IEC TR 60919-1

Edition 3.2 2017-05

FINAL VERSION

colour inside

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

IEC TR 60919-1:2010-05+AMD1:2013-04+AMD2:2017-05 CSV(en)

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 HVDC system with earth return 13
3.4 Monopolar HVDC system with metallic return 15
3.5 Bipolar earth return HVDC system 16
3.6 Bipolar HVDC system with metallic return 19
3.7 Two 12-pulse groups per pole 21
3.8 Converter transformer arrangements 21
3.9 DC switching considerations 25
3.10 Series capacitor compensated HVDC systems 27
3.11 LCC/VSC hybrid bipolar system 31
4 Environment information 32
5 Rated power, current and voltage 35
5.1 Rated power 35
5.1.1 General 35
5.1.2 Rated power of an HVDC system with transmission line 35
5.1.3 Rated power of an HVDC back-to-back system 35
5.1.4 Direction of power flow 36
5.2 Rated current 36
5.3 Rated voltage 36
6 Overload and equipment capability 36
6.1 Overload 36
6.2 Equipment capability 37
6.2.1 General 37
6.2.2 Converter valve capability 37
6.2.3 Capability of oil-cooled transformers and reactors 38
6.2.4 AC harmonic filter and reactive power compensation equipment capability 38
6.2.5 Switchgear and buswork capability 38
7 Minimum power transfer and no-load stand-by state 38
7.1 General 38
7.2 Minimum current 38
7.3 Reduced direct voltage operation 39
7.4 No-load stand-by state 39
7.4.1 General 39
7.4.2 Converter transformers – No-load stand-by 39
7.4.3 Converter valves – No-load stand-by 39
7.4.4 AC filters and reactive compensation – No-load stand-by 40
7.4.5 DC reactors and d.c. filters – No-load stand-by 40
7.4.6 Auxiliary power system – No-load stand-by 40
7.4.7 Control and protection – No-load stand-by 40
8 AC system 40

8.1 General 40
8.2 AC voltage 40
8.2.1 Rated a.c. voltage 40
8.2.2 Steady-state voltage range 40
8.2.3 Negative sequence voltage 41
8.3 Frequency 41
8.3.1 Rated frequency 41
8.3.2 Steady-state frequency range 41
8.3.3 Short-term frequency variation 42
8.3.4 Frequency variation during emergency 42
8.4 System impedance at fundamental frequency 42
8.5 System impedance at harmonic frequencies 42
8.6 Positive and zero-sequence surge impedance 42
8.7 Other sources of harmonics 42
8.8 Subsynchronous torsional interaction (SSTI) 43
9 Reactive power 43
9.1 General 43
9.2 Conventional HVDC systems 43
9.3 Series capacitor compensated HVDC schemes 45
9.4 Converter reactive power consumption 45
9.5 Reactive power balance with the a.c. system 45
9.6 Reactive power supply 46
9.7 Maximum size of switchable VAR banks 46
10 HVDC transmission line, earth electrode line and earth electrode 46
10.1 General 46
10.2 Overhead line(s) 46
10.2.1 General 46
10.2.2 Electrical parameters 47
10.3 Cable line(s) 47
10.3.1 General 47
10.3.2 Electrical parameters 47
10.4 Earth electrode line 48
10.5 Earth electrode 48
11 Reliability 48
11.1 General 48
11.2 Outage 48
11.2.1 General 48
11.2.2 Scheduled outage 48
11.2.3 Forced outage 49
11.3 Capacity 49
11.3.1 General 49
11.3.2 Maximum continuous capacity P_{m} 49
11.3.3 Outage capacity P_{o} 49
11.3.4 Outage derating factor (ODF) 49
11.4 Outage duration terms 49
11.4.1 Actual outage duration (AOD) 49
11.4.2 Equivalent outage duration (EOD) 49
11.4.3 Period hours (PH) 50
11.4.4 Actual outage hours (AOH) 50

11.4.5 Equivalent outage hours (EOH) 50
11.5 Energy unavailability (EU) 50
11.5.1 General 50
11.5.2 Forced energy unavailability (FEU) 51
11.5.3 Scheduled energy unavailability (SEU) 51
11.6 Energy availability (EA) 51
11.7 Maximum permitted number of forced outages 51
11.8 Statistical probability of outages 51
11.8.1 Component faults 51
11.8.2 External faults 51
12 HVDC control 51
12.1 Control objectives 51
12.2 Control structure 52
12.2.1 General 52
12.2.2 Converter unit firing control 52
12.2.3 Pole control 55
12.2.4 HVDC substation control 57
12.2.5 Master control 57
12.3 Control order settings 57
12.4 Current limits 58
12.5 Control circuit redundancy 58
12.6 Measurements 58
13 Telecommunication 59
13.1 Types of telecommunication links 59
13.2 Telephone 59
13.3 Power line carrier (PLC) 59
13.4 Microwave 60
13.5 Radio link 60
13.6 Optical fibre telecommunication 60
13.7 Classification of data to be transmitted 61
13.8 Fast response telecommunication 61
13.9 Reliability 61
14 Auxiliary power supplies 62
14.1 General 62
14.2 Reliability and load classification 62
14.3 AC auxiliary supplies 63
14.4 Batteries and uninterruptible power supplies (UPS) 63
14.5 Emergency supply 64
15 Audible noise 64
15.1 General 64
15.2 Public nuisance 65
15.2.1 General 65
15.2.2 Valves and valve coolers 65
15.2.3 Converter transformers 65
15.2.4 DC reactors 65
15.2.5 AC filter reactors 65
15.3 Noise in working areas 66
16 Harmonic interference – AC 66

