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INTERNATIONAL STANDARD

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colour inside

Power losses in voltage sourced converter (VSC) valves for high-voltage direct current (HVDC) systems – Part 2: Modular multilevel converters

Pertes de puissance dans les valves à convertisseur de source de tension (VSC) des systèmes en courant continu à haute tension (CCHT) – Partie 2: Convertisseurs multiniveaux modulaires

IEC 62751-2:2014-08(en-fr)

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

Part 2: Modular multilevel converters

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International Standard IEC 62751-2 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/303/CDV	22F/322A/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,
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POWER LOSSES IN VOLTAGE SOURCED CONVERTER (VSC) VALVES FOR HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS –

Part 2: Modular multilevel converters

1 Scope

This part of IEC 62751 gives the detailed method to be adopted for calculating the power losses in the valves for an HVDC system based on the “modular multi-level converter”, where each valve in the converter consists of a number of self-contained, two-terminal controllable voltage sources connected in series. It is applicable both for the cases where each modular cell uses only a single turn-off semiconductor device in each switch position, and the case where each switch position consists of a number of turn-off semiconductor devices in series (topology also referred to as “cascaded two-level converter”). The main formulae are given for the two-level “half-bridge” configuration but guidance is also given in Annex A as to how to extend the results to certain other types of MMC building block configuration.

The standard is written mainly for insulated gate bipolar transistors (IGBTs) but may also be used for guidance in the event that other types of turn-off semiconductor devices are used.

Power losses in other items of equipment in the HVDC station, apart from the converter valves, are excluded from the scope of this standard.

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

IEC 62751-1:2014, *Power losses in voltage sourced converter (VSC) valves for high-voltage direct current (HVDC) systems – Part 1: General* requirements

ISO/IEC Guide 98-3, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

3 Terms, definitions, symbols and abbreviated terms

For the purposes of this document, the terms and definitions given in IEC 60633, IEC 62747, IEC 62751-1, as well as the following apply.

3.1 Terms and definitions

3.1.1
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: This note applies to the French language only.

3.1.2
MMC building block
self-contained, two-terminal controllable voltage source together with d.c. capacitor(s) and immediate auxiliaries, forming part of a MMC

3.1.3
IGBT-diode pair
arrangement of IGBT and free-wheeling diode connected in inverse parallel

3.1.4
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.

3.1.5
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: This note applies to the French language only.

3.1.6
submodule
MMC building block where each switch position consists of only one IGBT-diode pair

3.1.7
cell
MMC building block where each switch position consists of more than one IGBT-diode pair connected in series

3.1.8
turn-off semiconductor device
controllable semiconductor device which may be turned on and off by a control signal, for example an IGBT

3.1.9
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: This note applies to the French language only.

3.1.10
operating state
condition in which the HVDC 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.

3.1.11
no-load operating state
condition in which the HVDC substation is energized but the IGBTs are blocked and all necessary substation service loads and auxiliary equipment are connected

3.1.12
idling operating state
condition in which the HVDC 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 behavior 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.

3.1.13
modulation index of PWM converters
M
ratio of the peak line to ground a.c. converter voltage, to half of the converter d.c. terminal to terminal voltage

$$M = \frac{\sqrt{2} \cdot U_{c1}}{\sqrt{3} \cdot \frac{U_{dc}}{2}}$$

where

U_{c1} is the r.m.s value of the fundamental frequency component of the line-to-line voltage U_c;

U_c is the output voltage of one VSC phase unit at its a.c. terminal;

U_{dc} is the output voltage of one VSC phase unit at its d.c. terminals.

Note 1 to entry: Some sources define modulation index in a different way such that a modulation index of 1 refers to a square-wave output, which means that the modulation index can never exceed 1. The modulation index according to that definition is given simply by $M \cdot (\pi/4)$. However, that definition is relevant mainly to two-level converters using PWM.

3.2 Symbols and abbreviated terms

3.2.1 Valve and simulation data

N_{tc} number of MMC building blocks per valve

N_c number of series-connected semiconductor devices per switch position

N_{sr} total number of series resistive elements contributing to conduction losses in the valve, other than in the IGBTs and diodes

N_{cv} number of d.c. capacitors in the valve

N_s number of switching cycles (on or off) experienced by each VSC valve level during the integration time t_i

N_{pr} total number of parallel resistive elements contributing to d.c. voltage dependent losses in the valve

N_{sn} number of snubber circuits per valve

t_i integration time used in the simulation

3.2.2 Semiconductor device characteristics

V_{0T} average IGBT threshold voltage for the relevant operating conditions

R_{0T} average IGBT slope resistance for the relevant operating conditions, valid at the device terminals

V_{0D} average diode threshold voltage for the relevant operating conditions

R_{0D} average diode slope resistance for the relevant operating condition, valid at the device terminals

E_{on} average turn-on energy dissipated in the IGBT for the relevant operating conditions

E_{off} average turn-off energy dissipated in the IGBT(s) for the relevant operating conditions

