

TECHNICAL REPORT



**Performance of high-voltage direct current (HVDC) systems with line-commutated converters –
Part 1: Steady-state conditions**



THIS PUBLICATION IS COPYRIGHT PROTECTED

Copyright © 2010 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.

Droits de reproduction réservés. Sauf indication contraire, aucune partie de cette publication ne peut être reproduite ni utilisée sous quelque forme que ce soit et par aucun procédé, électronique ou mécanique, y compris la photocopie et les microfilms, sans l'accord écrit de la CEI ou du Comité national de la CEI du pays du demandeur.

Si vous avez des questions sur le copyright de la CEI ou si vous désirez obtenir des droits supplémentaires sur cette publication, utilisez les coordonnées ci-après ou contactez le Comité national de la CEI de votre pays de résidence.

IEC Central Office
3, rue de Varembe
CH-1211 Geneva 20
Switzerland
Email: inmail@iec.ch
Web: www.iec.ch

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 corrigenda or an amendment might have been published.

- Catalogue of IEC publications: www.iec.ch/searchpub

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 It also gives information on projects, withdrawn and replaced publications.

- IEC Just Published: www.iec.ch/online_news/justpub

Stay up to date on all new IEC publications. Just Published details twice a month all new publications released. Available on-line and also by email.

- Electropedia: www.electropedia.org

The world's leading online dictionary of electronic and electrical terms containing more than 20 000 terms and definitions in English and French, with equivalent terms in additional languages. Also known as the International Electrotechnical Vocabulary online.

- Customer Service Centre: www.iec.ch/webstore/custserv

If you wish to give us your feedback on this publication or need further assistance, please visit the Customer Service Centre FAQ or contact us:

Email: csc@iec.ch
Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00

TECHNICAL REPORT



**Performance of high-voltage direct current (HVDC) systems with line-commutated converters –
Part 1: Steady-state conditions**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

PRICE CODE

ICS 29.200; 29.240.99

ISBN 978-2-88910-968-5

CONTENTS

FOREWORD.....	7
1 Scope.....	9
2 Normative references	10
3 Types of HVDC systems.....	11
3.1 General.....	11
3.2 HVDC back-to-back system.....	11
3.3 Monopolar earth return HVDC system	13
3.4 Monopolar metallic return HVDC system	15
3.5 Bipolar earth return HVDC system.....	16
3.6 Bipolar metallic return HVDC system.....	19
3.7 Two 12-pulse groups per pole	20
3.8 Converter transformer arrangements	20
3.9 DC switching considerations.....	22
3.10 Series capacitor compensated HVDC systems	25
4 Environment information.....	29
5 Rated power, current and voltage.....	31
5.1 Rated power.....	31
5.1.1 General	31
5.1.2 Rated power of an HVDC system with transmission line	32
5.1.3 Rated power of an HVDC back-to-back system.....	32
5.1.4 Direction of power flow	32
5.2 Rated current	32
5.3 Rated voltage.....	32
6 Overload and equipment capability.....	33
6.1 Overload	33
6.2 Equipment capability	33
6.2.1 General	33
6.2.2 Converter valve capability	34
6.2.3 Capability of oil-cooled transformers and reactors	34
6.2.4 AC harmonic filter and reactive power compensation equipment capability.....	34
6.2.5 Switchgear and buswork capability	35
7 Minimum power transfer and no-load stand-by state.....	35
7.1 General.....	35
7.2 Minimum current.....	35
7.3 Reduced direct voltage operation	35
7.4 No-load stand-by state	36
7.4.1 General	36
7.4.2 Converter transformers – No-load stand-by	36
7.4.3 Converter valves – No-load stand-by	36
7.4.4 AC filters and reactive compensation – No-load stand-by	36
7.4.5 DC reactors and d.c. filters – No-load stand-by.....	36
7.4.6 Auxiliary power system – No-load stand-by.....	36
7.4.7 Control and protection – No-load stand-by.....	36
8 AC system.....	36
8.1 General.....	36

