be calculated by using the total resistance of the capacitor bank as determined from the mean value of all grading resistors per capacitor unit obtained from production tests, and the capacitor bank configuration, using

$$P = \frac{U^2}{R}$$

where

U is the operating capacitor bank DC voltage, in volts;

R is the total bank resistance, in ohms.

5.7.3 DC filter reactor losses

The reactor losses shall be determined by calculating the harmonic currents in the reactor for the appropriate load level and corresponding operating parameters (see 4.3) and by measuring the reactor reactance and quality factor at the harmonic frequencies during factory tests, and corrected to the operating temperature of the winding. The reactor losses are given by the formula

$$P = \sum_{n=12}^{n=48} \frac{I_n^2 \times X_n}{Q_n}$$

where

n is the harmonic order;

I_n is the calculated RMS current through the reactor at the n^{th} harmonic, in amperes;

X_n is the reactor reactance at the n^{th} harmonic, in ohms;

Q_n is the quality factor measured at the n^{th} harmonic.

5.7.4 DC filter resistor losses

The resistor losses shall be calculated considering all harmonic currents together. The resistance value of the resistor R shall be determined by factory measurements.

The RMS value of the current of each harmonic through the resistor shall be calculated for the appropriate load level of the converter station and corresponding operating parameters (see 4.3). The losses in each resistor are obtained by the formula

$$P_R = R \times \sum_{n=12}^{n=48} I_n^2$$

where

R is the resistance value, in ohms;

I_n is the calculated RMS current through the resistor at the n^{th} harmonic, in amperes.

5.7.5 Total DC filter losses

The total DC filter losses shall be obtained by summing the losses of all capacitors, reactors, resistors and active devices, where applicable, that make up the DC filters.

5.8 Auxiliaries and station service losses

The auxiliary power consumed by the HVDC converter station depends on station service facilities, operating requirements and ambient conditions. Moreover, it is subject to variation with time as intermittent loads such as heating, cooling, lighting and maintenance equipment are utilized. The purchaser shall define the extent of the auxiliary services to be included in the loss evaluation if losses other than station essential auxiliary loads are required to be considered.

The total station auxiliary losses shall be determined on an averaged basis for no-load operation mode and for the appropriate load level(s) of the station. The losses shall be determined for normal steady-state operating conditions by calculation or direct measurements on the main feeder(s) at each source.

NOTE Purpose is to determine the average loss during normal operation but not to determine the maximum losses.

Station service auxiliaries used only under special circumstances, for example during maintenance outages, short-time overload or transient disturbances, shall not be considered in the evaluation of auxiliary losses.

If auxiliaries and station service losses are determined by measurement, the following procedures shall be considered.

To account for load variations with time due, for example, to intermittent operation of cooling pumps or fans or to heating and lighting loads which are required only at certain times of the day, a series of measurements shall be taken over a defined time interval and the results averaged.

If it is not practical to perform the measurement on auxiliary power consumption at a constant ambient temperature of 20 °C, an appropriate adjustment shall be made to those loads (such as cooling equipment) which are sensitive to the ambient temperature. The calculation shall be documented.

In cases where the feeder(s) for the auxiliary systems also supply equipment which is not within the responsibility of the supplier, or not part of guaranteed losses, the load(s) of this

equipment shall be measured separately and subtracted from the overall loss measurement for contractual purposes.

If the design of the auxiliary system is such that the total auxiliary power consumption cannot practically be determined by direct measurement, then an alternative calculation procedure may be agreed between purchaser and supplier. In this case, the calculation procedure shall be clearly documented.

5.9 Series filter losses

In addition to the AC and DC harmonic filters normally required at an HVDC station, certain applications require further equipment to prevent radio interference (RI) or interference with power line carrier (PLC) systems. In other applications, series filters are used to prevent harmonic interaction with the interconnected AC systems or for other purposes.

Such equipment may consist of series reactors in the AC or DC connections (with or without tuning capacitors connected in parallel), shunt branches or a combination thereof.

Losses in shunt branches are small and shall be neglected.

For series filters, only the losses in the reactor shall be considered. The reactor losses shall be calculated in accordance with the following formulae:

$$P = \sum_{n=1}^{n=49} \frac{I_n^2 \times X_n}{Q_n}$$

for filters in the AC connections, or

$$P = I_d^2 \times R + \sum_{n=12}^{n=48} \frac{I_n^2 \times X_n}{Q_n}$$

for filters in the DC connections,

where

R is the DC resistance of the reactor, in ohms;

n is the harmonic order;

I_n is the calculated current through the reactor at the n^{th} harmonic, in amperes;

I_d is the direct current through reactor for operating condition, in amperes.

X_n is the reactor reactance at the n^{th} harmonic, in ohms;

Q_n is the quality factor measured at the n^{th} harmonic.

When AC series filters are located on the AC system side of the AC harmonic filters, only the fundamental frequency ($n = 1$) component of current shall be considered. Where AC series filters are located between the shunt AC harmonic filters and the converter transformers, or between the converter transformers and the valves, then both the fundamental frequency and characteristic harmonic (up to $n = 49$) components of current shall be considered.

Harmonic currents shall be calculated in accordance with Clause A.1 and Clause A.2 or (for filters on the DC side) Clause A.4, as appropriate.

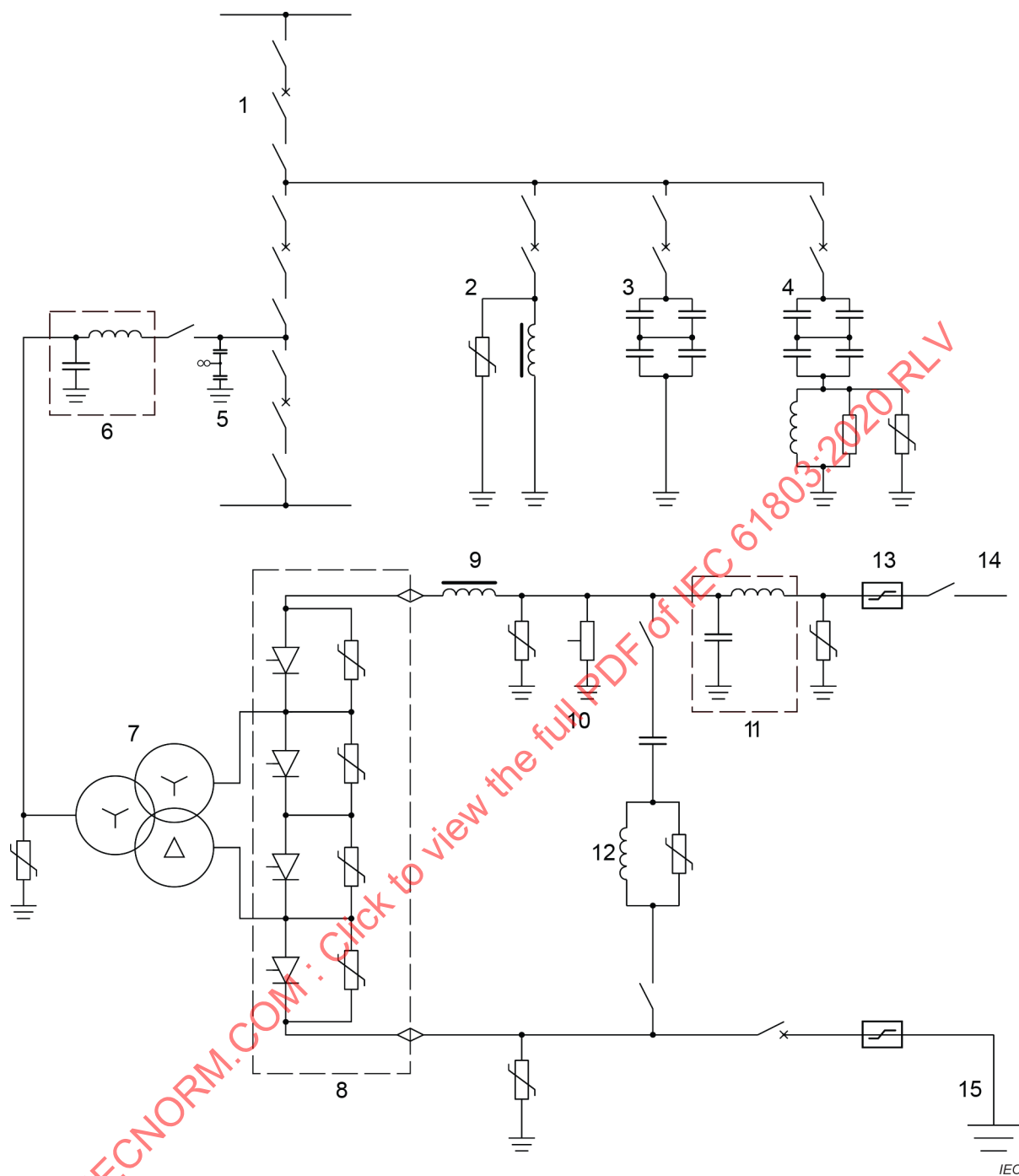
5.10 Other equipment losses

The losses caused by the remaining equipment, such as surge arresters, instrument transformers, switchgear, etc., shall be neglected. They are negligible in comparison with the main equipment losses discussed in 5.1 through 5.9, and neglecting them will not significantly affect the total converter station losses.