16.1 AC side harmonic generation 66
16.2 Filters 66
16.3 Interference disturbance criteria 70
16.4 Levels for interference 71
16.5 Filter performance 72
17 Harmonic interference – DC 72
17.1 DC side interference 72
17.1.1 Harmonic currents in HVDC transmission line 72
17.1.2 Characteristic and non-characteristic harmonics 72
17.1.3 Groups of harmonics 73
17.1.4 Calculation of harmonic currents 73
17.1.5 Calculation of induced voltages 73
17.1.6 Personnel safety 73
17.1.7 DC filters 74
17.2 DC filter performance 74
17.2.1 Requirements for voice communication circuits 74
17.2.2 Levels of interference 75
17.2.3 Safety 75
17.3 Specification requirements 75
17.3.1 Economic level of filtering 75
17.3.2 General criteria 76
17.3.3 Factors to be taken into account for calculations 77
17.3.4 Calculation of currents 77
18 Power line carrier interference (PLC) 78
18.1 General 78
18.2 Performance specification 78
19 Radio frequency interference 80
19.1 General 80
19.2 RFI from HVDC systems 80
19.2.1 RFI sources 80
19.2.2 RFI propagation 80
19.2.3 RFI characteristics 81
19.3 RFI performance specification 81
19.3.1 RFI risk assessment 81
19.3.2 Specification RFI limit and its verification 82
19.3.3 Design aspects 83
20 Power losses 83
20.1 General 83
20.2 Main contributing sources 84
20.2.1 General 84
20.2.2 AC filters and reactive power compensation 84
20.2.3 Converter bridges 84
20.2.4 Converter transformer 84
20.2.5 DC reactor 84
20.2.6 DC filter 84
20.2.7 Auxiliary equipment 85
20.2.8 Other components 85
21 Provision for extensions to the HVDC systems 85

21.1 General 85
21.2 Specification for extensions 85
Annex A (informative) Factors affecting reliability and availability of converter stations 88
Bibliography 95

Figure 1 – Twelve-pulse converter unit 9
Figure 2 – Examples of back-to-back HVDC systems 12
Figure 3 – Monopolar HVDC system with earth return 13
Figure 4 – Two 12-pulse units in series 14
Figure 5 – Two 12-pulse units in parallel 15
Figure 6 – Monopolar HVDC system with metallic return 16
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 20
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 25
Figure 13 – DC switching of converter poles 26
Figure 14 – DC switching – Overhead line to cable 27
Figure 15 – DC switching – Two-bipolar converters and lines 28
Figure 16 – DC switching – Intermediate 29
Figure 17 – Capacitor commutated converter configurations 30
Figure 18 – Variations of reactive power Q with active power P of an HVDC converter 44
Figure 19 – Control hierarchy 54
Figure 20 – Converter voltage-current characteristic 56
Figure 21 – Examples of a.c. filter connections for a bipole HVDC system 68
Figure 22 – Circuit diagrams for different filter types 69
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 dBm = 1 mW corresponding to 0,775 V at a pole-to-pole surge impedance of 600 Ω 79
Figure 24 – Extension methods for HVDC systems 87
Figure 25 – Recommended measurement procedure with definition of measuring point 83
Figure 26 – LCC/VSC hybrid bipolar system 32

Table 1 – Information supplied for HVDC substation 33
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.

This Consolidated version of IEC TR 60919-1 bears the edition number 3.2. It consists of the third edition (2010-05) [documents 22F/213/DTR and 22F/218/RVC], its amendment 1 (2013-04) [documents 22F/277/DTR and 22F/286A/RVC] and its amendment 2 (2017-05) [documents 22F/447/DTR and 22F/452/RVDTR]. The technical content is identical to the base edition and its amendments.

This Final version does not show where the technical content is modified by amendments 1 and 2. A separate Redline version with all changes highlighted is available in this publication.

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 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.

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 the base publication and its amendments 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.

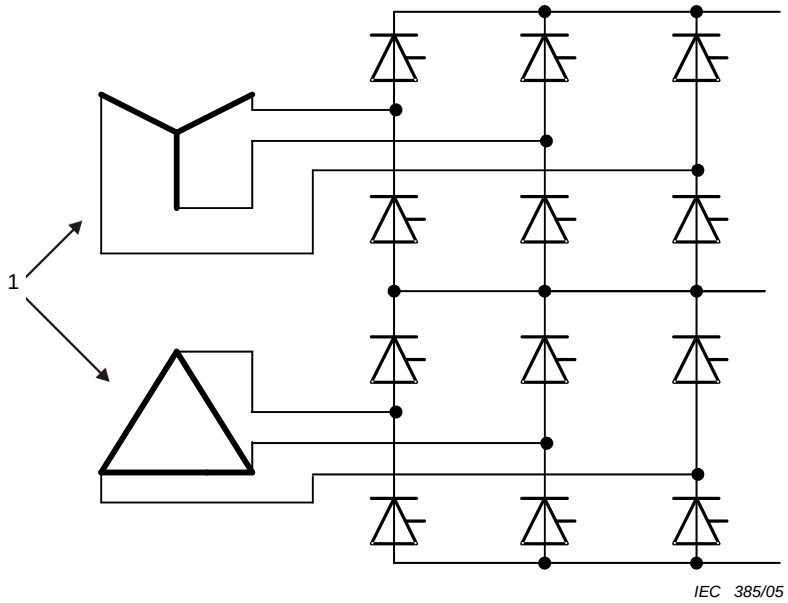
IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

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.