

TECHNICAL REPORT



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

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.200; 29.240.99

ISBN 978-2-8322-8226-7

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

CONTENTS

FOREWORD	8
INTRODUCTION	2
1 Scope	11
2 Normative references	12
3 Terms and definitions	12
4 Types of HVDC systems	12
4.1 General	12
4.2 HVDC back-to-back system	13
4.3 Monopolar HVDC system with earth return HVDC system	13
4.4 Monopolar HVDC system with metallic return HVDC system	17
4.5 Bipolar earth return HVDC system	18
4.6 Bipolar HVDC system with metallic return HVDC system	21
4.7 Two 12-pulse groups per pole	22
4.8 Converter transformer arrangements	25
4.9 DC switching considerations	26
4.10 Series-capacitor-compensated HVDC systems	29
4.11 LCC/VSC hybrid bipolar system	33
5 Environment information	34
6 Rated power, current and voltage	37
6.1 Rated power	37
6.1.1 General	37
6.1.2 Rated power of an HVDC system with transmission line	37
6.1.3 Rated power of an HVDC back-to-back system	37
6.1.4 Direction of power flow	37
6.2 Rated current	37
6.3 Rated voltage	38
7 Overload and equipment capability	38
7.1 Overload	38
7.2 Equipment capability	39
7.2.1 General	39
7.2.2 Converter valve capability	39
7.2.3 Capability of oil-cooled transformers and reactors	39
7.2.4 AC harmonic filter and reactive power compensation equipment capability	40
7.2.5 Switchgear and buswork capability	40
8 Minimum power transfer and no-load stand-by state	40
8.1 General	40
8.2 Minimum current	40
8.3 Reduced direct voltage operation	40
8.4 No-load stand-by state	41
8.4.1 General	41
8.4.2 Converter transformers – No-load stand-by	41
8.4.3 Converter valves – No-load stand-by	41
8.4.4 AC filters and reactive compensation – No-load stand-by	41
8.4.5 DC reactors and DC filters – No-load stand-by	42

8.4.6	Auxiliary power system – No-load stand-by.....	42
8.4.7	Control and protection – No-load stand-by.....	42
9	AC system.....	42
9.1	General.....	42
9.2	AC voltage.....	42
9.2.1	Rated AC voltage.....	42
9.2.2	Steady-state voltage range.....	42
9.2.3	Negative sequence voltage.....	43
9.3	Frequency.....	43
9.3.1	Rated frequency.....	43
9.3.2	Steady-state frequency range.....	43
9.3.3	Short-term frequency variation.....	43
9.3.4	Frequency variation during emergency.....	44
9.4	System impedance at fundamental frequency.....	44
9.5	System impedance at harmonic frequencies.....	44
9.6	Positive and zero-sequence surge impedance.....	44
9.7	Other sources of harmonics.....	44
9.8	Subsynchronous torsional interaction (SSTI).....	44
10	Reactive power.....	45
10.1	General.....	45
10.2	Conventional HVDC systems.....	45
10.3	Series capacitor compensated HVDC schemes.....	47
10.4	Converter reactive power consumption.....	47
10.5	Reactive power balance with the AC system.....	47
10.6	Reactive power supply.....	47
10.7	Maximum size of switchable VAR banks.....	48
11	HVDC transmission line, earth electrode line and earth electrode.....	48
11.1	General.....	48
11.2	Overhead line(s).....	48
11.2.1	General.....	48
11.2.2	Electrical parameters.....	48
11.3	Cable line(s).....	49
11.3.1	General.....	49
11.3.2	Electrical parameters.....	49
11.4	Earth electrode line.....	50
11.5	Earth electrode.....	50
12	Reliability.....	50
12.1	General.....	50
12.2	Outage.....	50
12.2.1	General.....	50
12.2.2	Scheduled outage.....	50
12.2.3	Forced outage.....	50
12.3	Capacity.....	51
12.3.1	General.....	51
12.3.2	Maximum continuous capacity P_m	51
12.3.3	Outage capacity P_o	51
12.3.4	Outage derating factor (ODF).....	51
12.4	Outage duration terms.....	51

