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TECHNICAL REPORT

AMENDMENT 1

High-voltage direct current (HVDC) power transmission using voltage sourced converters (VSC)

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High-voltage direct current (HVDC) power transmission using voltage sourced converters (VSC)

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FOREWORD

This amendment 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 amendment is based on the following documents:

DTR	Report on voting
22F/300A/DTR	22F/307/RVC

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

The committee has decided that the contents of this amendment and the base 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- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

CONTENTS

Add the title of subclauses 5.3.4, subclause 5.3.5 and 5.6.12 as follows:

Replace, in the list of figures, the titles of Figure 11 and Figure 12 as follows:

1 Scope

Replace, the last sentence of the first paragraph, by the following:

The scope includes 2-level and 3-level converters with pulse-width modulation (PWM), along with multi-level converters, modular multi-level converters and cascaded two-level converters, but excludes 2-level and 3-level converters operated without PWM, in squarewave output mode.

Figure 1– Major components that may be found in a VSC substation

Replace the footnote b by the following new footnote b:

In some designs of VSC, the VSC d.c. capacitor may be partly or entirely distributed amongst the three phase units of the VSC unit, where it is referred to as the d.c. cell or submodule capacitors.

3.3 Power semiconductor terms

Delete the first paragraph, that is the note and its contents.

3.3.1
switched valve devices

Replace the existing term 3.3.1 and its definition by the following new term, its definition and note:

3.3.1
turn-off semiconductor device
a controllable semiconductor device which may be turned on and off by a control signal, for example IGBT

NOTE There are several types of turn-off semiconductor devices which can be used in voltage sourced converters (VSC) for HVDC and currently the IGBT is the major device used in such converters. The term IGBT is used throughout this technical report to refer to the turn-off semiconductor device. However, the technical report is equally applicable to other types of devices with turn-off capability in most of the parts.

3.3.2
insulated gate bipolar transistor
IGBT

Replace the definition of this term by the following new definition and note:

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

NOTE By applying the appropriate gate to the emitter voltages, current in one direction can be controlled, i.e. turned on and turned off.

3.3.3
free-wheeling diode
FWD

Replace the definition of this term with the following new definition and notes:

power semiconductor device with diode characteristic

NOTE 1 A FWD has two terminals: an anode (A) and a cathode (K).

NOTE 2 The current through FWDs is in the opposite direction to the IGBT current.

NOTE 3 FWDs are characterized by the capability to cope with high rates of decrease of current caused by the switching behaviour of the IGBT.

3.4 VSC topologies

3.4.7
modular multi-level converter
MMC

Replace the definition of this term with the following definition:

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

Add, after 3.4.23, the following new terms 3.4.24 and 3.4.25 and their definitions:

3.4.24
MMC building block
self-contained, two-terminal controllable voltage source together with d.c. capacitor(s) and immediate auxiliaries, forming part of a MMC

Add, after 3.4.24, the following new term 3.4.25 and its definition as shown below:

3.4.25
cascaded two-level (CTL) converter

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

3.4.10
VSC valve

Replace the definition of this term by the following two new subentries 3.4.10.1 and 3.4.10.2 and their definitions:

3.4.10.1
switch type VSC valve
arrangement of IGBT-diode pairs connected in series and arranged to be switched simultaneously as a single function unit

3.4.10.2
controllable voltage source type VSC valve
complete controllable voltage source assembly, which is generally connected between one a.c. terminal and one d.c. terminal

3.4.11
diode valve

Replace the existing definition of term 3.4.11 *with the following new definition:*

semiconductor valve containing diodes as the main semiconductor devices and associated circuits and components if any, which might be used in some VSC topologies

3.4.13
VSC valve level

Replace the existing definition and note of 3.4.13 , by the following new definition and note:

the smallest indivisible functional unit of VSC valve

NOTE 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 without IGBT-diode pairs connected in series one valve level is one submodule together with its auxiliaries.

3.4.15
redundant levels

Replace the existing definition of term 3.4.15 *by the following definition and note:*

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, when exceeded, would require shutdown of the valve to replace the failed levels or acceptance of increased risk of failures

NOTE 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.