The losses of special equipment in a particular converter station, which are not included in the typical converter station considered in this document, shall be determined for each of the operating conditions of interest. The determination shall be based on the characteristics of the special equipment and sound engineering practice.

Typical values of losses in a HVDC substation are given in Annex B, and an illustration of a HVDC converter station loss evaluation is given in Annex C.

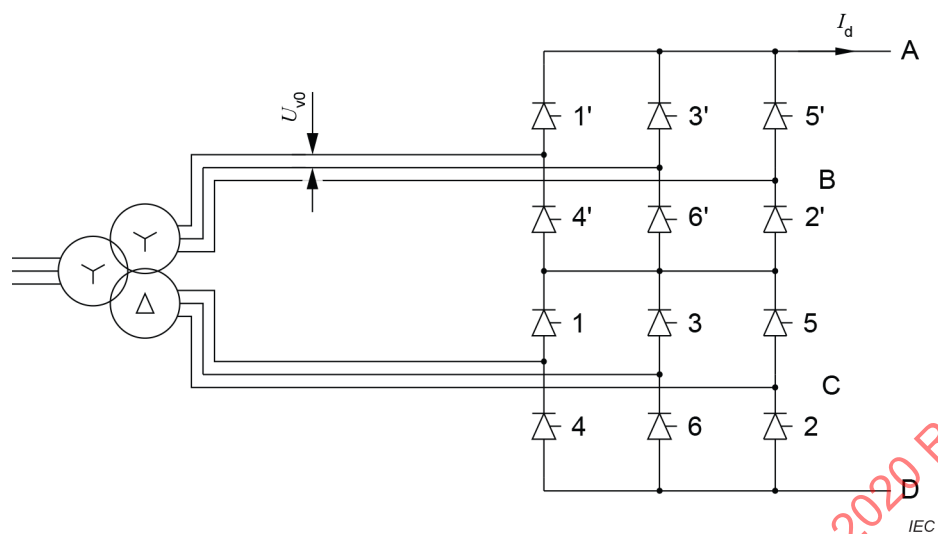
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Key

- | | | | |
|---|-------------------------------|----|-----------------------------|
| 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 | | |

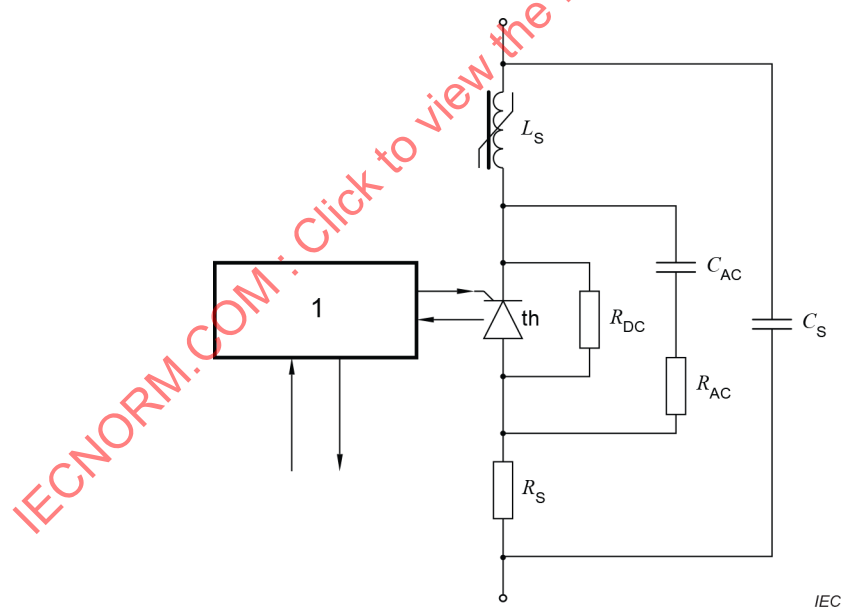
Figure 1 – Typical high-voltage direct current (HVDC) equipment for one pole

**Key**

A high-voltage DC terminal
B upper bridge

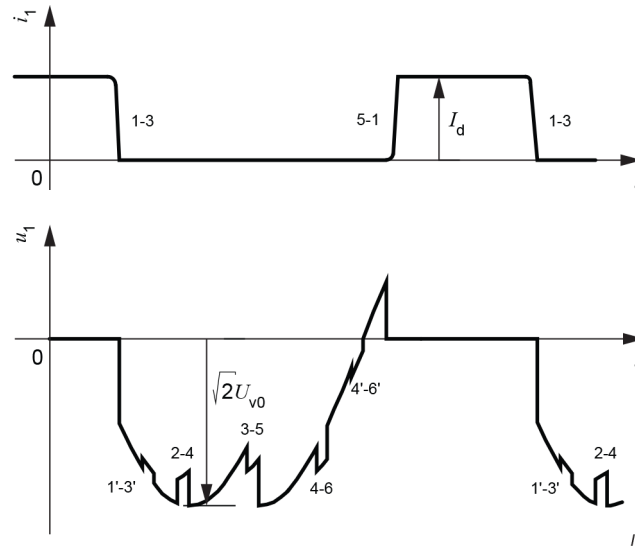
C lower bridge
D low voltage DC terminal

Figure 2 – Simplified three-phase diagram of an HVDC 12-pulse converter



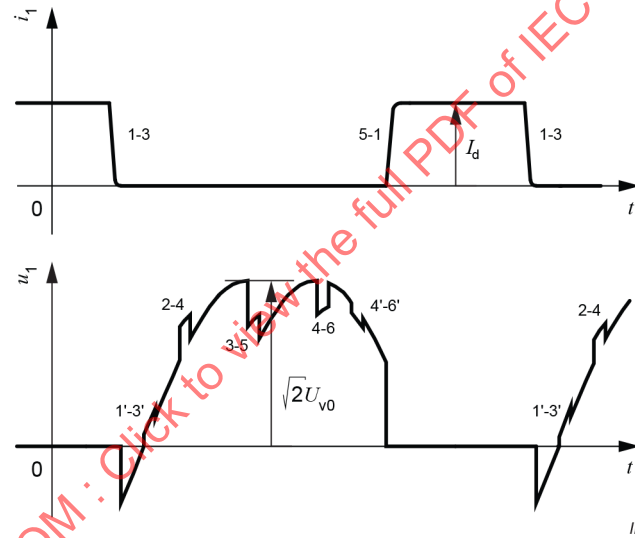
1 control and monitoring

Figure 3 – Simplified equivalent circuit of a typical thyristor valve



$$\alpha = 20^\circ \quad \mu = 10^\circ$$

a) – Rectifier operation



$$\gamma = 20^\circ \quad \mu = 10^\circ$$

b) – Inverter operation

NOTE Commutation overshoots are not shown.

Figure 4 – Current and voltage waveforms of a valve operating in a 12-pulse converter

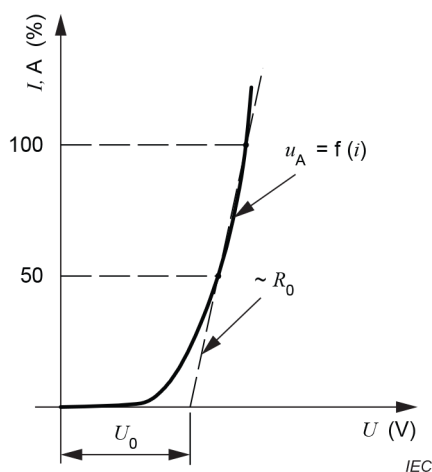
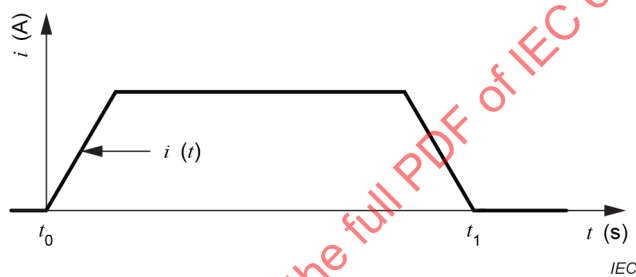
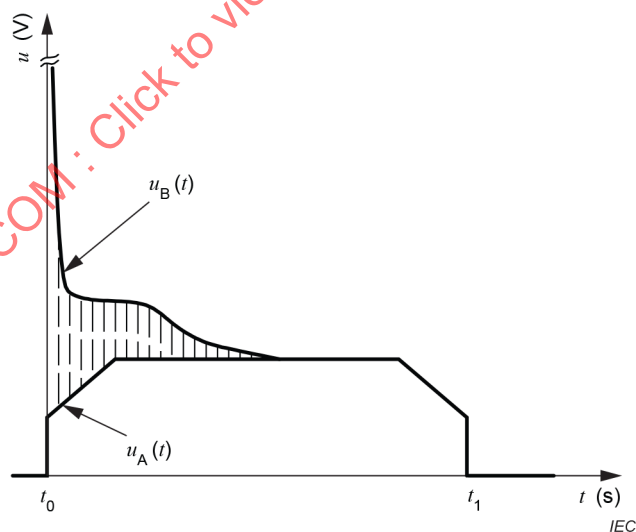


Figure 5 – Thyristor on-state characteristic



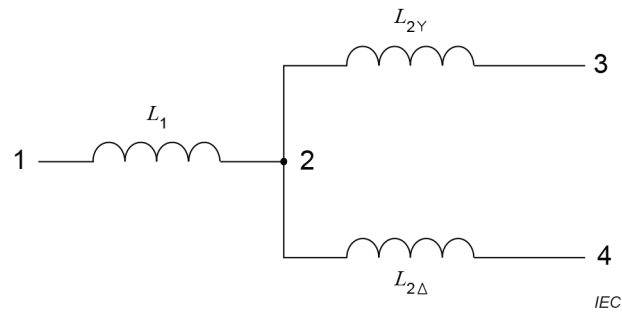
a) – Conduction current



b) – Voltage drop across an ideal thyristor A or a real thyristor B

In Figure 6 b), the ideal thyristor A is a thyristor with a conduction characteristic determined by U_0 and R_0 (as per Figure 5). The real thyristor B is a thyristor which displays the spreading effect.