12.4.1	Actual outage duration (AOD)	51
12.4.2	Equivalent outage duration (EOD)	51
12.4.3	Period hours (PH)	51
12.4.4	Actual outage hours (AOH)	52
12.4.5	Equivalent outage hours (EOH)	52
12.5	Energy unavailability (EU)	52
12.5.1	General	52
12.5.2	Forced energy unavailability (FEU)	53
12.5.3	Scheduled energy unavailability (SEU)	53
12.6	Energy availability (EA)	53
12.7	Maximum permitted number of forced outages	53
12.8	Statistical probability of outages	53
12.8.1	Component faults	53
12.8.2	External faults	53
13	HVDC control	54
13.1	Control objectives	54
13.2	Control structure	54
13.2.1	General	54
13.2.2	Converter unit firing control	54
13.2.3	Pole control	55
13.2.4	HVDC substation control	58
13.2.5	Master control	60
13.3	Control order settings	60
13.4	Current limits	60
13.5	Control circuit redundancy	61
13.6	Protection system	61
13.7	Measurements	61
14	Telecommunication	62
14.1	Types of telecommunication links	62
14.2	Telephone	62
14.3	Power line carrier (PLC)	62
14.4	Microwave	63
14.5	Radio link	63
14.6	Optical fibre telecommunication	63
14.7	Classification of data to be transmitted	63
14.8	Fast response telecommunication	64
14.9	Reliability	64
15	Auxiliary power supplies	65
15.1	General	65
15.2	Reliability and load classification	65
15.3	AC auxiliary supplies	66
15.4	Batteries and uninterruptible power supplies (UPS)	66
15.5	Emergency supply	67
16	Audible noise	67
16.1	General	67
16.2	Public nuisance	67
16.2.1	General	67
16.2.2	Valves and valve coolers	68

16.2.3	Converter transformers	68
16.2.4	DC reactors	68
16.2.5	AC filter reactors	68
16.3	Noise in working areas	68
17	Harmonic interference – AC	69
17.1	AC side harmonic generation	69
17.2	Filters	69
17.3	Interference disturbance criteria	72
17.4	Levels for interference	73
17.5	Filter performance	74
18	Harmonic interference – DC	74
18.1	DC side interference	74
18.1.1	Harmonic currents in HVDC transmission line	74
18.1.2	Characteristic and non-characteristic harmonics	74
18.1.3	Groups of harmonics	75
18.1.4	Calculation of harmonic currents	75
18.1.5	Calculation of induced voltages	75
18.1.6	Personnel safety	75
18.1.7	DC filters	75
18.2	DC filter performance	76
18.2.1	Requirements for voice communication circuits	76
18.2.2	Levels of interference	76
18.2.3	Safety	76
18.3	Specification requirements	77
18.3.1	Economic level of filtering	77
18.3.2	General criteria	78
18.3.3	Factors to be taken into account for calculations	78
18.3.4	Calculation of currents	79
19	Power line carrier interference (PLC)	80
19.1	General	80
19.2	Performance specification	81
20	Radio frequency interference	82
20.1	General	84
20.2	RFI from HVDC systems	84
20.2.1	RFI sources	84
20.2.2	RFI propagation	85
20.2.3	RFI characteristics	85
20.3	RFI performance specification	86
20.3.1	RFI risk assessment	86
20.3.2	Specification RFI limit and its verification	86
20.3.3	Design aspects	87
21	Power losses	82
21.1	General	87
21.2	Main contributing sources	88
21.2.1	General	88
21.2.2	AC filters and reactive power compensation	88
21.2.3	Converter bridges	88
21.2.4	Converter transformer	88