3.4.17
submodule d.c. capacitor

Replace the term 3.4.17 *and its definition by the following new term, definition and note:*

3.4.17
d.c. capacitor
capacitor used as part of a voltage sourced converter which experiences mainly d.c. voltage between its terminals

NOTE For valves of the controllable switch type, the d.c. capacitor is usually arranged as a single device between the d.c. terminals. For valves of the controllable voltage-sourced type, the d.c. capacitor is usually distributed amongst the MMC building blocks.

3.4.18
valve reactor

Replace the existing definition of term 3.4.18 *by the following new definition:*

a reactor (if any) which is connected in series to a VSC valve of the controllable voltage-source type

NOTE One or more valve reactors can be associated to one VSC valve and might be connected at different positions within the valve. According to the definition, valve reactors are not part of the VSC valve. However, it is also possible to integrate the valve reactors in the structural design of the VSC valve, e.g. into each valve level.

3.4.19
valve structure

Replace the existing definition of term 3.4.19 *by the following new definition:*

structural components of a valve, required in order to physically support the valve modules

3.4.21
multiple valve unit
MVU

Replace the existing definition of term 3.4.21 by the following new definition:

mechanical arrangement of 2 or more valves sharing a common valve support, where applicable

3.4.22
valve section

Replace the existing definition of term 3.4.22 *by the following new definition and note:*

electrical assembly, defined for test purposes, comprising a number of valve levels and other components, which exhibits pro-rated electrical properties of a complete valve

NOTE For valves of controllable voltage source type, the valve section shall include d.c. capacitor in addition to VSC valve levels.

3.4.23
valve base electronics
VBE

Replace existing definition of term 3.4.23 *by the following new definition:*

electronic unit, at earth potential, providing the electrical to optical conversion between the converter control system and the VSC valves

Add, after 3.4.25, the following new terms 3.4.26 and 3.4.27 and their definitions:

3.4.26
submodule
MMC building block where each switch position consists of only one IGBT-diode pair

3.4.27
cell
MMC building block where each switch position consists of more than one IGBT-diode pair connected in series

3.5.3
phase reactor

Replace existing definition of term 3.5.3 *by the following new definition:*

reactor connected directly to the a.c. terminal of the VSC phase unit, forming part of the coupling inductance

3.5.5
a.c. system side harmonic filter

Replace existing term 3.5.5 *and its definition with the following new term, definition and note:*

3.5.5
a.c. harmonic filters
filter circuits to prevent VSC-generated harmonics – if applicable – from penetrating into the a.c. system or to prevent amplification of background harmonics on the a.c. system

NOTE AC harmonic filters can be installed on either the line side or the converter side of the interface transformer.

3.5.7
HF blocking filter

Replace existing term 3.5.7 *and its definition with the following term, definition and note:*

3.5.7
high frequency filter
HF filter
filter circuits to prevent VSC-generated high frequency (HF) harmonics – if applicable – from penetrating into the a.c. system

NOTE High frequency filters can be installed on either the line side or the converter side of the interface transformer.

3.5.9
common mode blocking reactor

Replace the words "bipolar long distance" *with the words* "an HVDC" *in the definition.*

3.5.10
d.c. harmonic filter

Replace the existing definition of term 3.5.10 *by the following new definition and note:*

d.c. filters (if any) used to prevent harmonics generated by VSC valve from penetrating into the d.c. system

NOTE The filter can consist of a tuned shunt branch, smoothing reactor or common mode blocking reactor or combinations thereof.

3.5.11
d.c. reactor

Replace the existing definition of term 3.5.11 *with the following new definition:*

a reactor (if any) connected in series to a d.c. busbar

NOTE DC reactor is used to reduce harmonic currents flowing in the d.c. line or cable and to detune critical resonances within the d.c. circuit. A d.c. reactor might also be used for protection purposes.

3.6.3
STATCOM operation

Replace the existing definition of term 3.6.3 *with the following new definition:*

mode of operation of a converter when only reactive power (capacitive or inductive) is exchanged with the a.c. system

3.6.13
blocked state

Replace the existing definition of term 3.6.13 *with the following definition:*

condition in which all valves of the VSC unit are blocked

3.6.15
modulation index of PWM converters

Replace the existing term 3.6.15 *and its definition with the following new term and definition:*

3.6.15
modulation index
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 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* (π/4). However, that definition is relevant mainly to two-level converters using PWM.

