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INTERNATIONAL STANDARD

NORME INTERNATIONALE

colour inside

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

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

IEC 62751-1:2014-08(en-fr)

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

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CONTENTS

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

Part 1: General requirements

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International Standard IEC 62751-1 has been prepared by subcommittee 22F: Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment.

The text of this standard is based on the following documents:

CDV	Report on voting
22F/302/CDV	22F/321A/RVC

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

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

A list of all parts in the IEC 62751series, published under the general title *Power losses in voltage sourced converter (VSC) valves for high-voltage direct current (HVDC) systems*, can be found on the IEC website.

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

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- withdrawn,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

Part 1: General requirements

1 Scope

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

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

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

2 Normative references

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

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

IEC 60747-2, *Semiconductor devices – Discrete devices and integrated circuits – Part 2: Rectifier diodes*

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

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

3 Terms and definitions

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

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

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

3.1 Converter types

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

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

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

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

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

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

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

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

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

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

3.2 Semiconductor devices

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

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

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

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

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

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

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

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

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

3.3 Converter operating states

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

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

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

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

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

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

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

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

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

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

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

3.4 Device characteristics

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

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

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

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

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

3.5 Other definitions

3.5.1
VSC valve level
smallest indivisible functional unit of VSC valve

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

3.5.2
redundant levels
maximum number of series connected VSC valve levels or diode valve levels in a valve that may be short-circuited externally or internally during service without affecting the safe operation of the valve as demonstrated by type tests, and which if and when exceeded, would require shutdown of the valve to replace the failed levels or acceptance of increased risk of failures

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

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

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

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

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

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

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

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

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

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

4 General conditions

4.1 General

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

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

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

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

4.2 Causes of power losses

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

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

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

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

- conduction losses;
- switching losses.

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

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

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

4.3 Categories of valve losses

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

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

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

4.4 Operating conditions

4.4.1 General

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

4.4.2 Reference ambient conditions

The following default reference ambient conditions are applied:

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

4.4.3 Reference a.c. system conditions

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

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

4.4.4 Converter operating states

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

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

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

4.4.5 Treatment of redundancy

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

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

4.5 Use of real measured data

4.5.1 General

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

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

4.5.2 Routine testing

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

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

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

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

4.5.3 Characterisation testing

4.5.3.1 Characterisation testing of semiconductor devices

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

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

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

Operating variables are as follows:

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