

# TECHNICAL REPORT



---

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





**THIS PUBLICATION IS COPYRIGHT PROTECTED**  
**Copyright © 2022 IEC, Geneva, Switzerland**

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either IEC or IEC's member National Committee in the country of the requester. If you have any questions about IEC copyright or have an enquiry about obtaining additional rights to this publication, please contact the address below or your local IEC member National Committee for further information.

IEC Secretariat  
3, rue de Varembe  
CH-1211 Geneva 20  
Switzerland

Tel.: +41 22 919 02 11  
[info@iec.ch](mailto:info@iec.ch)  
[www.iec.ch](http://www.iec.ch)

**About the IEC**

The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

**About IEC publications**

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigendum or an amendment might have been published.

**IEC publications search - [webstore.iec.ch/advsearchform](http://webstore.iec.ch/advsearchform)**

The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee, ...). It also gives information on projects, replaced and withdrawn publications.

**IEC Just Published - [webstore.iec.ch/justpublished](http://webstore.iec.ch/justpublished)**

Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and once a month by email.

**IEC Customer Service Centre - [webstore.iec.ch/csc](http://webstore.iec.ch/csc)**

If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: [sales@iec.ch](mailto:sales@iec.ch).

**IEC Products & Services Portal - [products.iec.ch](http://products.iec.ch)**

Discover our powerful search engine and read freely all the publications previews. With a subscription you will always have access to up to date content tailored to your needs.

**Electropedia - [www.electropedia.org](http://www.electropedia.org)**

The world's leading online dictionary on electrotechnology, containing more than 22 300 terminological entries in English and French, with equivalent terms in 19 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

# TECHNICAL REPORT



---

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

INTERNATIONAL  
ELECTROTECHNICAL  
COMMISSION

---

ICS 29.200; 29.240.99

ISBN 978-2-8322-1090-6

**Warning! Make sure that you obtained this publication from an authorized distributor.**

## CONTENTS

FOREWORD.....	6
1 Scope.....	8
2 Normative references .....	8
3 Terms and definitions .....	8
3.1 General.....	8
3.2 Letter symbols .....	10
3.3 VSC transmission .....	10
3.4 Power losses .....	11
4 VSC transmission overview .....	11
4.1 Basic operating principles of VSC transmission.....	11
4.1.1 Voltage sourced converter as a black box.....	11
4.1.2 Principles of active and reactive power control .....	12
4.1.3 Operating principles of a VSC transmission scheme .....	14
4.1.4 Applications of VSC transmission .....	15
4.2 Design life.....	15
4.3 VSC transmission configurations.....	15
4.3.1 General .....	15
4.3.2 DC circuit configurations.....	16
4.3.3 Monopole configuration .....	16
4.3.4 Bipolar configuration.....	17
4.3.5 Parallel connection of two converters .....	18
4.3.6 Series connection of two converters .....	19
4.3.7 Parallel and series connection of more than two converters .....	19
4.4 Semiconductors for VSC transmission .....	19
5 VSC transmission converter topologies.....	21
5.1 General.....	21
5.2 Converter topologies with VSC valves of switch type .....	21
5.2.1 General .....	21
5.2.2 Operating principle .....	22
5.2.3 Topologies.....	22
5.3 Converter topologies with VSC valves of the controllable voltage source type.....	25
5.3.1 General .....	25
5.3.2 MMC topology with VSC levels in half-bridge topology.....	26
5.3.3 MMC topology with VSC levels in full-bridge topology.....	28
5.3.4 CTL topology with VSC cells in half-bridge topology .....	28
5.3.5 CTL topology with VSC cells in full-bridge topology .....	28
5.4 VSC valve design considerations .....	29
5.4.1 Reliability and failure mode.....	29
5.4.2 Current rating .....	29
5.4.3 Transient current and voltage requirements .....	29
5.4.4 Diode requirements .....	30
5.4.5 Additional design details.....	30
5.5 Other converter topologies.....	31
5.6 Other equipment for VSC transmission schemes.....	31
5.6.1 General .....	31
5.6.2 Power components of a VSC transmission scheme.....	31