3.11.1
auxiliary losses

Replace the existing definition of term 3.11.1 *with the following new definition and note:*

electric power required to feed the VSC substation auxiliary loads

NOTE The auxiliary losses depend on whether the substation is in no-load, idling or carrying load, in which case the auxiliary losses depend on the load level.

3.11.2
standby losses

Replace the existing term 3.11.2 *by the following new term:*

3.11.2
no-load operating losses

3.11.3
no-load operating losses

Replace the existing term 3.11.3 *by the following new term and its definition*:

3.11.3
idling operating losses
losses produced in an item of equipment with the VSC substation energized and with the VSCs de-blocked but with no real or reactive power output

4.4 Semiconductors for VSC transmission

Replace, in the second paragraph, the words "controllable switch*" by the words "*turn-off semiconductor device*".*

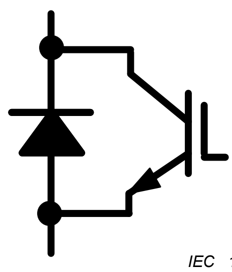
Replace, in the first and second sentence of the third paragraph, the words "semiconductor switches" *by the words* "turn-off semiconductor devices"

Figure 11 – Symbol of a controllable switch and associated free-wheeling diode

Replace, in the figure title, the words "controllable switch" by the words "turn-off semiconductor device"

Figure 12 – Symbol of an IGBT

Replace the figure by the following new figure and title:



IEC 1904/13

Figure 12 – Symbol of an IGBT and associated free-wheeling diode

5.1 General

Replace the first paragraph by the following two paragraphs:

For a high power VSC transmission system, the key issue that determines the cost and operating losses of the overall system is the power circuit structure to construct the a.c. output voltage waveform. The output voltage waveform should approximate a sine-wave in order to eliminate or minimize the need for harmonic filtering. The switching converter considered for practical implementation is a voltage sourced converter operated with a fixed d.c. voltage. The converter is a combination of turn-off semiconductor devices that connect the d.c. input voltage periodically to the output for some intervals to produce the a.c. output voltage. The converters at each end of a VSC transmission system can be arranged in a number of different ways, with the configuration of the converter normally being referred to as its topology. At the time of writing, two different converter types have been used for commercial projects: those in which the converter valves act as controllable switches and those in which the converter valves act as controllable voltage sources. These two types are described in subclauses 5.2 and 5.3 respectively.

Some other converter topologies which share the characteristics of both the "controllable switch" and "controllable voltage source" types have been described in the literature. The reader is referred to CIGRÉ Technical Brochure No. 492 "Voltage Source Converter (VSC) HVDC for Power Transmission – Economic Aspects and Comparison with other AC and DC Technologies", for details.

Figure 13 – Diagram of a three-phase 2-level converter and associated a.c. waveform for one phase

Replace the figure with the following new figure:

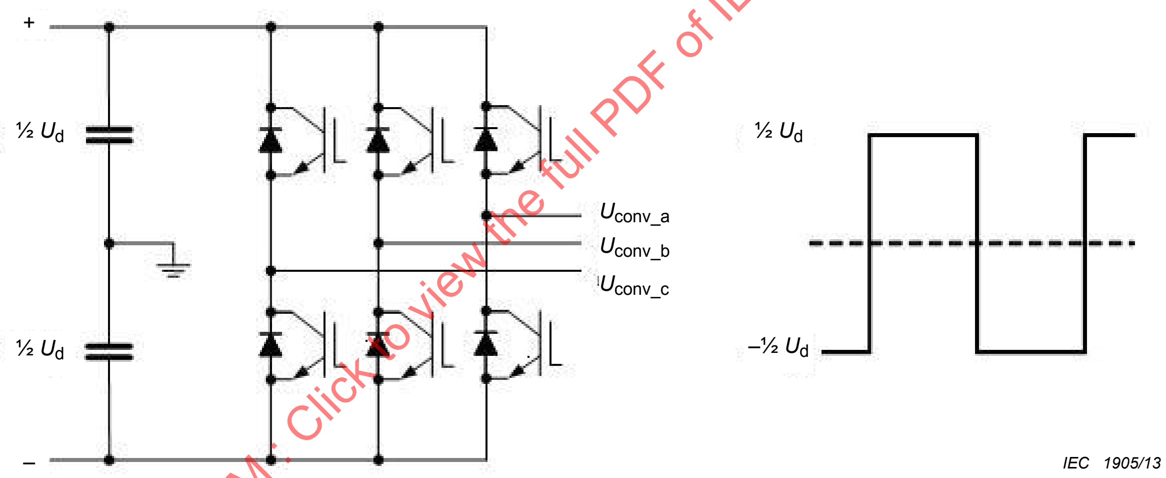
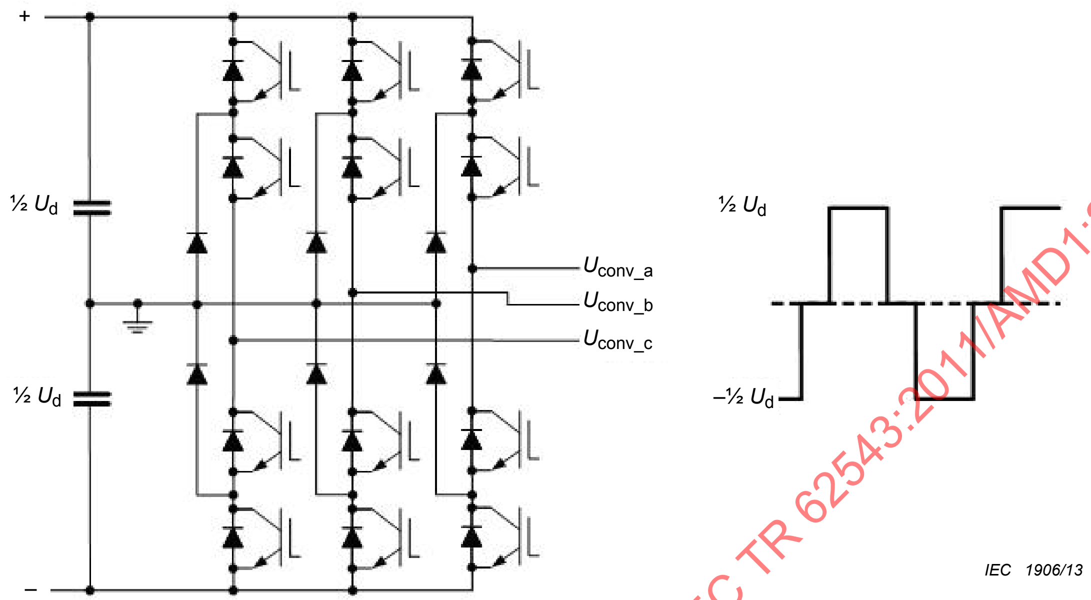


Figure 15– Diagram of a three-phase 3-level NPC converter and associated a.c. waveform for one phase

Replace the figure with the following new figure:



5.2.3.3 Other multi-level converter topologies

Replace the last sentence by the following:

These and other possible multi-level converter topologies are described in CIGRÉ Technical Brochures 269 and 447.

5.3 Converter topologies with VSC valves of the "controllable voltage source" type

5.3.1 General

Add, at the end of the second paragraph, the following text:

The VSC valve submodules or cells are controlled in that way so that the sum of the upper and lower arm of one phase unit equals to the d.c. voltage whereas the instantaneous voltage on the a.c. terminals is determined by the ratio of the voltages of the two converter phase arms of one phase unit.

Insert, at end of subclause 5.3.1, the following new paragraph:

This type of converter can also be realised with multiple IGBTs connected in series in each controllable switch, giving an output voltage waveform with fewer, larger, steps than the MMC. This configuration is referred to as the Cascaded Two Level (CTL) converter but is functionally identical to the MMC in every aspect apart from the harmonic performance which may be slightly poorer.