8.2	AC voltage	37
8.2.1	Rated a.c. voltage	37
8.2.2	Steady-state voltage range	37
8.2.3	Negative sequence voltage	38
8.3	Frequency	38
8.3.1	Rated frequency	38
8.3.2	Steady-state frequency range	38
8.3.3	Short-term frequency variation	38
8.3.4	Frequency variation during emergency	38
8.4	System impedance at fundamental frequency	38
8.5	System impedance at harmonic frequencies	38
8.6	Positive and zero-sequence surge impedance	39
8.7	Other sources of harmonics	39
8.8	Subsynchronous torsional interaction (SSTI)	39
9	Reactive power	39
9.1	General	39
9.2	Conventional HVDC systems	39
9.3	Series capacitor compensated HVDC schemes	41
9.4	Converter reactive power consumption	41
9.5	Reactive power balance with the a.c. system	41
9.6	Reactive power supply	42
9.7	Maximum size of switchable VAR banks	42
10	HVDC transmission line, earth electrode line and earth electrode	42
10.1	General	42
10.2	Overhead line(s)	42
10.2.1	General	42
10.2.2	Electrical parameters	43
10.3	Cable line(s)	43
10.3.1	General	43
10.3.2	Electrical parameters	43
10.4	Earth electrode line	44
10.5	Earth electrode	44
11	Reliability	44
11.1	General	44
11.2	Outage	44
11.2.1	General	44
11.2.2	Scheduled outage	44
11.2.3	Forced outage	44
11.3	Capacity	45
11.3.1	General	45
11.3.2	Maximum continuous capacity P_m	45
11.3.3	Outage capacity P_o	45
11.3.4	Outage derating factor (ODF)	45
11.4	Outage duration terms	45
11.4.1	Actual outage duration (AOD)	45
11.4.2	Equivalent outage duration (EOD)	45
11.4.3	Period hours (PH)	46
11.4.4	Actual outage hours (AOH)	46
11.4.5	Equivalent outage hours (EOH)	46

11.5	Energy unavailability (EU)	46
11.5.1	General	46
11.5.2	Forced energy unavailability (FEU)	47
11.5.3	Scheduled energy unavailability (SEU)	47
11.6	Energy availability (EA)	47
11.7	Maximum permitted number of forced outages	47
11.8	Statistical probability of outages	47
11.8.1	Component faults	47
11.8.2	External faults	47
12	HVDC control	47
12.1	Control objectives	47
12.2	Control structure	48
12.2.1	General	48
12.2.2	Converter unit firing control	48
12.2.3	Pole control	50
12.2.4	HVDC substation control	52
12.2.5	Master control	52
12.3	Control order settings	53
12.4	Current limits	53
12.5	Control circuit redundancy	53
12.6	Measurements	53
13	Telecommunication	54
13.1	Types of telecommunication links	54
13.2	Telephone	54
13.3	Power line carrier (PLC)	55
13.4	Microwave	55
13.5	Radio link	55
13.6	Optical fibre telecommunication	55
13.7	Classification of data to be transmitted	56
13.8	Fast response telecommunication	56
13.9	Reliability	57
14	Auxiliary power supplies	57
14.1	General	57
14.2	Reliability and load classification	57
14.3	AC auxiliary supplies	58
14.4	Batteries and uninterruptible power supplies (UPS)	58
14.5	Emergency supply	59
15	Audible noise	59
15.1	General	59
15.2	Public nuisance	60
15.2.1	General	60
15.2.2	Valves and valve coolers	60
15.2.3	Converter transformers	60
15.2.4	DC reactors	60
15.2.5	AC filter reactors	61
15.3	Noise in working areas	61
16	Harmonic interference – AC	61
16.1	AC side harmonic generation	61

16.2	Filters	61
16.3	Interference disturbance criteria	65
16.4	Levels for interference	66
16.5	Filter performance	67
17	Harmonic interference – DC	67
17.1	DC side interference	67
17.1.1	Harmonic currents in HVDC transmission line	67
17.1.2	Characteristic and non-characteristic harmonics	67
17.1.3	Groups of harmonics	68
17.1.4	Calculation of harmonic currents	68
17.1.5	Calculation of induced voltages	68
17.1.6	Personnel safety	68
17.1.7	DC filters	68
17.2	DC filter performance	69
17.2.1	Requirements for voice communication circuits	69
17.2.2	Levels of interference	69
17.2.3	Safety	70
17.3	Specification requirements	70
17.3.1	Economic level of filtering	70
17.3.2	General criteria	71
17.3.3	Factors to be taken into account for calculations	71
17.3.4	Calculation of currents	72
18	Power line carrier interference (PLC)	73
18.1	General	73
18.2	Performance specification	73
19	Radio interference	74
19.1	Radio interference (RI) from HVDC systems	74
19.1.1	RI sources	74
19.1.2	RI characteristics	75
19.2	RI performance specification	75
20	Power losses	76
20.1	General	76
20.2	Main contributing sources	76
20.2.1	General	76
20.2.2	AC filters and reactive power compensation	77
20.2.3	Converter bridges	77
20.2.4	Converter transformer	77
20.2.5	DC reactor	77
20.2.6	DC filter	77
20.2.7	Auxiliary equipment	77
20.2.8	Other components	77
21	Provision for extensions to the HVDC systems	77
21.1	General	77
21.2	Specification for extensions	78
	Bibliography	80
	Figure 1 – Twelve-pulse converter unit	9
	Figure 2 – Examples of back-to-back HVDC systems	12