Figure 6 – Conduction current and voltage drop



Key

- | | | | |
|---|--|---|---------------|
| 1 | from the source of the commutating voltage | 3 | to the valves |
| 2 | point of common coupling | 4 | to the valves |

Figure 7 – Distribution of commutating inductance between L_1 and L_2

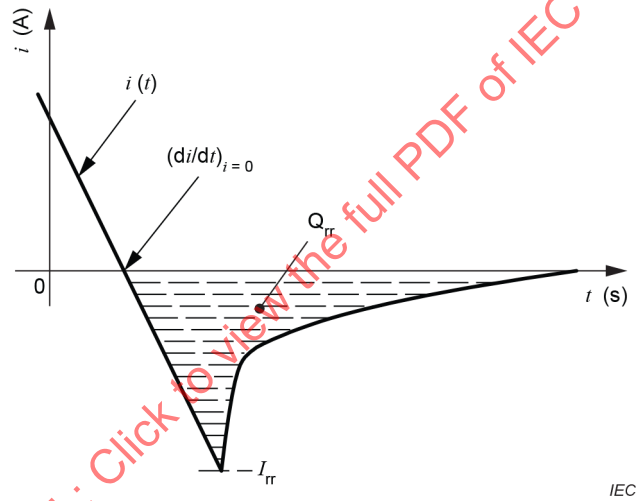


Figure 8 – Thyristor current during reverse recovery

Annex A (informative)

Calculation of harmonic currents and voltages

A.1 Harmonic currents in converter transformers

The RMS value of the six-pulse characteristic harmonic currents in each valve side terminal of the converter transformer is

$$I_n = \frac{\sqrt{6} \times I_d \times F_1}{\pi \times n}$$

where

n is the characteristic harmonic order, $n = k \times 6 \pm 1$, k being a positive integer in the range $1 \leq k \leq 8$;

$$F_1 = \frac{\left(k_1^2 + k_2^2 - 2k_1 \times k_2 \times \cos(2\alpha + \mu)\right)^{1/2}}{\cos\alpha - \cos(\alpha + \mu)}$$

where

$$k_1 = \frac{\sin\left((n-1) \times \frac{\mu}{2}\right)}{n-1};$$

$$k_2 = \frac{\sin\left((n+1) \times \frac{\mu}{2}\right)}{n+1}.$$

A.2 Harmonic currents in the AC filters

The RMS value of the 12-pulse characteristic harmonic currents on the line side of the converter transformer is

$$I_n = \frac{\sqrt{6} \times I_d \times F_1}{\pi \times n} \times \frac{U_v}{U_L} \times 2$$

where

n is the characteristic harmonic order, $n = k \times 12 \pm 1$, k being a positive integer in the range $1 \leq k \leq 4$;

U_v/U_L is the converter transformer voltage ratio, valve-side voltage divided by line-side voltage (including the actual tap position);

$$F_1 = \frac{\left(k_1^2 + k_2^2 - 2k_1 \times k_2 \times \cos(2\alpha + \mu)\right)^{1/2}}{\cos\alpha - \cos(\alpha + \mu)}$$

where

$$k_1 = \frac{\sin\left((n-1) \times \frac{\mu}{2}\right)}{n-1};$$

$$k_2 = \frac{\sin\left((n+1) \times \frac{\mu}{2}\right)}{n+1}.$$

A.3 Harmonic voltages on the DC side

The RMS value of the harmonic voltages from a 12-pulse bridge is

$$U_n = \frac{6\sqrt{2}}{\pi} \times U_{V0} \times F_2$$

where

n is the characteristic harmonic number, $n = k \times 12$, k being a positive integer in the range $1 \leq k \leq 4$;

$$F_2 = \frac{\left(k_3^2 + k_4^2 - 2k_3 \times k_4 \times \cos(2\alpha + \mu)\right)^{1/2}}{\sqrt{2}}$$

where

$$k_3 = \frac{\cos\left((n+1) \times \frac{\mu}{2}\right)}{n+1};$$

$$k_4 = \frac{\cos\left((n-1) \times \frac{\mu}{2}\right)}{n-1}.$$

If more than one 12-pulse converter is connected in series on the DC side, the harmonic voltage is U_n multiplied by the number of series-connected 12-pulse converters.

A.4 DC side harmonic currents in the smoothing reactor

The DC side harmonic currents through the smoothing reactor are calculated by representing the converter with a voltage source with harmonic voltages in accordance with Clause A.3. The converter impedance and the smoothing reactor, the DC filters and DC line/cable shall be represented by their actual impedances.

Annex B (informative)

Typical station losses

Typical values of losses are given in Table B.1 for information purposes.

Table B.1 – Typical values of losses

Item	Typical losses at nominal operating conditions %
Thyristor valves	20 to 40
Converter transformers	40 to 55
AC filters	4 to 10
Shunt capacitors (if used)	0,5 to 3
Shunt reactors (if used)	2 to 5
Smoothing reactor	4 to 13
DC filters	0,1 to 1
Auxiliaries	3 to 10
Total	100

The total station no-load operation losses range from 10 % to 20 % of the total station operating losses at rated power under nominal operating conditions.

Annex C (informative)

HVDC converter station loss evaluation – An illustration

C.1 General

Annex C is included to provide an illustration only to describe the basic concept behind the loss evaluation of HVDC converter stations and is to be considered by readers as a guide only.

One of the purposes of HVDC converter station loss determination is to evaluate expected life time cost of associated electrical losses reasonably well; not the maximum losses at any time. This is also a mechanism to arrive at an optimum compromise between initial capital investment cost and life time operating cost associated with electrical losses. Actions which take very little time (for example, a few seconds when moving a tap changer) are basically irrelevant in this aspect of evaluating losses as the loss evaluation is to cover a very long period (such as 25 years). Similarly, events which last for a short duration should be disregarded for purpose of loss evaluation (e.g. maximum ambient temperature, instead of use of yearly average ambient temperature to be considered). Further, considering operating loss at full load only may not represent the losses corresponding to actual load curve of most HVDC systems. Hence, a realistic method is recommended to be considered by adopting suitable weighting factors to a few sets of load as per expected loading patterns of the particular HVDC transmission link over a long period.

Cost of losses CL is associated with average price per hour of electricity, the interest rate applicable and design life of the HVDC project. The following formula is an example:

$$CL = CE \times T \left\{ \frac{1 - (1 + R)^{-L}}{R} \right\}$$

where

CL is the cost of 1 kWh of losses (\$);

CE is the cost of 1 kWh of electric energy at the present value (\$);

T is the number of hours in a year that the HVDC equipment is expected to be in operation (hours);

R is the interest rate applicable to the investment in HVDC project (%/100);

L is the life expectancy of the HVDC project (years).

Cost of losses may vary for example from 1 000 \$/kW to 5 000 \$/kW depending upon country, utility, project or other considerations. Different loss evaluation rates (\$/kW) are also used many times for no-load/standby losses and load/operating losses depending upon the evaluation (e.g. cost of lost opportunity of transmitting equivalent energy) perceived by the owner/utility. This means that the owner/utility profits from this evaluation in addition to the cost of lost energy. It may be noted that where a higher rate of loss evaluation rate is specified, it will lead to a higher initial capital investment cost which may not be optimum considering project utilisation.

The loss evaluation (also called "loss capitalisation") figures should be adapted to the application of the particular project considering necessary weighting factors depending upon the utilisation of the scheme/project and its expected cost of losses to the owner/utility. For a HVDC transmission scheme, the average time can be divided into:

a) energised and in standby (no-load);

- b) transmitting on average different powers for different time;
- c) not energised.

In some cases, it is necessary to keep the system energised in standby mode even when not transmitting power so that power can be transmitted without any delay and thus a concept of no-load and load loss is considered for loss evaluation (see case C and case D below).

In some other cases, it is not necessary to keep the system energised in standby mode when not transmitting power. In such a case, the concept of operating loss is to be considered for loss evaluation (see case A, case B and case C below).

Some typical scenarios are considered below:

- | | |
|--------|---|
| Case A | A 3 000 MW HVDC project is expected to be transmitting basically 100 % rated power 100 % of the time. |
| Case B | A 3 000 MW HVDC project is expected to be transmitting basically 100 % rated power for 9 months while not in operation for 3 months at all in a year. |
| Case C | A 3 000 MW HVDC project is expected to be transmitting basically 100 % rated power for 9 months on average while in remaining 3 months it has to be kept in standby mode so that power transmission can be started immediately whenever required. |
| Case D | <p>A 3 000 MW HVDC project is expected to be basically energised all the time and transmitting the following powers for the following periods</p> <p>0 % (0 MW) power but in standby – 10 % of the time</p> <p>10 % (300 MW) power – 10 % of the time</p> <p>50 % (1 500 MW) power – 60 % of the time</p> <p>100 % (3 000 MW) power – 20 % of the time</p> |

NOTE Above is just to illustrate a method of loss evaluation while the number of loading points to be selected will vary as per specific project requirement.