Figure 18 – VSC valve level arrangement and equivalent circuit in MMC topology in half-bridge topology

Replace the figure by the following new figure:

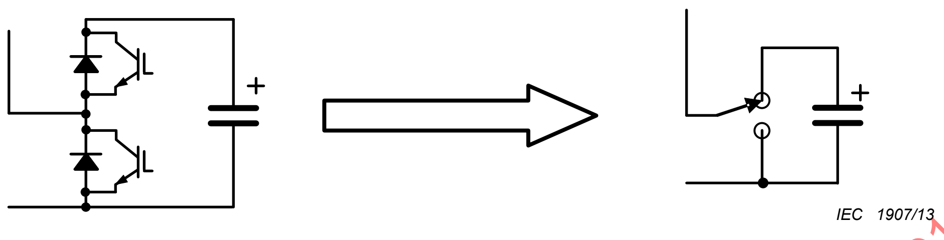


Figure 19 – Converter block arrangement with MMC topology in half-bridge topology

Replace the figure by the following new figure:

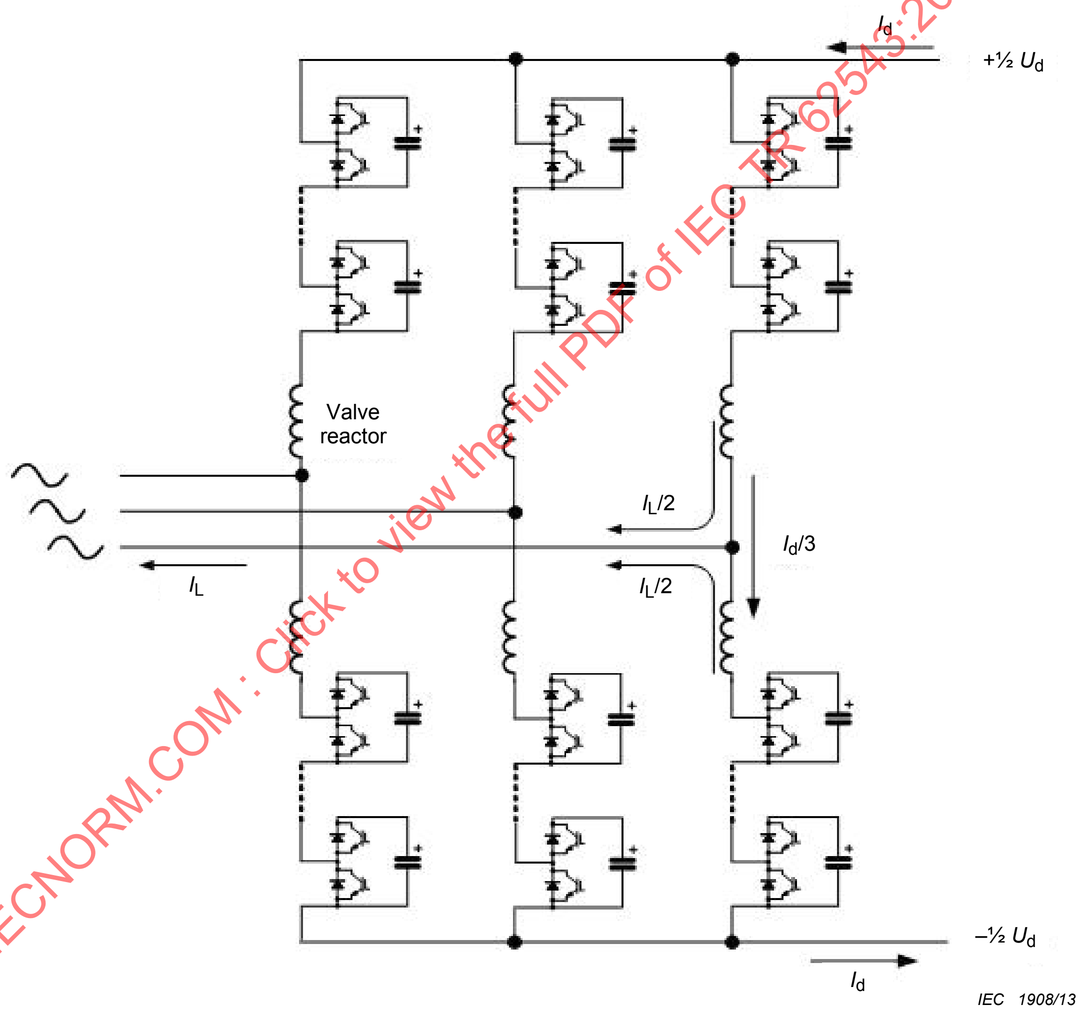
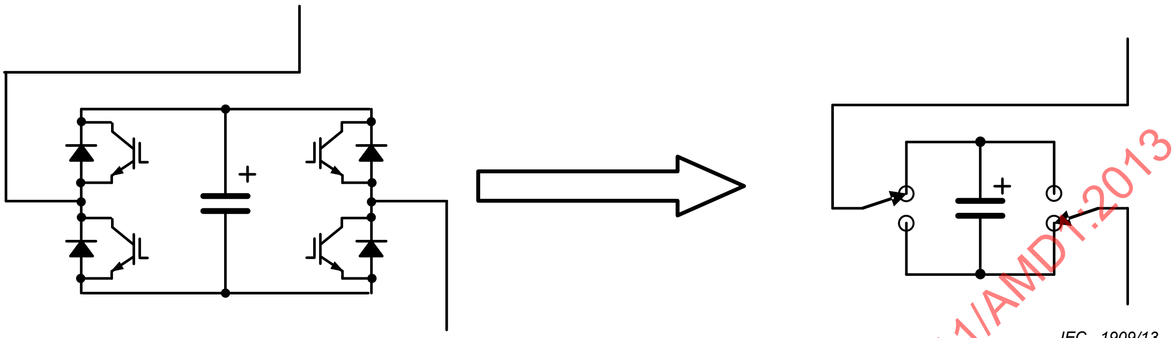