5.6.3	VSC substation circuit breaker.....	32
5.6.4	AC system side harmonic filters.....	32
5.6.5	Radio frequency interference filters.....	32
5.6.6	Interface transformers and phase reactors.....	32
5.6.7	Valve reactor.....	33
5.6.8	DC capacitors.....	33
5.6.9	DC reactor.....	35
5.6.10	DC filter.....	36
5.6.11	Dynamic braking system.....	36
6	Overview of VSC controls.....	36
6.1	General.....	36
6.2	Operational modes and operational options.....	37
6.3	Power transfer.....	38
6.3.1	General.....	38
6.3.2	Telecommunication between converter stations.....	38
6.4	Reactive power and AC voltage control.....	38
6.4.1	AC voltage control.....	38
6.4.2	Reactive power control.....	39
6.5	Black start capability.....	39
6.6	Supply from a wind farm.....	39
7	Steady-state operation.....	40
7.1	Steady-state capability.....	40
7.2	Converter power losses.....	41
8	Dynamic performance.....	42
8.1	AC system disturbances.....	42
8.2	DC system disturbances.....	42
8.2.1	DC cable fault.....	42
8.2.2	DC overhead line fault.....	43
8.3	Internal faults.....	43
9	HVDC performance requirements.....	44
9.1	Harmonic performance.....	44
9.2	Wave distortion.....	45
9.3	Fundamental and harmonics.....	45
9.3.1	Three-phase 2-level VSC.....	45
9.3.2	Multi-pulse and multi-level converters.....	45
9.4	Harmonic voltages on power systems due to VSC operation.....	46
9.5	Design considerations for harmonic filters (AC side).....	46
9.6	DC side filtering.....	46
10	Environmental impact.....	47
10.1	General.....	47
10.2	Audible noise.....	47
10.3	Electric and magnetic fields (EMF).....	47
10.4	Electromagnetic compatibility (EMC).....	47
11	Testing and commissioning.....	48
11.1	General.....	48
11.2	Factory tests.....	49
11.2.1	Component tests.....	49
11.2.2	Control system tests.....	49

11.3	Commissioning tests/system tests.....	49
11.3.1	General .....	49
11.3.2	Precommissioning tests .....	50
11.3.3	Subsystem tests .....	50
11.3.4	System tests.....	50
Annex A (informative)	Functional specification requirements for VSC transmission systems .....	55
A.1	General.....	55
A.2	Purchaser and manufacturer information requirements .....	55
A.2.1	General .....	55
A.2.2	General requirements .....	56
A.2.3	Detailed descriptions .....	57
Annex B (informative)	Modulation strategies for 2-level converters .....	61
B.1	Carrier wave PWM.....	61
B.2	Selective harmonic elimination modulation.....	62
Bibliography.....		64
Figure 1	– Major components that can be found in a VSC substation .....	9
Figure 2	– Diagram of a generic voltage source converter.....	12
Figure 3	– Principle of active power control.....	13
Figure 4	– Principle of reactive power control .....	14
Figure 5	– A point-to-point VSC transmission scheme.....	14
Figure 6	– VSC transmission with a symmetrical monopole.....	16
Figure 7	– VSC transmission with an asymmetrical monopole with metallic return.....	17
Figure 8	– VSC transmission with an asymmetrical monopole with earth return.....	17
Figure 9	– VSC transmission in bipolar configuration with earth return.....	17
Figure 10	– VSC transmission in bipolar configuration with dedicated metallic return .....	18
Figure 11	– VSC transmission in rigid bipolar configuration.....	18
Figure 12	– Parallel connection of two converter units .....	19
Figure 13	– Symbol of a turn-off semiconductor device and associated free-wheeling diode .....	20
Figure 14	– Symbol of an IGBT and associated free-wheeling diode .....	20
Figure 15	– Diagram of a three-phase 2-level converter and associated AC waveform for one phase.....	23
Figure 16	– Single-phase AC output for 2-level converter with PWM switching at 21 times fundamental frequency .....	23
Figure 17	– Diagram of a three-phase 3-level NPC converter and associated AC waveform for one phase.....	24
Figure 18	– Single-phase AC output for 3-level NPC converter with PWM switching at 21 times fundamental frequency .....	25
Figure 19	– Electrical equivalent for a converter with VSC valves acting like a controllable voltage source .....	26
Figure 20	– VSC valve level arrangement and equivalent circuit in MMC topology in half-bridge topology .....	27
Figure 21	– Converter block arrangement with MMC topology in half-bridge topology .....	27
Figure 22	– VSC valve level arrangement and equivalent circuit in MMC topology with full-bridge topology .....	28

