



TECHNICAL REPORT



**High-voltage direct current (HVDC) systems – Guidance to the specification and design evaluation of AC filters –
Part 1: Overview**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.200

ISBN 978-2-8322-4530-9

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

CONTENTS

FOREWORD.....	8
INTRODUCTION.....	2
1 Scope.....	11
2 Normative references	11
3 Terms and definitions	11
4 Outline of specifications of AC filters for HVDC systems	12
4.1 General.....	12
4.2 Boundaries of responsibility	13
4.3 Scope of studies	15
4.4 Scope of supply	16
4.5 Technical data to be supplied by contractor	16
4.6 Alternative proposals by bidders	17
5 Permissible distortion limits	17
5.1 General.....	17
5.2 Voltage distortion.....	18
5.2.1 General	18
5.2.2 Definitions of performance criteria	18
5.2.3 Discussion and recommendations.....	19
5.2.4 Determination of limits	19
5.2.5 Pre-existing harmonic levels.....	22
5.2.6 Relaxed limits for short term and infrequent conditions	23
5.2.7 Treatment of interharmonic frequencies.....	23
5.3 Distortion limits pertaining to the HV and EHV network equipment	24
5.3.1 HVAC transmission system equipment.....	24
5.3.2 Harmonic currents in synchronous machines	24
5.3.3 Nearby HVDC installations	25
5.4 Telephone interference	25
5.4.1 General	25
5.4.2 Causes of telephone interference	25
5.4.3 Definitions of performance criteria	26
5.4.4 Discussion.....	26
5.4.5 Determination of limits	26
5.4.6 Pre-existing harmonic levels.....	28
5.4.7 Limits for temporary conditions	28
5.5 Special criteria.....	29
6 Harmonic generation	29
6.1 General.....	29
6.2 Converter harmonic generation	30
6.2.1 Idealized conditions	30
6.2.2 Realistic conditions.....	31
6.3 Calculation methodology.....	33
6.3.1 General	33
6.3.2 Harmonic currents for performance, rating and other calculations	34
6.3.3 Combining harmonics from different converter bridges.....	34
6.3.4 Consistent sets.....	35
6.3.5 Harmonic generation for different DC power ranges.....	36

6.4	Sensitivity of harmonic generation	37
6.4.1	Direct current, control angle and commutation overlap	37
6.4.2	Effect of asymmetries on characteristic harmonics	37
6.4.3	Converter equipment parameter tolerances	37
6.4.4	Tap steps	38
6.4.5	Theoretically cancelled harmonics	38
6.4.6	Negative and zero-phase sequence voltages	38
6.4.7	Converter transformer saturation	39
6.4.8	Harmonic interaction across the converter	39
6.4.9	Back-to-back systems	39
6.5	Externally generated harmonics	40
7	Filter arrangements	40
7.1	Overview	40
7.2	Advantages and disadvantages of typical filters	41
7.3	Classification of filter types	42
7.4	Tuned filters	42
7.4.1	Single tuned filters	42
7.4.2	Double tuned filters	44
7.4.3	Triple tuned filters	46
7.5	Damped filters	47
7.5.1	Single tuned damped filters	47
7.5.2	Double tuned damped filters	50
7.6	Choice of filters	51
8	Filter performance calculation	52
8.1	Calculation procedure	52
8.1.1	General	52
8.1.2	Input data	52
8.1.3	Methodology	52
8.1.4	Calculation of converter harmonic currents	53
8.1.5	Selection of filter types and calculation of their impedances	54
8.1.6	Calculation of performance	54
8.2	Detuning and tolerances	55
8.2.1	General	55
8.2.2	Detuning factors	56
8.2.3	Resistance variations	57
8.2.4	Modelling	57
8.3	Network impedance for performance calculations	57
8.3.1	General	57
8.3.2	Network modelling using impedance envelopes	58
8.3.3	Sector diagram	59
8.3.4	Circle diagram	60
8.3.5	Discrete polygons	61
8.3.6	Zero-sequence impedance modelling	63
8.3.7	Detailed modelling of AC network for performance calculation	63
8.4	Outages of filter banks and sub-banks	64
8.5	Considerations of probability	65
8.6	Flexibility regarding compliance	67
8.7	Ratings of the harmonic filter equipment	67
9	Filter switching and reactive power management	68