C.2 Loss evaluation under various cases

A typical loss evaluation rate of 3 000 \$/kW for total station no-load operation losses and 2 000 \$/kW for total station operating losses is considered in the following examples.

Case A:

In such a case, concept of operating loss is recommended to be adopted. If total station operating losses of whole station loss at rated power (3 000 MW) load are d kW, then loss evaluation would be $d \times 2\,000$ \$.

Case B:

In such a case, concept of operating loss is recommended to be adopted. If total station operating losses of whole station loss at rated power (3 000 MW) load are d kW, then loss evaluation would be $d \times 2\,000 \times (9/12)$ \$.

Case C:

In such a case, concepts of standby and operating loss are recommended to be adopted. If total station operating losses of whole station loss at rated power (3 000 MW) load are d kW and total station no-load operation losses are a kW, then loss evaluation would be $d \times 2\,000 \times (9/12) + a \times 3\,000 (3/12)$ \$.

Case D:

Some purchasers may use the approach to evaluate the total station no-load operation losses and the total station load losses separately (case D2 below), whereas others may evaluate only the total station operating losses (case D1 below).

Case D1:

It is assumed that standby losses (which are considered the same as total station no-load operation losses) is a kW, whereas total station operating losses at 10 %, 50 % and 100 % load are b kW, c kW and d kW respectively. It may be noted that losses a are calculated at different conditions, for example at a tap position which may be different than conditions for which losses b , or d are calculated. Losses in such case would be evaluated according to conditions shown in Table C.1.

Table C.1 – Conditions for calculation of losses in case D1

	Total station operating losses	Time factor
10 % load	b	0,10
50 % load	c	0,60
100 % load	d	0,20

Loss evaluation would be $\{(a \times 0,10) \times 3\,000\} + \{(b \times 0,10 + c \times 0,60 + d \times 0,20) \times 2\,000\}$ \$.

Case D2:

It is assumed that standby losses (which are considered the same as total station no-load operation losses) is a kW, whereas total station load losses at 10 %, 50 % and 100 % load are e kW, f kW and g kW respectively. It may be noted that losses a are calculated at different conditions, for example at a tap position which may be different than conditions for which losses e , f or g are calculated. Losses in such case would be evaluated according to conditions shown in Table C.2.

Table C.2 – Conditions for calculation of losses in case D2

	Total station load losses	Time factor
10 % load	$e = (b - a)$	0,10
50 % load	$f = (c - a)$	0,60
100 % load	$g = (d - a)$	0,20

The equivalent load losses can be calculated as $(e \times 0,10 + f \times 0,60 + g \times 0,20)$.

The loss evaluation would be $\{a \times 3\,000\} + \{(e \times 0,10 + f \times 0,60 + g \times 0,20) \times 2\,000\}$ \$.

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COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

**DÉTERMINATION DES PERTES EN PUISSANCE DANS LES POSTES
DE CONVERSION EN COURANT CONTINU À HAUTE TENSION (CCHT)
MUNIS DE CONVERTISSEURS COMMUTÉS PAR LA LIGNE**

AVANT-PROPOS

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La Norme internationale IEC 61803 a été établie par le sous-comité 22F: Électronique de puissance pour les réseaux électriques de transport et de distribution, du comité d'études 22 de l'IEC: Systèmes et équipements électroniques de puissance.

Cette deuxième édition annule et remplace la première édition parue en 1999, l'Amendement 1:2010 et l'Amendement 2:2016. Cette édition constitue une révision technique.

Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente:

- a) en vue de faciliter l'application de la norme sans en détériorer la qualité, 5.1.8 et 5.8 ont été revus en tenant compte du fait que la technologie de production de thyristors actuelle occasionne considérablement moins de dispersion dans ses paramètres par rapport à la situation de 1999, lorsque la première édition de l'IEC 61803 a été élaborée. Ainsi, les données enregistrées de production de thyristors peuvent être utilisées pour les calculs de pertes de puissance;
- b) le calcul des pertes de charge au poste totales (cas D1 et D2 à l'Annexe C) a été corrigé.

Le texte de cette Norme internationale est issu des documents suivants:

CDV	Rapport de vote
22F/563/CDV	22F/580A/RVC

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à l'approbation de cette Norme internationale.

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DÉTERMINATION DES PERTES EN PUISSANCE DANS LES POSTES DE CONVERSION EN COURANT CONTINU À HAUTE TENSION (CCHT) MUNIS DE CONVERTISSEURS COMMUTÉS PAR LA LIGNE

1 Domaine d'application

Le présent document s'applique à tous les postes de conversion en courant continu à haute tension (CCHT), commutés par la ligne, et utilisés pour l'échange de puissance (transmission de puissance ou installation dos à dos) dans des systèmes de distribution d'énergie. Le présent document présuppose l'utilisation de convertisseurs à thyristors à 12 impulsions mais peut également, en prenant les précautions appropriées, s'appliquer à des convertisseurs à thyristors à 6 impulsions.

Dans certaines applications, il est admis de connecter des compensateurs synchrones ou des compensateurs var statiques (CVS) au nœud à courant alternatif du poste de conversion en courant continu à haute tension (CCHT). Les procédures de détermination de pertes pour ce type de matériel ne figurent pas dans le présent document.

Le présent document décrit un ensemble de procédures types permettant de déterminer l'ensemble des pertes d'un poste de conversion à CCHT. Les procédures s'appliquent à toutes les pièces, à l'exception de celles susmentionnées, et considèrent les pertes en fonctionnement à vide et les pertes en fonctionnement ainsi que leurs méthodes de calcul utilisant, dans la mesure du possible, des paramètres mesurés.

Les conceptions de poste de conversion utilisant des composants ou des configurations de circuit originaux par rapport à la conception type prise pour hypothèse dans le présent document, ou des conceptions équipées de circuits de distribution d'énergie auxiliaires inhabituels susceptibles de modifier les pertes, sont évaluées selon leurs propres mérites.

2 Références normatives

Les documents suivants cités dans le texte constituent, pour tout ou partie de leur contenu, des exigences du présent document. Pour les références datées, seule l'édition citée s'applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

IEC 60076-1, *Transformateurs de puissance – Partie 1: Généralités*

IEC 60076-6, *Transformateurs de puissance – Partie 6: Bobines d'inductance*

IEC 60633, *Transport d'énergie en courant continu à haute tension (CCHT) – Vocabulaire*

IEC 60700-1:2015, *Valves à thyristors pour le transport d'énergie en courant continu à haute tension (CCHT) – Partie 1: Essais électriques*

IEC 60871-1, *Condensateurs shunt pour réseaux à courant alternatif de tension assignée supérieure à 1 000 V – Partie 1: Généralités*

3 Termes, définitions et symboles

Pour les besoins du présent document, les termes et définitions de l'IEC 60633, ainsi que les suivants s'appliquent.

L'ISO et l'IEC tiennent à jour des bases de données terminologiques destinées à être utilisées en normalisation, consultables aux adresses suivantes:

- IEC Electropedia: disponible à l'adresse <http://www.electropedia.org/>
- ISO Online browsing platform: disponible à l'adresse <http://www.iso.org/obp>

3.1 Termes et définitions

3.1.1

pertes auxiliaires

puissance électrique nécessaire pour alimenter les charges auxiliaires des postes de conversion

Note 1 à l'article: Les pertes auxiliaires dépendent du nombre d'unités de conversion utilisées et varient selon que le poste fonctionne à vide ou en charge, auquel cas les pertes auxiliaires dépendent du niveau de charge.

3.1.2

pertes en fonctionnement à vide du matériel

pertes produites dans un élément du matériel tandis que le poste de conversion est sous tension mais que les convertisseurs sont bloqués et que toutes les charges de poste en service et le matériel auxiliaire sont connectés comme cela est exigé pour la captation immédiate d'une charge à la puissance minimale spécifiée

3.1.3

niveau de charge

courant continu, tension continue, angle d'allumage, tension alternative et position du changeur de prises du transformateur de conversion auxquels le poste de conversion fonctionne

3.1.4

pertes en fonctionnement du matériel

pertes produites dans un élément de matériel à un niveau de charge donné, tandis que le poste de conversion est sous tension et les convertisseurs sont en fonctionnement

3.1.5

charge assignée

charge liée au fonctionnement à des valeurs nominales de courant continu, de la tension continue, de la tension alternative et de l'angle d'allumage de convertisseur

Note 1 à l'article: Par hypothèse, le réseau à tension alternative doit être à la fréquence nominale et ses tensions triphasées sont nominales et équilibrées. La position du changeur de prises du transformateur de conversion et le nombre de filtres à courant alternatif et d'éléments d'inductance shunt connectés doivent être cohérents avec un fonctionnement sous une charge assignée coïncidant avec des conditions nominales.