21.2.5	DC reactor	88
21.2.6	DC filter	88
21.2.7	Auxiliary equipment	89
21.2.8	Other components	89
22	Provision for extensions to the HVDC systems	89
22.1	General.....	89
22.2	Specification for extensions	89
Annex A (informative) Factors affecting reliability and availability of converter stations		92
A.1	Design and documentation.....	92
A.1.1	General	92
A.1.2	General design principles	92
A.1.3	More detailed design principles	93
A.1.4	Software design principles.....	93
A.1.5	RAM records.....	94
A.2	Operation.....	94
A.2.1	Training	94
A.2.2	Maintenance programs affecting reliability	95
A.2.3	Spare parts.....	96
Bibliography.....		99
Figure 1 – Twelve-pulse converter unit		11
Figure 2 – Examples of back-to-back HVDC systems		14
Figure 3 – Monopolar HVDC system with earth return		15
Figure 4 – Two 12-pulse units in series.....		16
Figure 5 – Two 12-pulse units in parallel.....		17
Figure 6 – Monopolar HVDC system with metallic return system		18
Figure 7 – Bipolar system		19
Figure 8 – Metallic return operation of the unfaulted pole in a bipolar system.....		20
Figure 9 – Bipolar metallic return HVDC system with metallic return		22
Figure 10 – Bipolar system with two 12-pulse units in series per pole		24
Figure 11 – Bipolar system with two 12-pulse units in parallel per pole		25
Figure 12 – DC switching of line conductors		27
Figure 13 – DC switching of converter poles		28
Figure 14 – DC switching – Overhead line to cable		29
Figure 15 – DC switching – Two bipolar converters and lines		30
Figure 16 – DC switching – Intermediate.....		31
Figure 17 – Capacitor commutated converter configurations		32
Figure 18 – LCC/VSC hybrid bipolar system		34
Figure 19 – Variations of reactive power Q with active power P of an HVDC converter		46
Figure 20 – Control hierarchy for HVDC/UHVDC system.....		57
Figure 21 – Converter voltage-current characteristic		59
Figure 22 – Examples of AC filter connections for a bipole HVDC system		70
Figure 23 – Circuit diagrams for different filter types		71
Figure 24 – RY COM noise interference meter results averaged – Typical plot of converter noise interference levels on the DC line corrected and normalized to 3 kHz bandwidth – 0 dBm = 0,775 V		82

Figure 25 – Recommended measurement procedure with definition of measuring point	87
Figure 26 – Extension methods for HVDC systems	91
Table 1 – Information supplied for HVDC substation	35
Table 2 – Performance parameters for voice communication circuits: Subscribers and trunk circuits	77

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.

This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

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 TR 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 fourth edition cancels and replaces the third edition, published in 2010, 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) Figure 8 and Figure 20 have been updated, a new Figure 18 "LCC/VSC hybrid bipolar system" has been added;
- b) the HVDC system control objectives have been supplemented;
- c) additional explanations regarding the HVDC system control structure have been given;
- d) a new subclause 13.6 on HVDC system protection has been added.

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

Draft TR	Report on voting
22F/535/DTR	22F/549A/RVDTR

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 document 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 document will remain unchanged until the stability date indicated on the IEC website under "<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 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.

INTRODUCTION

The difference between system performance specifications and equipment design specifications for individual components of a system is realized. 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~~ is given to coordination of each part with the overall HVDC system performance objectives and to ensuring that the interface of each with the system ~~should be~~ is clearly defined. Typical of such parts, listed in the appropriate order of relative ease for separate treatment and interface definition, are:

- a) DC line, electrode line and earth electrode;
- b) telecommunication system;
- c) converter building, foundations and other civil engineering work;
- d) reactive power supply including AC shunt capacitor banks, shunt reactors, synchronous and static reactive power (var) compensators;
- e) AC switchgear;
- f) DC switchgear;
- g) auxiliary systems;
- h) AC filters;
- i) DC filters;
- j) DC 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~~ can be inadvisable.

Clause 4 to Clause 22 of this document set out a complete steady-state performance specification for an 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 11) are included only because of their influence on the HVDC system performance.