Figure 3 – Monopolar earth return system.....	13
Figure 4 – Two 12-pulse units in series.....	14
Figure 5 – Two 12-pulse units in parallel.....	15
Figure 6 – Monopolar metallic return system.....	16
Figure 7 – Bipolar system	17
Figure 8 – Metallic return operation of the unfaulted pole in a bipolar system.....	18
Figure 9 – Bipolar metallic return HVDC system.....	19
Figure 10 – Bipolar system with two 12-pulse units in series per pole	21
Figure 11 – Bipolar system with two 12-pulse units in parallel per pole	22
Figure 12 – DC switching of line conductors	23
Figure 13 – DC switching of converter poles	24
Figure 14 – DC switching – Overhead line to cable	25
Figure 15 – DC switching – Two-bipolar converters and lines.....	26
Figure 16 – DC switching – Intermediate.....	27
Figure 17 – Capacitor commutated converter configurations	28
Figure 18 – Variations of reactive power Q with active power P of an HVDC converter.....	40
Figure 19 – Control hierarchy.....	50
Figure 20 – Converter voltage-current characteristic	52
Figure 21 – Examples of a.c. filter connections for a bipole HVDC system	63
Figure 22 – Circuit diagrams for different filter types	64
Figure 23 – RY COM noise meter results averaged – Typical plot of converter noise levels on the d.c. line corrected and normalized to 3 kHz bandwidth $-0 \text{ dBm} = 0,775 \text{ V}$	74
Figure 24 – Extension methods for HVDC systems	79
Table 1 – Information supplied for HVDC substation	29
Table 2 – Performance parameters for voice communication circuits: Subscribers and trunk circuits	69

Document generated by EVS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

**PERFORMANCE OF HIGH-VOLTAGE DIRECT CURRENT
(HVDC) SYSTEMS WITH LINE-COMMUTATED CONVERTERS –****Part 1: Steady-state conditions**

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.

The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC 60919-1, which is a technical report, has been prepared by subcommittee 22F, Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment.

This third edition cancels and replaces the second edition, published in 2005. This edition constitutes a technical revision.

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

- a) the changes have been made to the description of multi 12-pulse groups per pole, especially for a large scale ultra high-voltage direct current (UHVDC) converter arrangement;
- b) the different arrangements of d.c. smoothing reactors have been included;
- c) the figures depicting two 12-pulse groups per pole arrangement have been added.

The text of this technical report is based on the following documents:

Draft of Technical Report	Report on voting
22F/213/DTR	22F/218/RVC

Full information on the voting for the approval of this technical report 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 of the IEC 60919 series, published under the general title *Performance of high-voltage direct current (HVDC) systems with line-commutated converters*, 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;
- replaced by a revised edition, or
- amended.

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

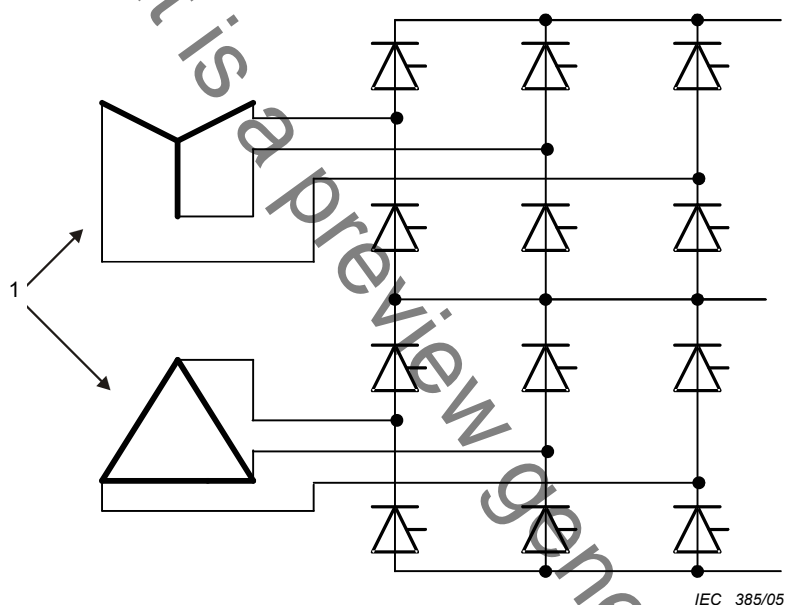
IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

PERFORMANCE OF HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS WITH LINE-COMMUTATED CONVERTERS –

Part 1: Steady-state conditions

1 Scope

This part of the IEC 60919 provides general guidance on the steady-state performance requirements of high-voltage direct current (HVDC) systems. It concerns the steady-state performance of two-terminal HVDC systems utilizing 12-pulse converter units comprised of three-phase bridge (double-way) connections (see Figure 1), but it does not cover multi-terminal HVDC transmission systems. Both terminals are assumed to use thyristor valves as the main semiconductor valves and to have power flow capability in both directions. Diode valves are not considered in this report.