3.1.6

pertes totales en fonctionnement à vide d'un poste

somme de toutes les pertes en fonctionnement à vide du matériel (3.1.2) et des pertes auxiliaires correspondantes (3.1.1)

3.1.7

pertes totales en fonctionnement d'un poste

somme de toutes les pertes en fonctionnement du matériel (3.1.4) et des pertes auxiliaires correspondantes (3.1.1) à un niveau de charge particulier

Note 1 à l'article: L'Annexe C, cas D1, illustre ceci par un exemple utilisant les pertes totales en fonctionnement d'un poste et l'évaluation des pertes correspondante.

3.1.8

pertes totales d'un poste en charge

différence entre les pertes totales en fonctionnement d'un poste (3.1.7) et les pertes totales en fonctionnement à vide d'un poste (3.1.6)

Note 1 à l'article: Les pertes totales d'un poste en charge ainsi calculées sont considérées comme équivalentes, sur un plan quantitatif, aux pertes dues à la charge telles que celles de la pratique pour un poste en courant alternatif.

Note 2 à l'article: Il est admis que certains acheteurs évaluent les pertes totales en fonctionnement à vide d'un poste (3.1.6) et les pertes totales en charge d'un poste de manière individuelle plutôt que d'évaluer les pertes totales en fonctionnement d'un poste (3.1.7).

Note 3 à l'article: L'Annexe C, cas D2, illustre ceci par un exemple permettant d'extraire les pertes dues à la charge, les pertes dues à la charge équivalentes et l'évaluation des pertes correspondante.

3.1.9

charge auxiliaire essentielle au poste

charges dont la défaillance affecte la capacité de conversion du poste de conversion CCHT (par exemple, le refroidissement des valves), ou les charges qui doivent continuer à fonctionner en cas de coupure totale de l'alimentation en courant alternatif (par exemple, les chargeurs de batterie, les mécanismes de fonctionnement)

3.2 Symboles

α	angle de retard (d'amorçage/allumage), en radians (rad)
μ	angle d'empiètement, en radians (rad)
f	fréquence du réseau à tension alternative, en hertz (Hz)
I_d	courant continu, en ampères (A)
I_n	courant efficace harmonique de rang n , en ampères (A)
L_1	inductance, en henrys (H), relative à l'enroulement de la valve, entre la source de tension de commutation et le point de couplage commun entre les enroulements connectés en étoile et en triangle. L_1 doit inclure toute inductance externe entre les bornes d'enroulement de ligne du transformateur et le point de connexion des filtres d'harmoniques à courant alternatif.
L_2	inductance, en henrys (H), relative à l'enroulement de la valve, entre le point de couplage commun entre les enroulements connectés en étoile et en triangle, et la valve. L_2 doit inclure l'inductance saturée des bobines d'inductance de la valve.
m	facteur de couplage électromagnétique à bande étroite $m = L_1 / (L_1 + L_2)$
n	rang de l'harmonique
N_t	nombre de thyristors connectés en série par valve
P	perte en puissance dans un élément de matériel, en watts (W)
Q_n	facteur de qualité pour un rang d'harmonique n
R	valeur de résistance, en ohms (Ω)
U_d	tension continue, en volts (V)
U_n	tension efficace harmonique de rang n , en volts (V)
U_{vo}	valeur efficace de la tension à vide entre phases sur le côté valve du transformateur de conversion à l'exclusion des harmoniques, en volts (V)
X_n	réactance inductive pour un rang d'harmonique n , en ohms (Ω)

4 Vue d'ensemble

4.1 Généralités

Il est nécessaire que les fournisseurs sachent précisément comment et où sont générées les pertes, en raison de leur influence sur les valeurs assignées des composants et matériels. Les acheteurs souhaitent disposer d'une valeur de perte vérifiable permettant une comparaison équitable des offres et, après la livraison, d'une procédure permettant de vérifier objectivement les exigences de caractéristiques fonctionnelles garanties par le fournisseur.

En règle générale, il est souhaitable de déterminer l'efficacité d'un poste de conversion à CCHT en mesurant directement ses pertes d'énergie. Cependant, d'après les tentatives faites pour déterminer les pertes de poste en soustrayant la puissance mesurée en sortie de la puissance mesurée en entrée, il convient de reconnaître que ces mesurages présentent une inexactitude inhérente, particulièrement lorsqu'ils sont réalisés à haute tension. Les pertes de poste de conversion CCHT à pleine charge sont généralement inférieures à 1 % de la puissance transmise. Par conséquent, il est probable que la perte mesurée, représentant une petite différence entre deux grandes quantités, ne fournisse pas une indication suffisamment exacte des pertes réelles.

Dans certaines circonstances particulières, il est possible, par exemple, de réaliser un montage d'essai temporaire dans lequel deux convertisseurs fonctionnent à partir de la même source de courant alternatif et sont également raccordés par l'intermédiaire de leurs bornes en courant continu. Dans ce raccordement, la puissance issue de la source de courant alternatif est égale aux pertes dans le circuit. Cependant, la source de courant alternatif doit également fournir un support var et une tension de commutation aux deux convertisseurs. Là encore, des difficultés liées au mesurage pratique sont rencontrées.

Pour éviter les problèmes décrits ci-dessus, le présent document normalise une méthode de calcul des pertes de poste de conversion à CCHT consistant à additionner les pertes calculées pour chaque élément de matériel. La méthode de calcul normalisée aide l'acheteur à réaliser une comparaison significative des offres concurrentes. Elle permet également de créer facilement des courbes représentant les caractéristiques fonctionnelles pour un large éventail de conditions de fonctionnement dans lesquelles ces caractéristiques doivent être connues. En l'absence de méthode expérimentale peu coûteuse permettant une vérification objective des pertes au cours d'essais de type, la méthode de calcul constitue la meilleure solution de remplacement car elle utilise, dans la mesure du possible, des données expérimentales obtenues à partir des mesurages réalisés sur un matériel et des composants individuels dans des conditions équivalentes à celles rencontrées en fonctionnement réel.

Le calcul des courants et tensions harmoniques dans le matériel CCHT est décrit à l'Annexe A.

Il est important de noter que la perte en puissance dans chaque élément de matériel dépend des conditions ambiantes dans lesquels il fonctionne, ainsi que des conditions de fonctionnement ou des cycles de service auxquels il est soumis. Par conséquent, les conditions ambiantes et de fonctionnement doivent être définies pour chaque élément de matériel sur la base des conditions ambiantes et de fonctionnement de l'ensemble du poste de conversion à CCHT.

4.2 Conditions ambiantes

4.2.1 Généralités

Un ensemble de conditions ambiantes de référence doit être utilisé pour déterminer les pertes en puissance des postes de conversion à CCHT.

4.2.2 Température extérieure de référence normalisée

Une température extérieure ambiante sèche de 20 °C doit être utilisée comme température de référence normalisée pour déterminer les pertes totales de poste de conversion. La température correspondante de l'ensemble de valves peut être définie par le fournisseur si nécessaire. La température humide équivalente (si nécessaire) doit être définie par l'acheteur.

Lorsqu'elle n'est pas définie, il est recommandé que la température humide soit de 14 °C, ce qui correspond approximativement à 50 % d'humidité relative pour une température sèche de 20 °C.

4.2.3 Température de référence normalisée de l'agent de refroidissement

Lorsqu'un refroidissement forcé est utilisé pour le matériel, le débit et la température de l'agent de refroidissement peuvent influencer la hausse de température et les pertes associées de ce matériel. Par conséquent, les températures et les débits de l'agent de refroidissement établis par l'acheteur et le fournisseur doivent servir de base pour déterminer les pertes.

4.2.4 Pression de l'air de référence normalisée

La pression de l'air de référence à utiliser pour l'évaluation des pertes totales en puissance d'un poste de conversion doit correspondre à la pression atmosphérique normalisée (101,3 kPa) corrigée en fonction de l'altitude de l'installation en question.

4.3 Paramètres de fonctionnement

Les pertes d'un poste de conversion à CCHT dépendent de ses paramètres de fonctionnement.

Les pertes des postes de conversion à CCHT sont classées en deux catégories désignées comme suit: pertes en fonctionnement (3.1.4 et 3.1.7) et pertes en fonctionnement à vide (3.1.2 et 3.1.6).

Les pertes en fonctionnement et les pertes auxiliaires sont influencées par le niveau de charge du poste, car le nombre de certains types de matériels sous tension (par exemple, filtres d'harmoniques et matériel de refroidissement) peut dépendre du niveau de charge et les pertes au niveau des éléments individuels de matériel eux-mêmes varient avec le niveau de charge.

Les pertes de poste de conversion à CCHT doivent être déterminées pour une tension alternative (balancée) et une fréquence nominales, des impédances symétriques du transformateur convertisseur, et des angles d'allumage symétriques. Par hypothèse, le changeur de prises du transformateur doit occuper la position correspondant à la tension nominale alternative ou telle que décidée par le système de commande pour la condition de fonctionnement définie.

Les pertes en fonctionnement doivent être déterminées pour les niveaux de charge spécifiés par l'acheteur, ou pour une charge assignée si ces conditions ne sont pas spécifiées. Pour chaque niveau de charge, la tension alternative de l'enroulement de valve, le courant continu, l'angle d'allumage du convertisseur, la compensation shunt et le matériel de filtrage d'harmonique doivent être compatibles avec le niveau de charge respectif et les autres exigences de caractéristiques fonctionnelles spécifiées, concernant, par exemple, la distorsion harmonique et la puissance réactive. Par hypothèse, le matériel de refroidissement et les autres matériels auxiliaires, en fonction de la température de référence normalisée (voir 4.2.2 et 4.2.3), doivent être connectés pour supporter le niveau de charge respectif.