9.1	General.....	68
9.2	Reactive power interchange with AC network.....	68
9.2.1	General	68
9.2.2	Impact on reactive compensation and filter equipment.....	68
9.2.3	Evaluation of reactive power interchange.....	69
9.3	HVDC converter reactive power capability	70
9.4	Bank/sub-bank definitions and sizing	70
9.4.1	General	70
9.4.2	Sizing	71
9.5	Hysteresis in switching points	73
9.6	Converter Q-V control near switching points	74
9.7	Operation at increased converter control angles	74
9.8	Filter switching sequence and harmonic performance	74
9.9	Demarcation of responsibilities	75
9.9.1	General	75
9.9.2	Customer.....	75
9.9.3	Contractor	76
10	Customer specified parameters and requirements	76
10.1	General.....	76
10.2	AC system parameters.....	76
10.2.1	Voltage.....	76
10.2.2	Voltage unbalance	77
10.2.3	Frequency	77
10.2.4	Short circuit level.....	77
10.2.5	Filter switching	78
10.2.6	Reactive power interchange.....	78
10.2.7	System harmonic impedance	78
10.2.8	Zero sequence data.....	78
10.2.9	System earthing.....	78
10.2.10	Insulation level	78
10.2.11	Creepage distances.....	78
10.2.12	Pre-existing voltage distortion.....	78
10.3	Harmonic distortion requirements.....	79
10.3.1	General	79
10.3.2	Redundancy requirements	79
10.4	Environmental conditions	79
10.4.1	Temperature.....	79
10.4.2	Pollution	80
10.4.3	Wind.....	80
10.4.4	Ice and snow loading (if applicable).....	80
10.4.5	Solar radiation	80
10.4.6	Isokeraunic levels.....	80
10.4.7	Seismic requirements	80
10.4.8	Audible noise.....	80
10.5	Electrical environment.....	80
10.6	Requirements for filter arrangements and components.....	81
10.6.1	Filter arrangements	81
10.6.2	Filter capacitors.....	81
10.6.3	Test requirements.....	81

10.7	Protection of filters.....	82
10.8	Loss evaluation.....	82
10.9	Field measurements and verifications	82
10.10	General requirements	82
11	Future developments	82
11.1	General.....	82
11.2	New Non-standard filter technology	83
11.2.1	General	83
11.2.2	Automatically tuned reactors.....	83
11.2.3	Single-phase redundancy	86
10.2.4	Fuseless capacitors	88
11.2.4	Stand-alone active filters	88
11.2.5	Compact design.....	89
10.2.7	Other filter circuit components	89
11.3	New Other LCC converter technology	90
11.3.1	General	91
11.3.2	Series commutated converters.....	91
10.3.3	PWM voltage-sourced converters	94
11.3.3	Transformerless converters	94
11.3.4	Unit connection.....	95
11.4	Changing external environment.....	95
11.4.1	Increased pre-existing levels of harmonic distortion.....	95
11.4.2	Developments in communication technology	96
11.4.3	Changes in structure of the power supply industry	96
11.4.4	Focus on power quality	97
11.4.5	Fewer large synchronous generators and more renewable and distributed generation	97
Annex A (informative) Alternative type of procurement procedure		98
Annex B (informative) Formulae for calculating the characteristic harmonics of a bridge converter.....		99
Annex C (informative) Definition of telephone interference parameters		101
C.1	General.....	101
C.2	Criteria according to European practice	101
C.3	Criteria according to North American practice	102
C.4	Discussion	104
Annex D (informative) Equivalent frequency deviation.....		105
Annex E (informative) Reactive power management		106
E.1	HVDC converter reactive power capability	106
E.1.1	Steady-state capability	106
E.1.2	Temporary capability	108
E.2	Converter Q-V control near switching points	109
E.3	Step change in voltage on switching a filter	110
Annex F (informative) Voltage-sourced converters		111
F.1	General.....	111
F.2	Two-level converter with PWM	112
F.3	Three-level converter with PWM	113
F.4	Multi-level converters.....	114
F.5	Modelling of VSCs for harmonic filtering purposes	115