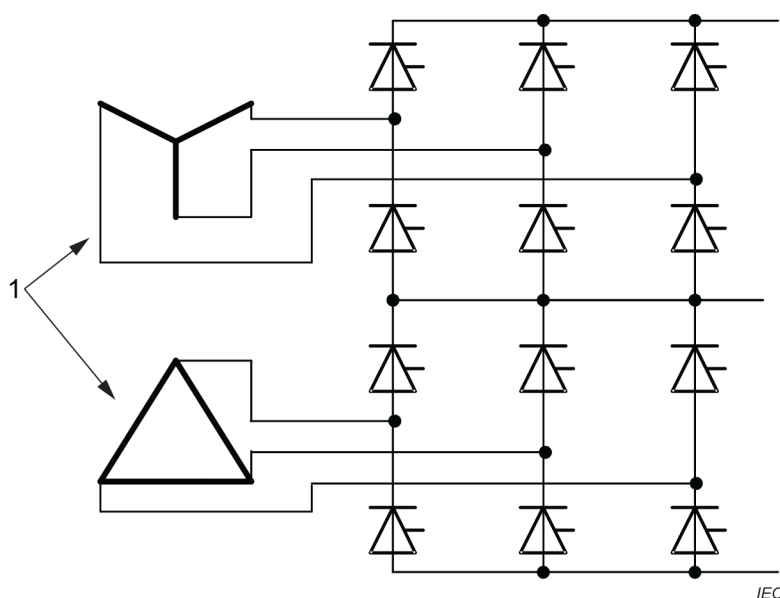
For the purpose of this document, an HVDC substation is assumed to consist of one or more converter units installed in a single location together with buildings, reactors, filters, reactive power supply, control, monitoring, protective, measuring and auxiliary equipment. While there is no discussion of AC switching substations in this document, AC filters and reactive power sources are included, although they ~~may~~ can be connected to an AC bus separate from the HVDC substation, as discussed in Clause 17.

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

Part 1: Steady-state conditions

1 Scope

This part of 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 document.



Key

1 Transformer valve windings

Figure 1 – Twelve-pulse converter unit

Only line-commutated converters are covered in this document, which includes capacitor commutated converter circuit configurations. General ~~requirements for~~ aspects of 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~~ distinction is made 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 document. Also excluded from this document are detailed seismic performance requirements. In addition, because there are many variations between different possible HVDC systems, this document does not consider these in detail; consequently, it ~~should~~ is 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.

This document, which covers steady-state performance, is followed by the additional documents of IEC TR 60919-2 on faults and switching as well as IEC TR 60919-3 on dynamic conditions. All three aspects are considered when preparing two-terminal HVDC system specifications.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 – Vocabulary

CIGRÉ Technical Brochure (TB) No. 391:2009, *Guide for measurement of radio frequency interference from HV and MV substations. Disturbance propagation, characteristics of disturbance sources, measurement techniques, conversion methodologies and limits*

TECHNICAL REPORT



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

CONTENTS

FOREWORD	8
INTRODUCTION	10
1 Scope	11
2 Normative references	12
3 Terms and definitions	12
4 Types of HVDC systems	12
4.1 General	12
4.2 HVDC back-to-back system	12
4.3 Monopolar HVDC system with earth return	13
4.4 Monopolar HVDC system with metallic return	16
4.5 Bipolar earth return HVDC system	17
4.6 Bipolar HVDC system with metallic return	20
4.7 Two 12-pulse groups per pole	21
4.8 Converter transformer arrangements	24
4.9 DC switching considerations	25
4.10 Series-capacitor-compensated HVDC systems	28
4.11 LCC/VSC hybrid bipolar system	32
5 Environment information	33
6 Rated power, current and voltage	36
6.1 Rated power	36
6.1.1 General	36
6.1.2 Rated power of an HVDC system with transmission line	36
6.1.3 Rated power of an HVDC back-to-back system	36
6.1.4 Direction of power flow	37
6.2 Rated current	37
6.3 Rated voltage	37
7 Overload and equipment capability	37
7.1 Overload	37
7.2 Equipment capability	38
7.2.1 General	38
7.2.2 Converter valve capability	38
7.2.3 Capability of oil-cooled transformers and reactors	39
7.2.4 AC harmonic filter and reactive power compensation equipment capability	39
7.2.5 Switchgear and buswork capability	39
8 Minimum power transfer and no-load stand-by state	39
8.1 General	39
8.2 Minimum current	39
8.3 Reduced direct voltage operation	40
8.4 No-load stand-by state	40
8.4.1 General	40
8.4.2 Converter transformers – No-load stand-by	40
8.4.3 Converter valves – No-load stand-by	40
8.4.4 AC filters and reactive compensation – No-load stand-by	41
8.4.5 DC reactors and DC filters – No-load stand-by	41