$E_{on,T1\_j,k}$ turn-on energy dissipated in IGBT T1 in the j^{th} MMC building block for the k^{th} turn-on event for the relevant operating conditions (voltage, current and junction temperature)

$E_{on,T2\_j,k}$ turn-on energy dissipated in IGBT T2 in the j^{th} MMC building block for the k^{th} turn-on event for the relevant operating conditions (voltage, current and junction temperature)

$E_{off,T1\_j,k}$ turn-off energy dissipated in IGBT T1 in the j^{th} MMC building block for the k^{th} turn-off event for the relevant operating conditions (voltage, current and junction temperature)

$E_{off,T2\_j,k}$ turn-off energy dissipated in IGBT T2 in the j^{th} MMC building block for the k^{th} turn-off event for the relevant operating conditions (voltage, current and junction temperature)

$E_{rec,D1\_j,k}$ diode recovery energy dissipated in diode D1 in the j^{th} MMC building block for the k^{th} diode turn-off event for the relevant operating conditions (voltage, current and junction temperature)

$E_{rec,D2\_j,k}$ diode recovery energy dissipated in diode D2 in the j^{th} MMC building block for the k^{th} diode turn-off event for the relevant operating conditions (voltage, current and junction temperature)

3.2.3 Other component characteristics

R_{s_k} total resistance of the k^{th} series resistive elements in the valve contributing to other conduction losses

R_{dc_k} resistance of the k^{th} parallel resistive component in the valve

R_{ESR_j} average equivalent series resistance of the j^{th} d.c. capacitor

$E_{sn,on\_j,k}$ energy dissipated in the snubber resistor of the j^{th} snubber circuit for the k^{th} turn-on event for the relevant operating conditions (voltage, and current where relevant to the design of the snubber)

$E_{sn,off\_j,k}$ energy dissipated in the snubber resistor of the j^{th} snubber circuit for the k^{th} turn-off event for the relevant operating conditions (voltage, and current where relevant to the design of the snubber)

3.2.4 Operating parameters

I_{T1av_j} mean current of IGBT T1 in the j^{th} MMC building block, averaged over an integration time t_i

I_{T2av_j} mean current of IGBT T2 in the j^{th} MMC building block, averaged over an integration time t_i

I_{T1rms_j} rms current of IGBT T1 in the j^{th} MMC building block, averaged over an integration time t_i

I_{T2rms_j} rms current of IGBT T2 in the j^{th} MMC building block, averaged over an integration time t_i

I_{D1av_j}	mean current of diode D1 in the j^{th} MMC building block, averaged over an integration time t_i
I_{D2av_j}	mean current of diode D2 in the j^{th} MMC building block, averaged over an integration time t_i
I_{D1rms_j}	rms current of diode D1 in the j^{th} MMC building block, averaged over an integration time t_i
I_{D2rms_j}	rms current of diode D2 in the j^{th} MMC building block, averaged over an integration time t_i
I_{rms_k}	rms current flowing in the k^{th} series resistive element for the relevant operating conditions
U_{rms_k}	rms value (including d.c. component) of the voltage across the k^{th} parallel resistive component in the valve
I_{crms_j}	rms current flowing in the j^{th} d.c. capacitor of the valve
$P_{GU\_j,k}$	average power input to the power supply of k^{th} IGBT in j^{th} MMC building block
$p_{GU\_j,k}(t)$	instantaneous power input to the power supply of k^{th} IGBT in j^{th} MMC building block
$u_{GU\_j,k}(t)$	instantaneous voltage input to the power supply of k^{th} IGBT in j^{th} MMC building block
$i_{GU\_j,k}(t)$	instantaneous current input to the power supply of k^{th} IGBT in j^{th} MMC building block
P_{GU_j}	average power input to the power supply in j^{th} MMC building block
$p_{GU\_j}(t)$	instantaneous power input to the power supply in j^{th} MMC building block
$u_{GU\_j}(t)$	instantaneous voltage input to the power supply in j^{th} MMC building block
$i_{GU\_j}(t)$	instantaneous current input to the power supply in j^{th} MMC building block

3.2.5 Loss parameters

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}	d.c. capacitor losses
P_{V6}	IGBT switching losses
P_{V7}	diode turn-off losses
P_{V8}	snubber losses
P_{V9}	valve electronics power consumption
P_{Vt}	total valve losses

4 General conditions

4.1 General

Modular multi-level converters (MMC) are a family of converters in which each valve forms a controllable voltage source. The converter a.c. voltage is synthesized by switching large numbers of relatively small, self-contained, two-terminal controllable voltage sources at different times, thereby obtaining a high-quality converter waveform with low switching losses and therefore a high overall efficiency. The MMC building blocks from which the overall converter is built up may use multiple IGBT-diode pairs connected in series (in which case the converter is referred to as the “Cascaded two level converter”, CTLC) or only a single IGBT-diode pair per switch position. A detailed description of these types of converter is beyond the scope of this standard; however, Annex A includes a general description of the operation of the MMC (see also IEC TR 62543).