Bibliography.....	118
Figure 1 – Idealized current waveforms on the AC side of converter transformer	30
Figure 2 – Realistic current waveforms on the AC side of converter transformer including effect of non-idealities.....	32
Figure 3 – Comparison of harmonic content of current waveform under idealized and realistic conditions	33
Figure 4 – Typical variation of characteristic harmonic magnitude with direct current	36
Figure 5 – Single tuned filter and frequency response.....	43
Figure 6 – Double tuned filter and frequency response	44
Figure 7 – Triple tuned filter and frequency response	46
Figure 8 – 2 nd order damped filter and frequency response.....	48
Figure 9 – 3 rd order damped filter and frequency response	48
Figure 10 – C-type filter and frequency response.....	49
Figure 11 – Double tuned damped filter and frequency response	50
Figure 12 – Circuit model for filter calculations	53
Figure 13 – AC system impedance general sector diagram, with minimum impedance	60
Figure 14 – AC system impedance general sector diagram, with minimum resistance.....	60
Figure 15 – AC system impedance general circle diagram, with minimum resistance	61
Figure 16 – Example of harmonic impedances for harmonics of order 2 to 4	62
Figure 17 – Example of harmonic impedances for harmonics of order 5 to 8	62
Figure 18 – Example of harmonic impedances for harmonics of order 9 to 13	63
Figure 19 – Example of harmonic impedances for harmonics of order 14 to 49	63
Figure 20 – Illustration of basic voltage quality concepts with time/location statistics covering the whole system (adapted from IEC TR 61000-3-6:2008)	66
Figure 21 – Example of range of operation where specifications on harmonic levels are not met for a filter scheme solution	67
Figure 22 – Branch, sub-bank and bank definition.....	71
Figure 23 – Typical switching sequence.....	75
Figure 24 – Reactive power components.....	76
Figure 25 – Design principle of a self-tuned reactor using DC control current in an orthogonal winding.....	84
Figure 26 – Control principle for self-tuned filter	85
Figure 27 – One method of switching a redundant single phase filter	87
Figure 28 – Fuseless capacitor design compared to internal and external fused units
Figure 28 – Various possible configurations of series compensated HVDC converters	93
Figure 30 – Circuit and waveforms of a DC link using voltage sourced converters
Figure E.1 – Capability diagram of a converter under different control strategies	106
Figure E.2 – Converter capability with $\gamma_{\min} = 17^\circ$, $\gamma_{\max} = 40^\circ$, $\alpha_{\min} = 5^\circ$, $\alpha_{\max} = 35^\circ$ and $U_{\text{dio max}} = 1,2U_{\text{dio N}}$	107
Figure E.3 – Reactive power absorption of a rectifier as a function of α with $U_{\text{dio}} = U_{\text{dio N}}$, $d_x = 9,4 \%$ and $d_r = 0,2 \%$	109
Figure E.4 – Reactive power absorption of a inverter as a function of γ with $U_{\text{dio}} = U_{\text{dio N}}$, $d_x = 9,4 \%$ and $d_r = 0,2 \%$	109

~~Figure F.1 – Simplified representation of a 2-level voltage sourced converter~~

~~Figure F.2 – Single phase AC output for 2-level converter with PWM switching at 21 times fundamental frequency~~

~~Figure F.3 – Simplified representation of a 3-level voltage sourced converter~~

~~Figure F.4 – Single phase AC output for 3-level converter with PWM switching at 21 times fundamental frequency~~

~~Figure F.5 – Basic operation of the MMC converters~~

~~Figure F.6 – Phase unit of the modular multi-level converter (MMC) in basic half-bridge, without series-connected IGBTs (left) and the cascaded two level (CTL) converter with series-connected IGBTs (right).....~~

~~Figure F.7 – Representation of a voltage sourced converter as a harmonic voltage source behind an inductance~~

INTERNATIONAL ELECTROTECHNICAL COMMISSION

HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS – GUIDANCE TO THE SPECIFICATION AND DESIGN EVALUATION OF AC FILTERS –

Part 1: Overview

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 IEC TR 62001-1:2016. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

IEC TR 62001-1 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 2016. This edition constitutes a technical revision.

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

- a) general updating of the document to reflect changes in practice;
- b) 10.2.4 on fuseless capacitors has been transferred to IEC TR 62001-4;
- c) Clause 11 on future developments has been expanded;
- d) 10.3.3 and Annex F on voltage sourced converters have been deleted as their content is covered by IEC TR 62543.

