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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

IEC 61803:2020-10(en-fr)

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

FOREWORD

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- withdrawn,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.

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° ($2\pi/3 + \mu$). 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).

$$P_{V2} = N_t \times f \times \int_0^{t1} \left[u_B(t) - u_A(t) \right] \times i(t) \, dt$$

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.

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

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.

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

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 $\mu < \pi/6$ (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.