Key

- 1 Transformer valve windings

Figure 1 – Twelve-pulse converter unit

Only line-commutated converters are covered in this report, which includes capacitor commutated converter circuit configurations. General requirements for semiconductor line-commutated converters are given in IEC 60146-1-1, IEC/TR 60146-1-2 and IEC 60146-1-3. Voltage-sourced converters are not considered.

This technical report, which covers steady-state performance, is followed by additional documents on dynamic performance and transient performance. All three aspects should be considered when preparing two-terminal HVDC system specifications.

The difference between system performance specifications and equipment design specifications for individual components of a system should be realized. Equipment specifications and testing requirements are not defined in this report. Also excluded from this report are detailed seismic performance requirements. In addition, because there are many variations between different possible HVDC systems, this report does not consider these in detail; consequently, it should not be used directly as a specification for a particular project,

but rather to provide the basis for an appropriate specification tailored to fit actual system requirements.

Frequently, performance specifications are prepared as a single package for the two HVDC substations in a particular system. Alternatively, some parts of the HVDC system can be separately specified and purchased. In such cases, due consideration should be given to co-ordination of each part with the overall HVDC system performance objectives and the interface of each with the system should be clearly defined. Typical of such parts, listed in the appropriate order of relative ease for separate treatment and interface definition, are:

- a) d.c. line, electrode line and earth electrode;
- b) telecommunication system;
- c) converter building, foundations and other civil engineering work;
- d) reactive power supply including a.c. shunt capacitor banks, shunt reactors, synchronous and static reactive power (VAR) compensators;
- e) a.c. switchgear;
- f) d.c. switchgear;
- g) auxiliary systems;
- h) a.c. filters;
- i) d.c. filters;
- j) d.c. reactors;
- k) converter transformers;
- l) surge arresters;
- m) series commutation capacitors;
- n) valves and their ancillaries;
- o) control and protection systems.

NOTE The last four items are the most difficult to separate, and, in fact, separation of these four may be inadvisable.

A complete steady-state performance specification for a HVDC system should consider Clauses 3 to 21 of this report.

Terms and definitions for high-voltage direct current (HVDC) transmission used in this report are given in IEC 60633.

Since the equipment items are usually separately specified and purchased, the HVDC transmission line, earth electrode line and earth electrode (see Clause 10) are included only because of their influence on the HVDC system performance.

For the purpose of this report, an HVDC substation is assumed to consist of one or more converter units installed in a single location together with buildings, reactors, filters, reactive power supply, control, monitoring, protective, measuring and auxiliary equipment. While there is no discussion of a.c. switching substations in this report, a.c. filters and reactive power sources are included, although they may be connected to an a.c. bus separate from the HVDC substation, as discussed in Clause 16.

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 60146-1-1, *Semiconductor converters – General requirements and line commutated converters – Part 1-1: Specifications of basic requirements*

IEC/TR 60146-1-2, *Semiconductor converters – General requirements and line commutated converters – Part 1-2: Application guide*

IEC 60146-1-3, *Semiconductor converters – General requirements and line commutated converters – Part 1-3: Transformers and reactors*

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

3 Types of HVDC systems

3.1 General

This part of the specification should include the following basic data:

- a) general information on the location of the HVDC substations and the purpose of the project;
- b) type of system needed, including a simple one-line diagram;
- c) number of 12-pulse converter units;
- d) pertinent information derived from the discussion in this section.

Generally, in studies of projects of the types discussed in this report, economic considerations should take into account the capital costs, the cost of losses, cost of outages and other expected annual expenses.

In terms of the type of system, the relatively new development of “capacitor-commutated converter (CCC)” and “controlled series capacitor converter (CSCC)” technology may be suitable alternatives to a conventional HVDC scheme. These are described in 3.10.

3.2 HVDC back-to-back system

In this arrangement there is no d.c. transmission line and both converters are located at one site. The valves for both converters may be located in one valve hall, or even in one integrated structure or separately as outdoor valves. Similarly, many other items for the two converters, such as the control system, cooling equipment, auxiliary system, etc., may be located in one area or even integrated in layout into configurations common to the two converters. Circuit configurations may vary. Examples are given in Figure 2. The performance and economics of these configurations differ and must be evaluated. D.C. filters are not needed.