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

DTR	Report on voting
22F/614/DTR	22F/623A/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. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC TR 62001 series, published under the general title *High-voltage direct current (HVDC) systems – Guidance to the specification and design evaluation of AC filters*, 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 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.

INTRODUCTION

The IEC TR 62001 series is structured in ~~four~~ five parts:

IEC TR 62001-1 – Overview

This part concerns specifications of AC filters for high-voltage direct current (HVDC) systems with line-commutated converters, permissible distortion limits, harmonic generation, filter arrangements, filter performance calculation, filter switching and reactive power management and customer specified parameters and requirements.

IEC TR 62001-2 – Performance

This part deals with current-based interference criteria, ~~design issues and special applications,~~ field measurements and verification.

IEC TR 62001-3 – Modelling

This part addresses the harmonic interaction across converters, pre-existing harmonics, AC network impedance modelling, simulation of AC filter performance.

IEC TR 62001-4 – Equipment

This part concerns steady-state and transient ratings of AC filters and their components, power losses, audible noise, design issues and special applications, filter protection, seismic requirements, equipment design and test parameters.

IEC TR 62001-5¹ – AC side harmonics and appropriate harmonic limits for high-voltage direct current (HVDC) systems with voltage sourced converters (VSC)

This document concerns specific issues of AC filter design related to VSC HVDC systems.

Parts 1 to 4 are written with focus on line commutated converters.

¹ Under preparation. Stage at the time of publication: IEC/RPUB 62001-5:2021.

HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS – GUIDANCE TO THE SPECIFICATION AND DESIGN EVALUATION OF AC FILTERS –

Part 1: Overview

1 Scope

This part of IEC 62001, which is a Technical Report, deals with the specification and design evaluation of AC side harmonic performance and AC side filters for HVDC schemes. It is intended to be primarily for the use of the utilities and consultants who are responsible for issuing the specifications for new HVDC projects and evaluating designs proposed by prospective suppliers.

This document provides guidance on the specifications of AC filters for high-voltage direct current (HVDC) systems with line-commutated converters and filter performance calculation.

The scope of this document covers AC side filtering for the frequency range of interest in terms of harmonic distortion and audible frequency disturbances. Where the term "HVDC converter" or "HVDC station" is referred to without qualification, in this document, it is understood to refer to LCC technology. It excludes filters designed to be effective in the power line carrier (PLC) and radio interference spectra.

The bulk of this document concentrates on the "conventional" AC filter technology and LCC (line-commutated converter) HVDC ~~converters. The changes entailed by new technologies are also discussed.~~ Voltage sourced converter (VSC) specific issues are discussed in CIGRE Technical Brochure 754 [1]² and in IEC TR 62001-5 [2].

2 Normative references

There are no normative references in this document.

² Numbers in square brackets refer to the Bibliography.

TECHNICAL REPORT



**High-voltage direct current (HVDC) systems – Guidance to the specification and design evaluation of AC filters –
Part 1: Overview**

CONTENTS

FOREWORD.....	7
INTRODUCTION.....	9
1 Scope.....	10
2 Normative references	10
3 Terms and definitions	10
4 Outline of specifications of AC filters for HVDC systems	11
4.1 General.....	11
4.2 Boundaries of responsibility	12
4.3 Scope of studies	14
4.4 Scope of supply	14
4.5 Technical data to be supplied by contractor	15
4.6 Alternative proposals by bidders	15
5 Permissible distortion limits	16
5.1 General.....	16
5.2 Voltage distortion.....	17
5.2.1 General	17
5.2.2 Definitions of performance criteria	17
5.2.3 Discussion and recommendations.....	18
5.2.4 Determination of limits	18
5.2.5 Pre-existing harmonic levels.....	21
5.2.6 Relaxed limits for short term and infrequent conditions	22
5.2.7 Treatment of interharmonic frequencies.....	22
5.3 Distortion limits pertaining to the HV and EHV network equipment	23
5.3.1 HVAC transmission system equipment.....	23
5.3.2 Harmonic currents in synchronous machines	23
5.3.3 Nearby HVDC installations	24
5.4 Telephone interference	24
5.4.1 General	24
5.4.2 Causes of telephone interference	24
5.4.3 Definitions of performance criteria	24
5.4.4 Discussion.....	25
5.4.5 Determination of limits	25
5.4.6 Pre-existing harmonic levels	27
5.4.7 Limits for temporary conditions	27
5.5 Special criteria.....	28
6 Harmonic generation	28
6.1 General.....	28
6.2 Converter harmonic generation	28
6.2.1 Idealized conditions	28
6.2.2 Realistic conditions.....	30
6.3 Calculation methodology.....	32
6.3.1 General	32
6.3.2 Harmonic currents for performance, rating and other calculations	32
6.3.3 Combining harmonics from different converter bridges.....	33
6.3.4 Consistent sets.....	33
6.3.5 Harmonic generation for different DC power ranges.....	34