8.4.6	Auxiliary power system – No-load stand-by.....	41
8.4.7	Control and protection – No-load stand-by.....	41
9	AC system.....	41
9.1	General.....	41
9.2	AC voltage.....	41
9.2.1	Rated AC voltage.....	41
9.2.2	Steady-state voltage range.....	41
9.2.3	Negative sequence voltage.....	42
9.3	Frequency.....	42
9.3.1	Rated frequency.....	42
9.3.2	Steady-state frequency range.....	43
9.3.3	Short-term frequency variation.....	43
9.3.4	Frequency variation during emergency.....	43
9.4	System impedance at fundamental frequency.....	43
9.5	System impedance at harmonic frequencies.....	43
9.6	Positive and zero-sequence surge impedance.....	43
9.7	Other sources of harmonics.....	44
9.8	Subsynchronous torsional interaction (SSTI).....	44
10	Reactive power.....	44
10.1	General.....	44
10.2	Conventional HVDC systems.....	44
10.3	Series capacitor compensated HVDC schemes.....	46
10.4	Converter reactive power consumption.....	46
10.5	Reactive power balance with the AC system.....	46
10.6	Reactive power supply.....	46
10.7	Maximum size of switchable VAR banks.....	47
11	HVDC transmission line, earth electrode line and earth electrode.....	47
11.1	General.....	47
11.2	Overhead line(s).....	47
11.2.1	General.....	47
11.2.2	Electrical parameters.....	47
11.3	Cable line(s).....	48
11.3.1	General.....	48
11.3.2	Electrical parameters.....	48
11.4	Earth electrode line.....	49
11.5	Earth electrode.....	49
12	Reliability.....	49
12.1	General.....	49
12.2	Outage.....	49
12.2.1	General.....	49
12.2.2	Scheduled outage.....	49
12.2.3	Forced outage.....	49
12.3	Capacity.....	50
12.3.1	General.....	50
12.3.2	Maximum continuous capacity P_m	50
12.3.3	Outage capacity P_o	50
12.3.4	Outage derating factor (ODF).....	50
12.4	Outage duration terms.....	50

12.4.1	Actual outage duration (AOD)	50
12.4.2	Equivalent outage duration (EOD)	50
12.4.3	Period hours (PH)	50
12.4.4	Actual outage hours (AOH)	51
12.4.5	Equivalent outage hours (EOH)	51
12.5	Energy unavailability (EU)	51
12.5.1	General	51
12.5.2	Forced energy unavailability (FEU)	51
12.5.3	Scheduled energy unavailability (SEU)	52
12.6	Energy availability (EA)	52
12.7	Maximum permitted number of forced outages	52
12.8	Statistical probability of outages	52
12.8.1	Component faults	52
12.8.2	External faults	52
13	HVDC control	52
13.1	Control objectives	52
13.2	Control structure	53
13.2.1	General	53
13.2.2	Converter unit firing control	53
13.2.3	Pole control	54
13.2.4	HVDC substation control	56
13.2.5	Master control	58
13.3	Control order settings	58
13.4	Current limits	58
13.5	Control circuit redundancy	59
13.6	Protection system	59
13.7	Measurements	59
14	Telecommunication	60
14.1	Types of telecommunication links	60
14.2	Telephone	60
14.3	Power line carrier (PLC)	60
14.4	Microwave	61
14.5	Radio link	61
14.6	Optical fibre telecommunication	61
14.7	Classification of data to be transmitted	61
14.8	Fast response telecommunication	62
14.9	Reliability	62
15	Auxiliary power supplies	63
15.1	General	63
15.2	Reliability and load classification	63
15.3	AC auxiliary supplies	64
15.4	Batteries and uninterruptible power supplies (UPS)	64
15.5	Emergency supply	65
16	Audible noise	65
16.1	General	65
16.2	Public nuisance	65
16.2.1	General	65
16.2.2	Valves and valve coolers	66