Figure 20 – VSC valve level arrangement and equivalent circuit in MMC topology with full-bridge topology

Replace the figure by the following new figure:



Add, after 5.3.3 the following two new subclauses 5.3.4 and 5.3.5:

5.3.4 CTL topology with VSC cells in half-bridge topology

Each of the 6 variable voltage sources shown in Figure 17 is realized with a series connection of identical VSC valve cells. One VSC valve cell acts as a single-phase two-level converter and functions electrically equivalent to one level of the MMC described in Subclause 5.3.2, except that the voltage rating is higher. Instead of a single IGBT/diode level in one MMC level, multiple IGBT/diode levels are connected in series and synchronously controlled as one switch in one CTL cell.

The electrical arrangement of VSC valve cells and valve reactors in a converter block is similar to Figure 19. The IGBT/diode levels depicted in Figure 19 are substituted by valve cells in CTL topology.

The cell d.c. capacitor voltage in the CTL topology corresponds to one valve voltage step.

5.3.5 CTL topology with VSC cells in full-bridge topology

The CTL topology with "full-bridge" VSC cells functions similarly, in principle, to the MMC topology with VSC levels in full-bridge topology, in Subclause 5.3.3. The main difference between CTL topology with VSC cells in full-bridge topology and MMC topology with VSC levels in full-bridge topology is the number of IGBT/diode levels per CTL cell or MMC level. Each CTL cell consists of multiple IGBT/diode levels in series connection and each MMC level is of one IGBT/diode level.

5.4.5 Additional design details

Replace, in the first sentence, the words "switching device" *with the words* "turn-off semiconductor device"*.*

5.5 Other converter topologies

Replace, the last sentence of the first paragraph by the following:

Some existing known topologies are already described in CIGRÉ Technical Brochure 447.

5.6 Other equipment for VSC transmission schemes

5.6.1 General

Replace, the third bullet point as follows:

- a d.c. voltage source provided by at least one VSC d.c. capacitor, submodule d.c. capacitor or cell d.c. capacitor.

5.6.8.2 Submodule d.c. capacitor

Replace the title of this subclause as follows:

5.6.8.2 Submodule/cell d.c. capacitor

5.6.8.2.1 General

Replace the whole text of this subclause by the following:

In principle, the design and function of the submodule/cell capacitors for the MMC and CTL technologies are similar to that of the VSC d.c. capacitors.