Pour le mode de fonctionnement à vide, les transformateurs de conversion doivent être mis sous tension et les convertisseurs doivent être bloqués. Par hypothèse, tous les filtres et matériels de compensation de puissance réactive doivent être déconnectés à l'exception de ceux qui sont exigés pour maintenir un fonctionnement à vide afin, par exemple, de satisfaire aux exigences de puissance réactive spécifiées. Par hypothèse, les charges de poste en service et le matériel auxiliaire (par exemple, des pompes à eau de refroidissement) doivent être connectés selon les exigences pour une captation immédiate de charge au niveau du poste de conversion (sans attendre le déplacement du changeur de prises) à la puissance minimale spécifiée.

5 Détermination des pertes du matériel

5.1 Pertes de valves à thyristors

5.1.1 Généralités

Les mécanismes de production de pertes applicables lorsque les valves sont bloquées (pertes en fonctionnement à vide) sont différents des mécanismes applicables en fonctionnement normal (pertes en fonctionnement). Les pertes en fonctionnement sont traitées de 5.1.2 à 5.1.11, et les pertes en fonctionnement à vide sont traitées en 5.1.12. Les pertes auxiliaires sont examinées en 5.8.

La Figure 1 illustre le matériel type en courant continu à haute tension (CCHT) pour un pôle d'une station CCHT.

Un schéma triphasé simplifié d'un convertisseur à 12 impulsions en courant continu à haute tension est représenté à la Figure 2. Les valves individuelles sont marquées selon l'ordre de leur séquence en conduction.

Un circuit équivalent simplifié d'une valve type est représenté à la Figure 3. Le symbole th combine les effets de N_t thyristors raccordés en série dans la valve. C_{AC} et R_{AC} sont les valeurs combinées correspondantes des circuits d'amortissement R-C utilisés pour le partage de tension et la suppression de surtension. R_{DC} représente des résistances de gradation de courant continu et d'autres composants résistifs subissant des pertes lorsque la valve bloque la tension. Elle inclut également les effets du courant de fuite des thyristors (voir 5.1.5 et 5.1.12). C_s inclut à la fois des capacités parasites et des condensateurs de distribution de surtension (le cas échéant). L_s représente les inductances saturables utilisées pour limiter les valeurs des contraintes di/dt à des valeurs de sécurité et pour améliorer la répartition des tensions à court temps de montée. R_s représente les résistances des composants conducteurs de courant de la valve, tels que les bus d'alimentation, les résistances de contact, la résistance des enroulements des inductances saturables, etc. Les pertes en puissance au niveau du parafoudre de la valve (non représentées) doivent être omises.

La Figure 4 représente, à titre d'exemple, les formes d'onde de courant et de tension de la valve 1 (d'après la Figure 2) fonctionnant en modes redresseur – Figure 4 a) – et inverseur – Figure 4 b). Dans l'exemple représenté, les instants d'allumage des valves du pont supérieur sont retardés de 30° par rapport aux valves du pont inférieur du fait du déphasage entre les deux secondaires. Pour chaque valve, la longueur des intervalles de conduction est de 130° ($2\pi/3 + \mu$). Pendant les commutations, il est admis, pour le présent document, que le courant de la valve varie de façon linéaire tandis qu'en réalité les courants de valve suivent des portions d'ondes sinusoïdales. Cette simplification a un effet négligeable sur les pertes résultantes, tandis que la forme d'onde trapézoïdale simplifie considérablement les calculs. La tension bloquée par la valve présente des encoches provoquées par des commutations entre des valves individuelles.

5.1.2 Pertes de conduction de thyristors par valve

Une courbe caractéristique d'un thyristor à l'état passant type est représentée à la Figure 5. Cette composante de perte de conduction de thyristor est le produit du courant de conduction $i(t)$ – Figure 6 a) – et de la tension fictive à l'état passant correspondante, comme le représente la Figure 5. La formule P_{V1a} doit être utilisée à condition que le courant continu de pont soit correctement lissé. Dans l'éventualité où la racine carrée de la somme des carrés des courants harmoniques côté continu, déterminée en fonction de l'Article A.4, dépasse 5 % de la composante continue, la formule P_{V1b} doit être utilisée.

$$P_{V1a} = \frac{N_t \times I_d}{3} \left[U_0 + R_0 \times I_d \times \left(\frac{2\pi - \mu}{2\pi} \right) \right]$$

$$R_{V1b} = \frac{N_t \times I_d \times U_0}{3} + \frac{N_t \times R_0}{3} \left(I_d^2 + \sum_{n=12}^{n=48} I_n^2 \right) \left(\frac{2\pi - \mu}{2\pi} \right)$$

où

U_0 est la composante, indépendante du courant, de la tension à l'état passant du thyristor moyen (voir note ci-dessous), en volts;

R_0 est la résistance de la pente de la caractéristique à l'état passant du thyristor moyen (voir note ci-dessous), en ohms;

I_n est la valeur efficace calculée du courant harmonique n au niveau du montage en pont à courant continu suivant l'Article A.4, en ampères.

NOTE U_0 et R_0 (voir Figure 5) sont déterminées à partir de la tension à l'état passant entièrement étalée et mesurée pour le courant et la température de jonction appropriés. La valeur moyenne de U_0 et R_0 est obtenue à partir des enregistrements de production des thyristors. La dépendance de U_0 et R_0 vis-à-vis de la température est établie à partir d'essais de type ou d'essais individuels de série sur un nombre statistiquement significatif de thyristors utilisés, et est employée, si nécessaire, pour corriger U_0 et R_0 en fonction de la température de jonction de service appropriée. Si une connexion parallèle de p thyristors est utilisée, le courant approprié à 100 % représente le courant nominal de pont continu divisé par p . Le résultat calculé est alors multiplié par p .

5.1.3 Affaiblissement géométrique de thyristors par valve

Cette composante d'affaiblissement est une perte résistive supplémentaire des thyristors résultant du retard d'établissement de la conduction complète du silicium après le branchement du thyristor. La perte supplémentaire est le produit du courant et de la tension représentant la valeur de dépassement de la tension du thyristor par rapport à la chute de tension du thyristor fictif à l'état passant – voir la zone hachurée de la Figure 6 b).

$$R_{V2} = N_t \times f \times \int_0^{t_1} [u_B(t) - u_A(t)] \times i(t) dt$$

où

t_1 est la longueur de l'intervalle de conduction, en secondes, donnée par la relation suivante:

$$t_1 = \frac{\frac{2}{3} \pi + \mu}{2\pi f};$$

$u_B(t)$ est la tension instantanée à l'état passant, en volts, d'un thyristor dont la tension entièrement étalée à l'état passant est typique pour les thyristors utilisés; la tension instantanée à l'état passant doit être déterminée pour la température de jonction appropriée, mesurée avec une impulsion de courant trapézoïdale présentant les périodes de recouvrement d'amplitude et de commutation correctes (voir Figure 5 et Figure 6);

$u_A(t)$ est la tension instantanée à l'état passant calculée du thyristor moyen à la même température de jonction pour la même impulsion de courant, mais la zone de conduction est entièrement établie sur l'ensemble de la conduction, d'après sa courbe caractéristique à l'état passant représentée par U_0 et R_0 seulement (voir Figure 6);

$i(t)$ est le courant instantané dans le thyristor, en ampères.

Les données de tension instantanée à l'état passant, y compris les effets de l'étalement, ne sont généralement pas disponibles d'après les registres de production. Il convient donc de relever les mesurages de tension type de thyristor à l'état passant, y compris l'étalement, au cours de l'essai de type sur l'allumage et l'extinction périodiques de la valve

(voir l'IEC 60700-1:2015, Article 9) ou à partir d'un essai en laboratoire distinct effectué sur un nombre de thyristors statistiquement significatif.

5.1.4 Autres pertes de conduction par valve

Il s'agit des pertes de conduction dans le circuit principal de la valve dues à des composants autres que les thyristors.

$$P_{V3} = \frac{R_s \cdot I_d^2}{3} \left(\frac{2\pi - \mu}{2\pi} \right)$$

où

R_s est la résistance en courant continu du circuit entre bornes de la valve, à l'exclusion des thyristors, en ohms (voir Figure 3).

La valeur de R_s est déterminée en effectuant un mesurage direct sur une section de valve représentative qui comprend tous les éléments du circuit principal d'une valve dans les proportions correctes, mais dans laquelle les thyristors ont été remplacés par des blocs de cuivre de dimension appropriée, les contacts étant traités de la même façon que pour des thyristors réels. Une autre possibilité consiste à calculer la résistance, auquel cas les méthodes de calcul doivent être documentées.