16.2.3	Converter transformers	66
16.2.4	DC reactors	66
16.2.5	AC filter reactors	66
16.3	Noise in working areas	66
17	Harmonic interference – AC	67
17.1	AC side harmonic generation	67
17.2	Filters	67
17.3	Interference disturbance criteria	70
17.4	Levels for interference	71
17.5	Filter performance	72
18	Harmonic interference – DC	72
18.1	DC side interference	72
18.1.1	Harmonic currents in HVDC transmission line	72
18.1.2	Characteristic and non-characteristic harmonics	72
18.1.3	Groups of harmonics	73
18.1.4	Calculation of harmonic currents	73
18.1.5	Calculation of induced voltages	73
18.1.6	Personnel safety	73
18.1.7	DC filters	73
18.2	DC filter performance	74
18.2.1	Requirements for voice communication circuits	74
18.2.2	Levels of interference	74
18.2.3	Safety	74
18.3	Specification requirements	75
18.3.1	Economic level of filtering	75
18.3.2	General criteria	76
18.3.3	Factors to be taken into account for calculations	76
18.3.4	Calculation of currents	77
19	Power line carrier interference (PLC)	77
19.1	General	77
19.2	Performance specification	78
20	Radio frequency interference	79
20.1	General	79
20.2	RFI from HVDC systems	80
20.2.1	RFI sources	80
20.2.2	RFI propagation	80
20.2.3	RFI characteristics	80
20.3	RFI performance specification	81
20.3.1	RFI risk assessment	81
20.3.2	Specification RFI limit and its verification	81
20.3.3	Design aspects	82
21	Power losses	82
21.1	General	82
21.2	Main contributing sources	83
21.2.1	General	83
21.2.2	AC filters and reactive power compensation	83
21.2.3	Converter bridges	83
21.2.4	Converter transformer	83

21.2.5	DC reactor	83
21.2.6	DC filter	84
21.2.7	Auxiliary equipment	84
21.2.8	Other components	84
22	Provision for extensions to the HVDC systems	84
22.1	General.....	84
22.2	Specification for extensions	84
Annex A	(informative) Factors affecting reliability and availability of converter stations	87
A.1	Design and documentation.....	87
A.1.1	General	87
A.1.2	General design principles	87
A.1.3	More detailed design principles	88
A.1.4	Software design principles.....	88
A.1.5	RAM records.....	89
A.2	Operation.....	89
A.2.1	Training	89
A.2.2	Maintenance programs affecting reliability	90
A.2.3	Spare parts.....	91
Bibliography	94
Figure 1	– Twelve-pulse converter unit	11
Figure 2	– Examples of back-to-back HVDC systems	13
Figure 3	– Monopolar HVDC system with earth return	14
Figure 4	– Two 12-pulse units in series.....	15
Figure 5	– Two 12-pulse units in parallel.....	16
Figure 6	– Monopolar HVDC system with metallic return	17
Figure 7	– Bipolar system	18
Figure 8	– Metallic return operation of the unfaulted pole in a bipolar system.....	19
Figure 9	– Bipolar HVDC system with metallic return	21
Figure 10	– Bipolar system with two 12-pulse units in series per pole	23
Figure 11	– Bipolar system with two 12-pulse units in parallel per pole	24
Figure 12	– DC switching of line conductors	26
Figure 13	– DC switching of converter poles	27
Figure 14	– DC switching – Overhead line to cable	28
Figure 15	– DC switching – Two bipolar converters and lines	29
Figure 16	– DC switching – Intermediate.....	30
Figure 17	– Capacitor commutated converter configurations	31
Figure 18	– LCC/VSC hybrid bipolar system	33
Figure 19	– Variations of reactive power Q with active power P of an HVDC converter	45
Figure 20	– Control hierarchy for HVDC/UHVDC system.....	55
Figure 21	– Converter voltage-current characteristic	57
Figure 22	– Examples of AC filter connections for a bipole HVDC system	68
Figure 23	– Circuit diagrams for different filter types	69
Figure 24	– RY COM interference meter results averaged – Typical plot of converter interference levels on the DC line	79

Figure 25 – Recommended measurement procedure with definition of measuring point	82
Figure 26 – Extension methods for HVDC systems	86
Table 1 – Information supplied for HVDC substation	34
Table 2 – Performance parameters for voice communication circuits: Subscribers and trunk circuits	75

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 TR 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 fourth edition cancels and replaces the third edition, published in 2010, 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) Figure 8 and Figure 20 have been updated, a new Figure 18 "LCC/VSC hybrid bipolar system" has been added;
- b) the HVDC system control objectives have been supplemented;
- c) additional explanations regarding the HVDC system control structure have been given;
- d) a new subclause 13.6 on HVDC system protection has been added.