However, due to their operation principle, the current stresses are different for d.c. submodule or cell capacitors. The individual submodules or cells can be individually switched "off" or "on" depending on output voltage generation. When the submodule or cell is switched "off" the valve current does not pass through the d.c. submodule/cell capacitor and the capacitor current is zero. Conversely, when the submodule or cell is switched "on", the full valve current flows through the capacitor. In the "on" state, components of d.c. current and fundamental and low order currents have to be considered. The current flow in the "on" state results in a significant ripple voltage of the submodule/cell capacitors per power cycle. The average and RMS capacitor current stresses are calculated based on current contribution in the "on" state.

Add, after subclause 5.6.11, a new subclause 5.6.12 as follows:

5.6.12 Dynamic braking system

In some VSC HVDC schemes, but particularly where the HVDC system is exporting power from a small islanded a.c. system with little or no load (for example an offshore wind farm) the HVDC system may be required to include a dynamic braking system, for example as a chopper connected to the d.c. terminals of the VSC system. The function of the dynamic braking system is to absorb and dissipate the power generated in the islanded AC system during faults in the receiving-end AC system, typically for durations of 1 to 2 s.

There are several possible ways of implementing such a dynamic braking system but the valves in this system will, in general, be of similar design to the main VSC valves used for power transmission.

9.1 Harmonic performance

Add, at the end of the subclause, the following sentence:

Some multi-level converter topologies may generate sufficiently low levels of harmonics that harmonic filters can in some cases be omitted.

11.2.1 Component tests

Replace, in the last sentence, the words “the CIGRE B4.48 report” *by* “the CIGRÉ Technical Brochure 447”.

B.4 Losses in submodule d.c. capacitors

Replace the title and text of Clause B.4 as shown below:

B.4 Losses in submodule and cell d.c. capacitors

The submodule capacitors in MMC-type valves and the cell capacitors in CTL-type valves carry an appreciable component of current at fundamental or low-order harmonic frequencies. As a result, the power losses in the capacitors of valves of this type cannot be neglected.

In general, capacitor losses can be divided into ohmic losses and dielectric losses.

Ohmic losses represent $I^2.R$ losses in the metallic components within the capacitor, chiefly the film metallisation and internal leads.

Dielectric losses in a capacitor are related to the energy lost in the dielectric material over each voltage cycle. Dielectric losses are caused by the periodic re-alignment of the molecules within the dielectric as the voltage stress across the dielectric changes during the cycle, and are analogous to hysteresis losses in ferromagnetic materials.

The effects of ohmic and dielectric losses are frequently combined into a single term referred to as the equivalent series resistance R_{ESR} of the capacitor. R_{ESR} is a function of frequency and is related to, but not exactly equal to, the actual internal series resistance.

The total d.c. submodule or cell capacitor losses per valve are then calculated as follows:

$$P_{V5} = N_t \cdot I_{crms}{}^2 \cdot R_{ESR} \qquad \text{(B.10)}$$

where

I_{crms} is the rms current flowing in each d.c. submodule or cell capacitor;

R_{ESR} is the equivalent series resistance of the capacitor.

NOTE 1 Dielectric losses are normally most significant in a.c. applications where the capacitor voltage polarity reverses twice per cycle. For d.c. capacitors the voltage is usually non-reversing and dielectric losses are therefore small, but depending on the capacitor technology used, may not be negligible.

NOTE 2 There may also be a third component of loss caused by the finite insulation resistance of the dielectric material, but this is normally very small. It is covered by d.c. voltage-dependent losses as described in the preceding subclause.

NOTE 3 ESR is a non-linear, frequency-dependent quantity. For accurate results, it is important that ESR be determined by real measurements on a capacitor of the same type as used in the valve, under realistic conditions of voltage, current and frequency.

Bibliography

Replace reference 17 by the following:

IEC/TS 61973, *High voltage direct current (HVDC) substation audible noise*

Replace reference 20 by the following:

Component Testing of VSC System for HVDC Applications, CIGRÉ Technical Brochure No. 447