6.4	Sensitivity of harmonic generation to various factors.....	35
6.4.1	Direct current, control angle and commutation overlap.....	35
6.4.2	Effect of asymmetries on characteristic harmonics.....	35
6.4.3	Converter equipment parameter tolerances	35
6.4.4	Tap steps	36
6.4.5	Theoretically cancelled harmonics	36
6.4.6	Negative and zero sequence voltages	36
6.4.7	Converter transformer saturation	37
6.4.8	Harmonic interaction across the converter	37
6.4.9	Back-to-back systems.....	38
6.5	Externally generated harmonics	38
7	Filter arrangements	38
7.1	Overview	38
7.2	Advantages and disadvantages of typical filters	39
7.3	Classification of filter types	40
7.4	Tuned filters.....	40
7.4.1	Single tuned filters.....	40
7.4.2	Double tuned filters	42
7.4.3	Triple tuned filters.....	44
7.5	Damped filters	45
7.5.1	Single tuned damped filters	45
7.5.2	Double tuned damped filters	48
7.6	Choice of filters.....	49
8	Filter performance calculation.....	50
8.1	Calculation procedure	50
8.1.1	General	50
8.1.2	Input data	50
8.1.3	Methodology	50
8.1.4	Calculation of converter harmonic currents	51
8.1.5	Selection of filter types and calculation of their impedances	52
8.1.6	Calculation of performance	52
8.2	Detuning and tolerances	53
8.2.1	General	53
8.2.2	Detuning factors	54
8.2.3	Resistance variations	55
8.2.4	Modelling.....	55
8.3	Network impedance for performance calculations	55
8.3.1	General	55
8.3.2	Network modelling using impedance envelopes	56
8.3.3	Sector diagram	57
8.3.4	Circle diagram	58
8.3.5	Discrete polygons	59
8.3.6	Zero-sequence impedance modelling.....	61
8.3.7	Detailed modelling of AC network for performance calculation	61
8.4	Outages of filter banks and sub-banks	62
8.5	Considerations of probability.....	63
8.6	Flexibility regarding compliance	65
8.7	Ratings of the harmonic filter equipment	65
9	Filter switching and reactive power management.....	66

9.1	General.....	66
9.2	Reactive power interchange with AC network.....	66
9.2.1	General	66
9.2.2	Impact on reactive compensation and filter equipment.....	66
9.2.3	Evaluation of reactive power interchange.....	67
9.3	HVDC converter reactive power capability	68
9.4	Bank/sub-bank definitions and sizing	68
9.4.1	General	68
9.4.2	Sizing	69
9.5	Hysteresis in switching points	71
9.6	Converter Q-V control near switching points	72
9.7	Operation at increased converter control angles	72
9.8	Filter switching sequence and harmonic performance	72
9.9	Demarcation of responsibilities	73
9.9.1	General	73
9.9.2	Customer.....	73
9.9.3	Contractor	74
10	Customer specified parameters and requirements	74
10.1	General.....	74
10.2	AC system parameters.....	74
10.2.1	Voltage.....	74
10.2.2	Voltage unbalance	75
10.2.3	Frequency	75
10.2.4	Short circuit level.....	75
10.2.5	Filter switching	75
10.2.6	Reactive power interchange.....	76
10.2.7	System harmonic impedance	76
10.2.8	Zero sequence data.....	76
10.2.9	System earthing.....	76
10.2.10	Insulation level	76
10.2.11	Creepage distances.....	76
10.2.12	Pre-existing voltage distortion.....	76
10.3	Harmonic distortion requirements.....	77
10.3.1	General	77
10.3.2	Redundancy requirements	77
10.4	Environmental conditions	77
10.4.1	Temperature.....	77
10.4.2	Pollution	77
10.4.3	Wind.....	77
10.4.4	Ice and snow loading (if applicable).....	78
10.4.5	Solar radiation	78
10.4.6	Isokeraunic levels.....	78
10.4.7	Seismic requirements	78
10.4.8	Audible noise.....	78
10.5	Electrical environment.....	78
10.6	Requirements for filter arrangements and components.....	79
10.6.1	Filter arrangements	79
10.6.2	Filter capacitors.....	79
10.6.3	Test requirements.....	79