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

Draft TR	Report on voting
22F/535/DTR	22F/549A/RVDTR

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 document 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 document will remain unchanged until the stability date indicated on the IEC website under "<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 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.

INTRODUCTION

The difference between system performance specifications and equipment design specifications for individual components of a system is realized. 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 is given to coordination of each part with the overall HVDC system performance objectives and to ensuring that the interface of each with the system is clearly defined. Typical of such parts, listed in the appropriate order of relative ease for separate treatment and interface definition, are:

- a) DC line, electrode line and earth electrode;
- b) telecommunication system;
- c) converter building, foundations and other civil engineering work;
- d) reactive power supply including AC shunt capacitor banks, shunt reactors, synchronous and static reactive power (var) compensators;
- e) AC switchgear;
- f) DC switchgear;
- g) auxiliary systems;
- h) AC filters;
- i) DC filters;
- j) DC 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 can be inadvisable.

Clause 4 to Clause 22 of this document set out a complete steady-state performance specification for an HVDC system.

Since the equipment items are usually separately specified and purchased, the HVDC transmission line, earth electrode line and earth electrode (see Clause 11) are included only because of their influence on the HVDC system performance.

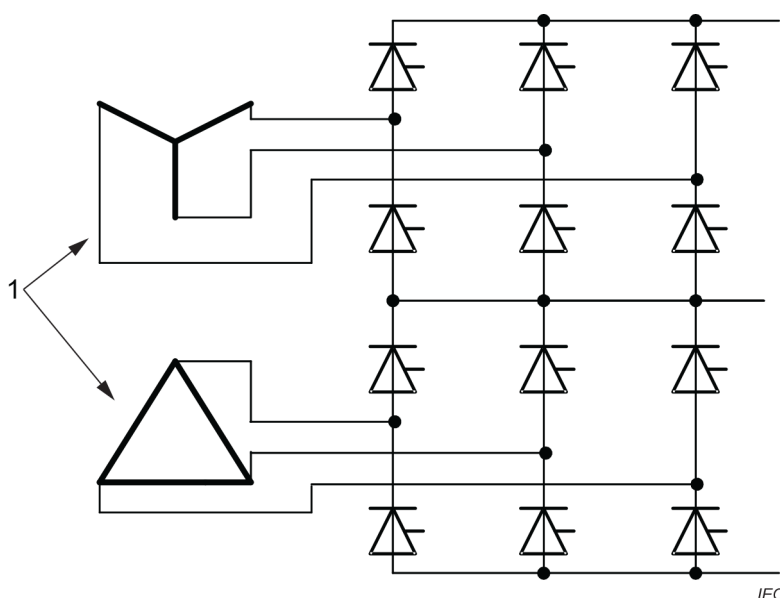
For the purpose of this document, an HVDC substation is assumed to consist of one or more converter units installed in a single location together with buildings, reactors, filters, reactive power supply, control, monitoring, protective, measuring and auxiliary equipment. While there is no discussion of AC switching substations in this document, AC filters and reactive power sources are included, although they can be connected to an AC bus separate from the HVDC substation, as discussed in Clause 17.

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

Part 1: Steady-state conditions

1 Scope

This part of 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 document.



Key

1 Transformer valve windings

Figure 1 – Twelve-pulse converter unit

Only line-commutated converters are covered in this document, which includes capacitor commutated converter circuit configurations. General aspects of 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.

The distinction is made between system performance specifications and equipment design specifications for individual components of a system. Equipment specifications and testing requirements are not defined in this document. Also excluded from this document are detailed seismic performance requirements. In addition, because there are many variations between different possible HVDC systems, this document does not consider these in detail; consequently, it is not 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.

This document, which covers steady-state performance, is followed by the additional documents of IEC TR 60919-2 on faults and switching as well as IEC TR 60919-3 on dynamic

conditions. All three aspects are considered when preparing two-terminal HVDC system specifications.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 60633, *High-voltage direct current (HVDC) transmission – Vocabulary*

CIGRÉ Technical Brochure (TB) No. 391:2009, *Guide for measurement of radio frequency interference from HV and MV substations. Disturbance propagation, characteristics of disturbance sources, measurement techniques, conversion methodologies and limits*