5.1.5 Pertes dépendant de la tension continue par valve

Cette composante de perte représente la perte au niveau de la résistance parallèle R_{DC} de la valve (voir Figure 3), provenant de la tension apparaissant entre les bornes de valve durant l'intervalle de non-conduction (voir Figure 4). Elle inclut les pertes dues aux fuites du thyristor à l'état bloqué et en polarisation inverse, les pertes au niveau des résistances de gradation en courant continu, d'autres circuits et éléments résistifs connectés en parallèle avec les thyristors, la résistance de l'agent de refroidissement dans les conduits de refroidissement, les effets de résistivité de la structure, des fibres optiques, etc.

$$P_{V4} = \frac{U_{v0}^2}{2\pi R_{DC}} \left\{ \frac{4}{3}\pi + \frac{\sqrt{3}}{4} [\cos(2\alpha) + \cos(2\alpha + 2\mu)] + \frac{6m^2 - 12m - 7}{8} [\sin(2\alpha) - \sin(2\alpha + 2\mu) + 2\mu] \right\}$$

où

R_{DC} est la résistance effective en courant continu à l'état bloqué d'une valve entière, déterminée par le mesurage du courant absorbé au cours de l'essai de type sur la valve sous tension continue entre bornes (conformément à l'IEC 60700-1:2015, 8.3.1) en ohms; si aucun essai de type n'est réalisé sur la valve à thyristors, R_{DC} doit être déterminée par référence à un essai de type précédent (voir également l'alinéa après la Note 1 ci-dessous);

$$m = L_1 / (L_1 + L_2);$$

L_1 est l'inductance, en henrys, se rapportant à l'enroulement de la valve, entre la source de tension de commutation et le point de couplage commun des enroulements en étoile et en triangle; L_1 doit inclure toute inductance externe entre les bornes d'enroulement de ligne du transformateur et le point de connexion des filtres d'harmoniques à courant alternatif (voir Figure 7);

L_2 est l'inductance, en henrys, se rapportant à l'enroulement de la valve, entre le point de couplage commun des enroulements en étoile et en triangle, et la valve; L_2 doit inclure l'inductance saturée des bobines d'inductance de la valve (voir Figure 7).

La valeur de L_2 doit être identique pour les deux secondaires ($L_{2\Delta} = L_{2Y}$) (voir la Note 2 et le dernier alinéa ci-dessous).

NOTE 1 La formule concernant P_{V4} s'applique pour $\mu < \pi/6$ (30°) seulement.

Le courant de fuite résistif du thyristor étant généralement beaucoup plus élevé pour les températures de fonctionnement que pour la température de l'air ambiant prédominante, il est nécessaire de chauffer les thyristors de la valve à la température de fonctionnement correcte avant de mesurer R_{DC} ou d'effectuer des corrections ultérieures à la valeur mesurée à l'aide des données relatives au thyristor moyen obtenues séparément, afin d'inclure l'effet de la température mentionné (voir également 5.1.11). Il en va de même pour le liquide de refroidissement.

NOTE 2 La valeur de m quantifie les effets du couplage inductif entre les deux secondaires du transformateur de conversion. Elle détermine l'amplitude des encoches provoquées par la commutation dans l'autre pont (encoches de 1' à 3' et de 4' à 6' à la Figure 4). Si $m = 0$, alors il n'existe pas de couplage entre les deux ponts et les encoches de 1' à 3' et de 4' à 6' disparaissent tout à fait. Les encoches à la Figure 4 correspondent à $m = 0,2$.

Les valeurs de L_1 et L_2 sont obtenues à partir des mesurages d'impédance de court-circuit effectués sur les transformateurs de conversion, et en ajoutant toutes les inductances externes comme cela est exigé. La valeur de L_1 comprend toutes les inductances externes communes (telles que les filtres de courant porteur sur ligne d'énergie) entre le point de couplage commun et la source de tension de commutation. Dans les cas où aucun filtre d'harmoniques à courant alternatif n'est connecté, L_1 inclut également l'impédance du réseau à tension alternative. Lorsque des transformateurs séparés alimentent les ponts en étoile et en triangle et qu'aucune inductance secondaire de ligne supplémentaire n'est incluse, $L_1 = 0$, et donc $m = 0$. Lorsqu'un montage de transformateurs à trois enroulements est utilisé, une impédance d'enroulement commune et les effets de couplage mutuels des deux enroulements secondaires donnent pour L_1 des valeurs différentes de zéro, susceptibles d'être positives ou négatives. Pour des montages de transformateurs plus complexes, tels que des filtres connectés à un enroulement tertiaire, les valeurs de L_1 et L_2 doivent être déterminées avec soin.

5.1.6 Pertes d'amortissement par valve (terme dépendant de la résistance)

Cette composante de perte dépend de la valeur des éléments résistifs des circuits couplés à tension alternative par le biais de condensateurs en série, et de la tension apparaissant entre les bornes de valve durant l'intervalle de non-conduction.

$$P_{V5} = 2\pi f^2 U_{V0}^2 C_{AC}^2 R_{AC} \left\{ \begin{aligned} & \left(\frac{4\pi}{3} - \frac{\sqrt{3}}{2} + \frac{3\sqrt{3}m^2}{8} + (6m^2 - 12m - 7) \frac{\mu}{4} + \left(\frac{7}{8} + \frac{9m}{4} - \frac{39m^2}{32} \right) \sin 2\alpha + \right. \\ & \left. \left(\frac{7}{8} + \frac{3m}{4} + \frac{3m^2}{32} \right) \sin(2\alpha + 2\mu) - \left(\frac{\sqrt{3}m}{16} + \frac{3\sqrt{3}m^2}{8} \right) \cos 2\alpha + \frac{\sqrt{3}m}{16} \cos(2\alpha + 2\mu) \right\} \end{aligned} \right.$$

où

C_{AC} est la valeur effective entre bornes de la capacité d'amortissement de la valve, en farads (voir Figure 3);

R_{AC} est la valeur effective entre bornes de la résistance d'amortissement associée, connectée en série, en ohms (voir Figure 3);

C_{AC} doit être la valeur nominale d'une capacité d'amortissement par niveau divisée par le nombre de niveaux de thyristors dans une valve;

R_{AC} doit être la valeur nominale d'une résistance d'amortissement par niveau multipliée par le nombre de niveaux de thyristors dans une valve.

Si la valve utilise plus d'un réseau d'amortissement ou de répartition des potentiels intégrant des branches R-C connectées en série, chaque branche doit être évaluée séparément, les résultats étant ensuite additionnés.

Si l'énergie est extraite du réseau de répartition des potentiels R-C en vue de l'alimentation des circuits d'allumage et/ou de contrôle des thyristors, il doit être démontré que les pertes supplémentaires sont négligeables ou la perte supplémentaire doit être calculée séparément puis ajoutée au chiffre obtenu à partir de la formule P_{V5} .

NOTE Les notes 1 et 2 et le dernier alinéa du 5.1.5 s'appliquent également à P_{V5} .

5.1.7 Pertes d'amortissement par valve (variation du terme énergie du condensateur)

Cette composante de perte est due à la modification de l'énergie stockée au niveau des capacités de la valve résultant des variations en échelon (ΔU) de la tension bloquée par la valve. Chaque variation en échelon subit une perte d'énergie égale à $\frac{1}{2}C \times \Delta U^2$. La formule ci-dessous est dérivée de la somme des énergies perdues en raison des 12 sauts de tension survenant au cours d'un cycle de tension de blocage (Figure 4), multipliée par la fréquence du réseau.

$$P_{V6} = \frac{U_{V0}^2 \times f \times C_{HF} \times (7 + 6m^2)}{4} \left[\sin^2(\alpha) + \sin^2(\alpha + \mu) \right]$$

où

C_{HF} est la somme de la capacité effective entre bornes de toutes les branches du réseau capacitif de répartition des potentiels de la valve (intégrant ou non des résistances en série) et de la capacité parasite effective totale entre les bornes de la valve due au matériel connecté à l'extérieur et à proximité de la masse et/ou d'objets adjacents au voisinage de la valve (voir Note 3 ci-dessous); $C_{HF} = C_{AC} + C_S$ (voir Figure 3).

NOTE 1 Les notes 1 et 2 et le dernier alinéa du 5.1.5 s'appliquent également à P_{V6} .

NOTE 2 La formule relative à P_{V6} produit des résultats trop pessimistes concernant les recouvrements de commutation dont la longueur est inférieure à 3 constantes de temps du réseau d'amortissement R-C.

NOTE 3 La capacité parasite externe provient principalement de l'enroulement et des traversées du transformateur de conversion (ainsi que des traversées de parois séparées si elles existent), qui peuvent tous être mesurés lors de la fabrication. Selon la conception, la capacité parasite doit éventuellement être incluse entre la valve et la terre. Les parafoudres, les bus d'alimentation et la structure de valve contribuent à la capacité parasite, mais ces contributions sont minimes et sont omises. La capacité parasite effective étant différente pour chaque rangée de valves, la valeur moyenne est utilisée pour le calcul des pertes.

5.1.8 Pertes au blocage par valve

Il s'agit de pertes supplémentaires générées par le courant inverse dans les thyristors au moment du blocage (voir Figure 8).

$$P_{V7} = Q_{rr} \times f \times \sqrt{2} \times U_{V0} \times \sin(\alpha + \mu + 2\pi \times f \times t_0)$$

où

Q_{rr} est la valeur moyenne de la charge stockée dans les thyristors, en coulombs;

t_0 est le temps déterminé à partir de la relation

$$t_0 = \sqrt{\frac{Q_{rr}}{(di/dt)_{i=0}}}$$

où

$(di/dt)_{i=0}$ est la di/dt de commutation mesurée pour un courant nul, en ampères par seconde.

