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INTERNATIONAL STANDARD

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colour inside

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 le réseau

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

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The technical content is therefore identical to the base edition and its amendment and has been prepared for user convenience. A vertical line in the margin shows where the base publication has been modified by amendment 1. Additions and deletions are displayed in red, with deletions being struck through.

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

Annex A forms an integral part of this standard.

Annexes B and C are for information only.

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

1 Scope

This International Standard applies to all line-commutated high-voltage direct current (HVDC) converter stations used for power exchange in utility systems. This standard 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 a.c. bus of the HVDC converter station. The loss determination procedures for such equipment are not included in this standard.

This standard 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 standard, or designs equipped with unusual auxiliary circuits that could affect the losses, shall be assessed on their own merits.

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2 Normative references

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

IEC 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 60700-1~~:1998~~, *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 Definitions and symbols

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

3.1 Definitions

3.1.1
auxiliary losses
the electric power required to feed the converter station auxiliary loads. The auxiliary losses depend on 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
no-load operation losses
the losses produced in an item of equipment with the converter station energized but with the converters blocked and all station service loads and auxiliary equipment connected as required for immediate pick-up of load

3.1.3
load level
this term specifies the direct current, direct voltage, firing angle, a.c. voltage, and converter transformer tap-changer position at which the converter station is operating

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

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3.1.5
rated load
this load is related to operation at nominal values of d.c. current, d.c. voltage, a.c. voltage and converter firing angle. The a.c. 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 a.c. filters and shunt reactive elements connected shall be consistent with operation at rated load, coincident with nominal conditions

3.1.6
total station losses
the total station loss is the sum of all operating or no-load operation losses and the corresponding auxiliary losses

3.1.7
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 must remain working in case of complete loss of a.c. power supply (e.g. battery chargers, operating mechanisms)

NOTE Total “operating losses” minus “no load operation losses” may be considered as being quantitatively equivalent to “load losses” as in conventional a.c. substation practice.

3.2 Letter symbols

α	~~firing~~ (trigger) delay angle, in radians (rad)
μ	~~commutation~~ overlap angle, in radians (rad)
f	a.c. system frequency, in hertz (Hz)
I_d	direct current, ~~in the bridge d.c. connection,~~ in amperes (A)
I_n	harmonic r.m.s. current of order n, in amperes (A)
L_1	the 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 a.c. harmonic filters
L_2	the 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	the 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 r.m.s. voltage of order n, in volts (V)
U_{vo}	r.m.s. 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)

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4 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 a.c. source and also connected together via their d.c. terminals. In this connection, the power drawn from the a.c. source equals the losses in the circuit. However, the a.c. source must 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 standard standardizes a method of calculating the HVDC converter station losses by summing the losses calculated for each item of equipment. The standardized calculation method will help the purchaser to meaningfully compare the competing bids. It will also allow an easy generation of performance curves for the wide range of operating conditions in which the performance has to be known. In the absence of an inexpensive experimental method which could be employed for an objective verification of losses during type tests, the calculation method is the next best alternative as it uses, wherever possible, experimental data obtained from measurements on individual equipment and components under conditions equivalent to those encountered in real operation.

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

4.2 Ambient conditions

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

4.2.1 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.

NOTE 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.

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4.2.2 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.

4.2.3 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 operating losses and auxiliary losses are affected by the load level of the station because the numbers of certain types of energized 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) a.c. 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 a.c. 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 a.c. voltage, d.c. 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 4.2.1 and 4.2.2), shall be assumed to be connected to support the respective load level.

For the no-load operation mode, converter transformers shall be energized 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.

5 Determination of equipment losses

5.1 Thyristor valve losses

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 subclauses 5.1.1 to 5.1.10, and no-load operation losses are dealt with in 5.1.11. Auxiliary losses are dealt with in 5.8.

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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 d.c. 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 5.1.4 and 5.1.11). 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 and inverter 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 standard, 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.

5.1.1 Thyristor conduction loss per valve

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

$$P_{\mathrm{V1a}} = \frac{N_{\mathrm{t}} \times I_{\mathrm{d}}}{3}\left[U_0 + R_0 \times I_{\mathrm{d}} \times \left(\frac{2\pi - \mu}{2\pi}\right)\right]$$

$$P_{\mathrm{V1b}} = \frac{N_{\mathrm{t}} \times I_{\mathrm{d}} \times U_0}{3} + \frac{N_{\mathrm{t}} \times R_0}{3}\left(I_{\mathrm{d}}^2 + \sum_{n=12}^{n=48} I_n^2\right)\left(\frac{2\pi - \mu}{2\pi}\right)$$

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 r.m.s. value of the nth harmonic current in the bridge d.c. 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 d.c. bridge current divided by p. The calculated result is then multiplied by p.

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5.1.2 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).

$$P_{\mathrm{V2}} = N_{\mathrm{t}} \times f \times \int_0^{t1} \left[u_{\mathrm{B}}(t) - u_{\mathrm{A}}(t)\right] \times i(t)\,\mathrm{d}t$$

where

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

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

$u_{\mathrm{B}}(t)$ 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 figures 5 and 6);

$u_{\mathrm{A}}(t)$ 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 (see IEC 60700-1) or, alternatively, from a separate laboratory test on a statistically significant number of thyristors.

5.1.3 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 d.c. 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.

5.1.4 D.C. 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 d.c. 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.

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

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

where

R_{DC} is the effective off-state d.c. resistance of a complete valve determined by measuring the current drawn during the valve terminal-to-terminal d.c. voltage type test (see IEC 60700) 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 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 a.c. 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 ($L_{2d} = L_{2y}$) (see notes 3 and 4 below).

NOTE 1 The equation 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 5.1.10). The same pertains to the liquid coolant.

NOTE 3 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 a.c. harmonic filters are connected, L_1 also includes the a.c. 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 be determined with care.

5.1.5 Damping loss per valve (resistor-dependent term)

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

$$P_{V5} = 2\pi f^2 U_{v0}^2 C_{AC}^2 R_{AC} \left\{ \begin{aligned} & \frac{4\pi}{3} - \frac{\sqrt{3}}{2} + \frac{3\sqrt{3}m^2}{8} + \left(6m^2 - 12m - 7\right)\frac{\mu}{4} + \left(\frac{7}{8} + \frac{9m}{4} - \frac{39m^2}{32}\right)\sin 2\alpha + \\ & \left(\frac{7}{8} + \frac{3m}{4} + \frac{3m^2}{32}\right)\sin(2\alpha + 2\mu) - \left(\frac{\sqrt{3}m}{16} + \frac{3\sqrt{3}m^2}{8}\right)\cos 2\alpha + \frac{\sqrt{3}m}{16}\cos(2\alpha + 2\mu) \end{aligned} \right\}$$

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where

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

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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 energize 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 equation P_{V5}.

NOTE Notes 1, 3 and 4 in 5.1.4 also apply to P_{V5}.