10.7	Protection of filters.....	79
10.8	Loss evaluation.....	79
10.9	Field measurements and verifications	79
10.10	General requirements	79
11	Future developments	80
11.1	General.....	80
11.2	Non-standard filter technology	80
11.2.1	General	80
11.2.2	Automatically tuned reactors.....	80
11.2.3	Single-phase redundancy	83
11.2.4	Stand-alone active filters	84
11.2.5	Compact design.....	86
11.3	Other LCC converter technology	86
11.3.1	General	86
11.3.2	Series commutated converters.....	86
11.3.3	Transformerless converters	89
11.3.4	Unit connection.....	89
11.4	Changing external environment.....	90
11.4.1	Increased pre-existing levels of harmonic distortion	90
11.4.2	Developments in communication technology	90
11.4.3	Changes in structure of the power supply industry	91
11.4.4	Focus on power quality	91
11.4.5	Fewer large synchronous generators and more renewable and distributed generation	91
Annex A (informative)	Alternative type of procurement procedure	92
Annex B (informative)	Formulae for calculating the characteristic harmonics of a bridge converter	93
Annex C (informative)	Definition of telephone interference parameters	95
C.1	General.....	95
C.2	Criteria according to European practice	95
C.3	Criteria according to North American practice	96
C.4	Discussion	98
Annex D (informative)	Equivalent frequency deviation.....	99
Annex E (informative)	Reactive power management	100
E.1	HVDC converter reactive power capability	100
E.1.1	Steady-state capability	100
E.1.2	Temporary capability	102
E.2	Converter Q-V control near switching points	103
E.3	Step change in voltage on switching a filter	104
Bibliography	106
Figure 1	– Idealized current waveforms on the AC side of converter transformer	29
Figure 2	– Realistic current waveforms on the AC side of converter transformer including effect of non-idealities.....	30
Figure 3	– Comparison of harmonic content of current waveform under idealized and realistic conditions	31
Figure 4	– Typical variation of characteristic harmonic magnitude with direct current	34
Figure 5	– Single tuned filter and frequency response.....	41

Figure 6 – Double tuned filter and frequency response	42
Figure 7 – Triple tuned filter and frequency response	44
Figure 8 – 2 nd order damped filter and frequency response	46
Figure 9 – 3 rd order damped filter and frequency response	46
Figure 10 – C-type filter and frequency response	47
Figure 11 – Double tuned damped filter and frequency response	48
Figure 12 – Circuit model for filter calculations	51
Figure 13 – AC system impedance general sector diagram, with minimum impedance	58
Figure 14 – AC system impedance general sector diagram, with minimum resistance	58
Figure 15 – AC system impedance general circle diagram, with minimum resistance	59
Figure 16 – Example of harmonic impedances for harmonics of order 2 to 4	60
Figure 17 – Example of harmonic impedances for harmonics of order 5 to 8	60
Figure 18 – Example of harmonic impedances for harmonics of order 9 to 13	61
Figure 19 – Example of harmonic impedances for harmonics of order 14 to 49	61
Figure 20 – Illustration of basic voltage quality concepts with time/location statistics covering the whole system (adapted from IEC TR 61000-3-6:2008)	64
Figure 21 – Example of range of operation where specifications on harmonic levels are not met for a filter scheme solution	65
Figure 22 – Branch, sub-bank and bank definition	69
Figure 23 – Typical switching sequence	73
Figure 24 – Reactive power components	74
Figure 25 – Design principle of a self-tuned reactor using DC control current in an orthogonal winding	82
Figure 26 – Control principle for self-tuned filter	82
Figure 27 – One method of switching a redundant single phase filter	84
Figure 28 – Various possible configurations of series compensated HVDC converters	88
Figure E.1 – Capability diagram of a converter under different control strategies	100
Figure E.2 – Converter capability with $\gamma_{\min} = 17^\circ$, $\gamma_{\max} = 40^\circ$, $\alpha_{\min} = 5^\circ$, $\alpha_{\max} = 35^\circ$ and $U_{\text{diomax}} = 1,2U_{\text{dioN}}$	101
Figure E.3 – Reactive power absorption of a rectifier as a function of α with $U_{\text{dio}} = U_{\text{dioN}}$, $d_x = 9,4 \%$ and $d_r = 0,2 \%$	103
Figure E.4 – Reactive power absorption of a inverter as a function of γ with $U_{\text{dio}} = U_{\text{dioN}}$, $d_x = 9,4 \%$ and $d_r = 0,2 \%$	103