NOTE 1 La valeur de Q_{rr} utilisée est l'intégrale complète du courant inverse (voir Figure 8), et non une triangulation approximative comme celle proposée dans l'IEC 60747-6. Q_{rr} est déterminée à partir de mesurages de production réalisés sur un nombre de thyristors statistiquement significatif ou, en variante, une valeur moyenne de Q_{rr} à utiliser si les thyristors sont choisis dans une bande prédéfinie de Q_{rr} et, si nécessaire, est corrigée en fonction de la température de jonction, du $(di/dt)_{i=0}$ et de la tension de rétablissement inverse correspondant aux conditions de fonctionnement pour lesquelles les pertes sont déterminées. Il est important que l'amplitude et la

durée du courant de conduction soient suffisamment importantes pour réaliser une conduction totale de la jonction de thyristor.

NOTE 2 La plus grande partie des pertes au blocage du thyristor issues de ce mécanisme se dissipe à l'intérieur du thyristor lui-même, bien qu'une partie des pertes puisse être dissipée dans d'autres composants comme la résistance d'amortissement et la bobine d'inductance de valve.

5.1.9 Perte d'inductance par valve

Une perte d'inductance comprend trois composantes: perte par résistance dans l'enroulement, perte par courants de Foucault et perte par hystérésis dans le noyau magnétique. Si un circuit d'amortissement supplémentaire est employé au niveau de l'enroulement, il subit également une perte.

La perte correspondant à l'enroulement de la bobine d'inductance ainsi que la perte par courants de Foucault du noyau de la bobine (et/ou la perte par résistance d'amortissement de la bobine) sont déjà prises en compte dans les formules concernant P_{V3} et P_{V6} .

La perte par hystérésis doit être calculée de la façon suivante. Une courbe de magnétisation en courant continu pour le ou les matériaux du noyau doit être déterminée pour la boucle d'excitation que connaît normalement une bobine d'inductance de valve en courant continu à haute tension. Cette courbe doit être établie à partir d'une force de magnétisation survenant pour une valeur représentant au moins 1,5 fois la valeur crête du courant inverse I_{rr} au moment du blocage (voir Figure 8) dans une polarité en direction de la région saturée de l'autre, puis dans le sens inverse. À partir de la zone délimitée par la boucle, une perte par hystérésis caractéristique en joules par kilogramme doit être déterminée et appliquée à la conception de la bobine d'inductance en question, c'est-à-dire

$$P_{V8} = n_L \times M \times k \times f$$

où

n_L est le nombre de noyaux d'inductance dans une valve;

M est la masse de chaque noyau, en kilogrammes;

k est la perte caractéristique, en joules par kilogramme.

Si l'intensité du courant de saturation est élevée pour la bobine d'inductance par rapport au courant de pont assigné, et que le di/dt de commutation normal est également élevé (correspondant à des angles d'empiètement réduits dans les conditions assignées), alors des pertes supplémentaires par courants de Foucault du noyau de la bobine d'inductance sont générées durant les périodes de commutation. Si c'est le cas, il convient de démontrer soit que ces pertes supplémentaires sont négligeables, soit qu'elles respectent la tolérance définie dans la déclaration concernant les pertes.

5.1.10 Pertes totales de valve

Les pertes totales en fonctionnement par valve sont indiquées par la somme des huit composantes individuelles spécifiées de 5.1.2 à 5.1.9.

$$P_{VT} = \sum_{i=1}^{i=8} P_{Vi}$$

Les pertes totales du convertisseur en fonctionnement sont égales aux pertes par valve multipliées par le nombre de valves du convertisseur.

5.1.11 Effets de la température

Tous les composants de la valve possèdent des caractéristiques électriques qui sont sensibles à la température. Cependant, il arrive souvent que le seul composant possédant

des caractéristiques sensibles à la température, pouvant influencer de manière significative les pertes de valve, soit le thyristor lui-même.

La température de jonction de thyristor T_j est déterminée par

$$T_j = T_c + P_j \times R_{\theta JC}$$

où

T_c est la température de l'agent de refroidissement correspondant à la moyenne des températures d'entrée et de sortie de la valve;

P_j est la perte de puissance totale par thyristor, correspondant à la somme de ses composantes individuelles dues à la conduction, à la répartition de potentiels et au blocage;

$R_{\theta JC}$ est la résistance thermique, de la jonction de thyristor à l'agent de refroidissement.

5.1.12 Perte en fonctionnement à vide par valve

La perte en fonctionnement à vide par valve est la somme des pertes causées par les courants entraînés par la tension bloquée par la valve au travers des résistances de la valve. Elle comprend deux termes. Le premier quantifie la perte au niveau des résistances connectées en parallèle avec les thyristors de blocage, le second détermine la perte au niveau des résistances couplées par capacité. Dans un mode de fonctionnement à vide, la valve bloque la forme d'onde sinusoïdale de la tension phase-neutre. En conséquence:

$$P_{VSB} = \frac{U_{V0}^2}{3} \left(\frac{1}{R_{DC}} + \frac{R_{AC}}{Z_{AC}^2} \right)$$

où

$$Z_{AC} = \sqrt{R_{AC}^2 + \left(\frac{1}{2\pi \times f \times C_{AC}} \right)^2}$$

Si la valve utilise plus d'une branche de réseau de répartition de potentiels intégrant R et C connectés en série, chaque branche doit être évaluée séparément et les résultats doivent être ajoutés.

Si l'énergie est extraite du réseau de répartition des potentiels R-C en vue de l'alimentation des circuits d'allumage et/ou de contrôle des thyristors, il doit être démontré que les pertes supplémentaires sont négligeables ou la perte supplémentaire doit être calculée séparément puis ajoutée au chiffre obtenu à partir de la formule P_{VSB} .

Les pertes totales du convertisseur en fonctionnement à vide sont égales à la perte en fonctionnement à vide par valve multipliée par le nombre de valves du convertisseur.

5.2 Pertes d'un transformateur de conversion

5.2.1 Généralités

Le courant parcourant les enroulements de transformateurs de conversion contient des harmoniques dont les amplitudes dépendent des paramètres de fonctionnement du poste de conversion. Les pertes dues à la charge dépendant du courant, au niveau du transformateur, et résultant des formes de courant non sinusoïdales, sont supérieures à celles qui surviennent avec un courant sinusoïdal de même valeur efficace à la fréquence fondamentale.

5.2.2 Pertes en fonctionnement à vide

En mode de fonctionnement à vide, le transformateur étant sous tension et les valves bloquées, les pertes du transformateur sont les pertes à vide. Les pertes à vide (pertes dans le circuit magnétique) doivent être déterminées conformément à l'IEC 60076-1.

La position du changeur de prises du transformateur doit être telle que définie en 4.3.

5.2.3 Pertes en fonctionnement

En mode de fonctionnement, les pertes du transformateur en fonctionnement doivent correspondre à la somme des pertes de magnétisation (pertes dans le circuit magnétique) et des pertes (dus à la charge) dépendant du courant.

Dans des conditions de charge, des tensions harmoniques sont imposées sur le transformateur. Les pertes dans le circuit magnétique en charge doivent être considérées comme étant égales aux pertes à vide pour la position de prise correspondant au niveau de charge à l'étude, sous tension nominale alternative. L'effet des tensions harmoniques sur le courant de magnétisation du transformateur, par rapport à l'effet de la composante de fréquence fondamentale de la tension, est négligeable.

Les pertes dues à la charge du transformateur doivent prendre en compte à la fois la fréquence fondamentale et les composantes harmoniques du courant et doivent être déterminées en fonction de la procédure suivante.

- Mesurer les pertes P_1 dues à la charge, à la fréquence fondamentale f_1 (50 Hz ou 60 Hz) conformément à l'IEC 60076-1.
- Calculer $P_{WE1} + P_{SE1} = P_1 - P_R$.
- Mesurer les pertes P_m dues à la charge à une fréquence plus élevée f_m égale ou supérieure à 150 Hz.

Une source de tension utilisée pour les essais de tension induite est normalement disponible. Une exactitude acceptable est atteinte pour des courants atteignant seulement 10 % à 20 % du courant assigné à condition que la répartition du flux parasite parmi les pièces métalliques ait été prise en compte dans la conception du transformateur. Si un courant réduit est utilisé, et le courant est moins que 10 %, P_m doit être recalculé en fonction du courant assigné.

- Calculer P_{WE1} et P_{SE1} sur la base des mesurages réalisés à la fréquence fondamentale et à la fréquence plus élevée en résolvant

$$P_1 = P_R + P_{WE1} + P_{SE1}$$

$$P_m = P_R + P_{WE1} \times (f_m/f_1)^2 + P_{SE1} \times (f_m/f_1)^{0,8}.$$

- Les pertes totales en service dues à la charge doivent être calculées pour chaque enroulement de valve comme suit:

$$P = P_R + P_{WE1} \times \sum_{n=1}^{n=49} (I_n/I_N)^2 \times (f_n/f_1)^2 + P_{SE1} \times \sum_{n=1}^{n=49} (I_n/I_N)^2 \times (f_n/f_1)^{0,8}$$

où

P_1 représente les pertes totales dues à la charge à la fréquence fondamentale (50 Hz ou 60 Hz);

I_N est le courant assigné;

I_n est le courant efficace pour harmonique n ;

P_R représente les pertes ohmiques pour le courant assigné;