Figure 23 – Typical SSOA for the IGBT ..... 29

Figure 24 – A 2-level VSC bridge with the IGBTs turned off ..... 30

Figure 25 – Representing a VSC unit as an AC voltage of magnitude  $U$  and phase angle  $\delta$  behind reactance ..... 36

Figure 26 – Concept of vector control ..... 37

Figure 27 – VSC power controller ..... 38

Figure 28 – AC voltage controller ..... 39

Figure 29 – A typical simplified PQ diagram ..... 41

Figure 30 – Protection concept of a VSC substation ..... 43

Figure 31 – Waveforms for three-phase 2-level VSC ..... 45

Figure 32 – Equivalent circuit at the PCC of the VSC ..... 46

Figure B.1 – Voltage harmonics spectra of a 2-level VSC with carrier frequency at 21st harmonic ..... 62

Figure B.2 – Phase output voltage for selective harmonic elimination modulation (SHEM) ..... 63

## INTERNATIONAL ELECTROTECHNICAL COMMISSION

**HIGH-VOLTAGE DIRECT CURRENT (HVDC) POWER  
TRANSMISSION USING VOLTAGE SOURCED CONVERTERS (VSC)**

## FOREWORD

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as “IEC Publication(s)”). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
- 2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
- 3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
- 5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this publication.
- 7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
- 8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
- 9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

IEC TR 62543 has been prepared by subcommittee 22F: Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment. It is a Technical Report.

This second edition cancels and replaces the first edition published in 2011, Amendment 1:2013 and Amendment 2:2017. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) in Clause 3, some redundant definitions which were identical to those listed in IEC 62747 have been deleted;
- b) in 4.3.4, description and diagrams have been added for the cases of a bipole with dedicated metallic return and a rigid bipole;
- c) in 4.4, mention is made of the bi-mode insulated gate transistor (BiGT) and injection enhanced gate transistor (IEGT) as possible alternatives to the IGBT;



d) in 5.6, the reference to common-mode blocking reactors has been deleted since these are very rarely used nowadays.

The text of this Technical Report is based on the following documents:

Draft	Report on voting
22F/649/DTR	22F/669/RVDTR

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

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at [www.iec.ch/members\\_experts/refdocs](http://www.iec.ch/members_experts/refdocs). The main document types developed by IEC are described in greater detail at [www.iec.ch/publications](http://www.iec.ch/publications).

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under [webstore.iec.ch](http://webstore.iec.ch) in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

**IMPORTANT – The "colour inside" logo on the cover page of this document indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.**

# HIGH-VOLTAGE DIRECT CURRENT (HVDC) POWER TRANSMISSION USING VOLTAGE SOURCED CONVERTERS (VSC)

## 1 Scope

This document gives general guidance on the subject of voltage sourced converters (VSC) used for transmission of power by high voltage direct current (HVDC). It describes converters that are not only voltage sourced (containing a capacitive energy storage medium and where the polarity of DC voltage remains fixed) but also self-commutated, using semiconductor devices which can both be turned on and turned off by control action. 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 square-wave output mode.

HVDC power transmission using voltage sourced converters is known as "VSC transmission".

The various types of circuit that can be used for VSC transmission are described in this document, along with their principal operational characteristics and typical applications. The overall aim is to provide a guide for purchasers to assist with the task of specifying a VSC transmission scheme.

Line-commutated and current-sourced converters are specifically excluded from this document.

## 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 62501, *Voltage sourced converter (VSC) valves for high-voltage direct current (HVDC) power transmission – Electrical testing*

IEC 62747, *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 62747, IEC 62501 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

### 3.1 General

Basic terms and definitions for voltage sourced converters used for HVDC transmission are given in IEC 62747. Terminology on electrical testing of VSC valves for HVDC transmission is given in IEC 62501.