INTERNATIONAL ELECTROTECHNICAL COMMISSION

**HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS –
GUIDANCE TO THE SPECIFICATION AND DESIGN
EVALUATION OF AC FILTERS –****Part 1: Overview****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 62001-1 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 2016. This edition constitutes a technical revision.

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

- a) general updating of the document to reflect changes in practice;
- b) 10.2.4 on fuseless capacitors has been transferred to IEC TR 62001-4;
- c) Clause 11 on future developments has been expanded;
- d) 10.3.3 and Annex F on voltage sourced converters have been deleted as their content is covered by IEC TR 62543.

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

DTR	Report on voting
22F/614/DTR	22F/623A/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. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC TR 62001 series, published under the general title *High-voltage direct current (HVDC) systems – Guidance to the specification and design evaluation of AC filters*, 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 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.

INTRODUCTION

The IEC TR 62001 series is structured in five parts:

IEC TR 62001-1 – Overview

This part concerns specifications of AC filters for high-voltage direct current (HVDC) systems with line-commutated converters, permissible distortion limits, harmonic generation, filter arrangements, filter performance calculation, filter switching and reactive power management and customer specified parameters and requirements.

IEC TR 62001-2 – Performance

This part deals with current-based interference criteria, field measurements and verification.

IEC TR 62001-3 – Modelling

This part addresses the harmonic interaction across converters, pre-existing harmonics, AC network impedance modelling, simulation of AC filter performance.

IEC TR 62001-4 – Equipment

This part concerns steady-state and transient ratings of AC filters and their components, power losses, audible noise, design issues and special applications, filter protection, seismic requirements, equipment design and test parameters.

IEC TR 62001-5¹ – AC side harmonics and appropriate harmonic limits for high-voltage direct current (HVDC) systems with voltage sourced converters (VSC)

This document concerns specific issues of AC filter design related to VSC HVDC systems.

Parts 1 to 4 are written with focus on line commutated converters.

¹ Under preparation. Stage at the time of publication: IEC/RPUB 62001-5:2021.

HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS – GUIDANCE TO THE SPECIFICATION AND DESIGN EVALUATION OF AC FILTERS –

Part 1: Overview

1 Scope

This part of IEC 62001, which is a Technical Report, deals with the specification and design evaluation of AC side harmonic performance and AC side filters for HVDC schemes. It is intended to be primarily for the use of the utilities and consultants who are responsible for issuing the specifications for new HVDC projects and evaluating designs proposed by prospective suppliers.

This document provides guidance on the specifications of AC filters for high-voltage direct current (HVDC) systems with line-commutated converters and filter performance calculation.

The scope of this document covers AC side filtering for the frequency range of interest in terms of harmonic distortion and audible frequency disturbances. Where the term "HVDC converter" or "HVDC station" is referred to without qualification, in this document, it is understood to refer to LCC technology. It excludes filters designed to be effective in the power line carrier (PLC) and radio interference spectra.

The bulk of this document concentrates on the "conventional" AC filter technology and LCC (line-commutated converter) HVDC. Voltage sourced converter (VSC) specific issues are discussed in CIGRE Technical Brochure 754 [1]² and in IEC TR 62001-5 [2].

2 Normative references

There are no normative references in this document.

² Numbers in square brackets refer to the Bibliography.