4.2 Principles for loss determination

Theoretically, the losses of a converter station can be determined either by direct measurements of the input and output powers or by means of component characteristics, using suitable mathematical models of the individual components of a converter. The selection of the principle under which the losses are to be determined shall take into consideration the uncertainties.

The overall uncertainty of the value of losses is an important parameter for a converter and for a converter station since it is used to compare investment cost to capitalised cost over the life-time of the converter station. To ensure that estimates are undisputed, adherence to the provisions of this standard and the provisions of ISO/IEC Guide 98-3 is indispensable. All measurements shall furthermore be traceable to national and/or international standards of measurement.

As mentioned above, a determination of the losses of a converter station could in principle be performed by making a direct measurement a.c. and d.c. side power. The difference between these two power values is however small, and a good accuracy will be very difficult to reach. In practice this measurement would require the use of state-of-the-art measurement equipment that rivals the best equipment available at national metrology institutes, equipment that is not intended for on-site use. While not impossible, this method is unlikely to be used.

In rare cases, where there are two converters in a substation, there may be an opportunity to connect the two converters in a temporary back-to-back configuration and circulate d.c. power between them, with their total loss being supplied by the a.c. grid. This loss can be measured, using standard energy meters and voltage transformers, but with special current transformers that have a rated current that is on the order of 5 % to 10 % of the normal operating current of the converters in order to reach sufficient accuracy at the power levels to be measured. In order to enable back-to-back measurements, additional equipment and/or control and protection enhancements could be needed, which will increase the investment cost of the converter station.

For most cases, however, the losses have to be estimated from component characteristics, using suitable mathematical models of the converters, as discussed in this standard. It is however important that all such estimates have a base in actual measurements having sufficiently low uncertainty. Care should also be taken to show the propagation of uncertainties from measurements and how they interact with the model. Estimates of the uncertainty contributions from imperfections in the models themselves should also be considered.

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} d.c. capacitor losses

P_{V6} IGBT switching losses

P_{V7} diode turn-off losses

P_{V8} snubber losses

P_{V9} valve electronics power consumption

For the MMC topology, because the switching frequency is usually low (less than 200 Hz) the largest contributors to the valve losses are usually the IGBT and diode conduction losses P_{V1} and P_{V2}. With half-bridge converters, P_{V1} is dominant in inverter mode and P_{V2} is dominant in rectifier mode, while with full-bridge converters there is no major difference between rectifier and inverter modes. IGBT switching losses P_{V6} and diode turn-off losses P_{V7} are also a significant (although not dominant) contribution. The other components of valve losses are generally minor.

4.4 Loss calculation method

The proposed method for determining valve losses is based on analytical formulae for the operating conditions. However, some of the necessary input parameters are difficult to obtain by purely analytical means. Numerical solutions using real-time or non-real-time simulations shall be applied, to derive such input parameters, for example valve currents and switching energies. For that, the input parameters described in 4.5 are required.

Important requirement for such simulations is an accurate modelling of the system under investigation. Multi-level converters offer a high degree of freedom in terms of control strategies. Therefore the resulting valve currents strongly depend on the realization and the algorithms of the control itself.

In alignment with the statement presented in 4.2, uncertainties of numerical simulations shall be clearly stated and justified by the manufacturer.

4.5 Input parameters

4.5.1 General

This subclause describes the input parameters necessary for the calculation of power losses in the valves of an MMC to take place. These input parameters refer to the data needed for the performance of numerical simulations as well as the converter and component data needed for calculation of losses. At the same time, converter and component data is divided into two categories: converter station data such as the number of MMC building blocks per valve and the on-state characteristics of the IGBT and free-wheeling diode, and operating parameters such as the converter a.c. and d.c. currents, converter voltage (amplitude and waveshape, including 3rd harmonic injection where applicable), a.c. system frequency and mean MMC building block switching frequency.

4.5.2 Input data for numerical simulations

For numerical simulations, the following requirements shall be considered.

– The simulation model shall include a control block which represents the real control behaviour and realistic behaviour regarding measurements, dead and transfer times, interlocking times, etc.

– The calculations shall be performed for a period of time with stable conditions in terms of active and reactive power transfer on the a.c. side and active power on the d.c. side.

– After the simulation has settled to steady-state conditions, a minimum integration time t_i of 1 s shall be used for operating state losses, but a longer time may be required for standby and no-load operating states, depending on the switching strategies used.

– The simulation models shall represent real conditions of the converter station in terms of number of MMC building blocks, main components, parasitic elements, original control algorithms, voltage and current sensors. For the calculation of valve losses, all redundant VSC levels shall be assumed to be in operation.

– A simplification of the simulation model with a reduced number of MMC building blocks is possible if it can be demonstrated that the resulting valve currents are not influenced by the simplification.

– The simulation shall also consider the junction temperature dependent semiconductor properties, such as on-state voltages, switching and recovery losses. These properties are based on the characterisation testing as described in IEC 62751-1:2014, 4.4.2. The steady-state junction temperatures of the semiconductors are calculated iteratively for the relevant operating point to derive the semiconductor losses. Further outputs of the