



BSI Standards Publication

High-voltage direct current (HVDC) systems — Guidance to the specification and design evaluation of AC filters

Part 1: Overview

National foreword

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TECHNICAL REPORT



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

Part 1: Overview

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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CONTENTS

FOREWORD	8
INTRODUCTION	10
1 Scope	11
2 Terms and definitions	11
3 Outline of specifications of AC filters for HVDC systems	12
3.1 General	12
3.2 Boundaries of responsibility	13
3.3 Scope of studies	14
3.4 Scope of supply	15
3.5 Technical data to be supplied by contractor	16
3.6 Alternative proposals by bidders	16
4 Permissible distortion limits	17
4.1 General	17
4.2 Voltage distortion	18
4.2.1 General	18
4.2.2 Voltage distortion – Definitions of performance criteria	18
4.2.3 Voltage distortion – Discussion and recommendations	18
4.2.4 Voltage distortion – Determination of limits	19
4.2.5 Voltage distortion – Pre-existing harmonic levels	22
4.2.6 Voltage distortion – Relaxed limits for short term and infrequent conditions	23
4.2.7 Treatment of interharmonic frequencies	23
4.3 Distortion limits pertaining to the HV and EHV network equipment	24
4.3.1 HVAC transmission system equipment	24
4.3.2 Harmonic currents in synchronous machines	24
4.3.3 Nearby HVDC installations	25
4.4 Telephone interference	25
4.4.1 General	25
4.4.2 Causes of telephone interference	25
4.4.3 Telephone interference – Definitions of performance criteria	25
4.4.4 Telephone interference – Discussion	25
4.4.5 Telephone interference – Determination of limits	26
4.4.6 Telephone interference – Pre-existing harmonic levels	28
4.4.7 Telephone interference – Limits for temporary conditions	28
4.5 Special criteria	29
5 Harmonic generation	29
5.1 General	29
5.2 Converter harmonic generation	29
5.2.1 Idealized conditions	29
5.2.2 Realistic conditions	31
5.3 Calculation methodology	33
5.3.1 General	33
5.3.2 Harmonic currents for performance, rating and other calculations	33
5.3.3 Combining harmonics from different converter bridges	34
5.3.4 Consistent sets	34
5.3.5 Harmonic generation for different DC power ranges	34

5.4	Sensitivity of harmonic generation to various factors	36
5.4.1	Direct current, control angle and commutation overlap.....	36
5.4.2	Effect of asymmetries on characteristic harmonics	37
5.4.3	Converter equipment parameter tolerances	37
5.4.4	Tap steps	37
5.4.5	Theoretically cancelled harmonics.....	37
5.4.6	Negative and zero phase sequence voltages	38
5.4.7	Converter transformer saturation.....	38
5.4.8	Harmonic interaction across the converter.....	39
5.4.9	Back-to-back systems	39
5.5	Externally generated harmonics	39
6	Filter arrangements	40
6.1	Overview	40
6.2	Advantages and disadvantages of typical filters.....	41
6.3	Classification of filter types	41
6.4	Tuned filters.....	42
6.4.1	Single tuned filters	42
6.4.2	Double tuned filters.....	43
6.4.3	Triple tuned filters	45
6.5	Damped filters	46
6.5.1	Single tuned damped filters.....	46
6.5.2	Double tuned damped filters.....	49
6.6	Choice of filters.....	49
7	Filter performance calculation.....	50
7.1	Calculation procedure	50
7.1.1	General	50
7.1.2	Input data	51
7.1.3	Methodology	51
7.1.4	Calculation of converter harmonic currents.....	52
7.1.5	Selection of filter types and calculation of their impedances	52
7.1.6	Calculation of performance	53
7.2	Detuning and tolerances	54
7.2.1	General	54
7.2.2	Detuning factors	54
7.2.3	Resistance variations.....	55
7.2.4	Modelling.....	55
7.3	Network impedance for performance calculations	56
7.3.1	General	56
7.3.2	Network modelling using impedance envelopes	57
7.3.3	Sector diagram	58
7.3.4	Circle diagram	59
7.3.5	Discrete polygons	59
7.3.6	Zero-sequence impedance modelling	61
7.3.7	Detailed modelling of AC network for performance calculation	61
7.4	Outages of filter banks and sub-banks.....	62
7.5	Considerations of probability	63
7.6	Flexibility regarding compliance	65
7.7	Ratings of the harmonic filter equipment.....	65
8	Filter switching and reactive power management	65

8.1	General	65
8.2	Reactive power interchange with AC network	66
8.2.1	General	66
8.2.2	Impact on reactive compensation and filter equipment	66
8.2.3	Evaluation of reactive power interchange	67
8.3	HVDC converter reactive power capability	67
8.4	Bank/sub-bank definitions and sizing	67
8.4.1	General	67
8.4.2	Sizing	68
8.5	Hysteresis in switching points	70
8.6	Converter Q-V control near switching points	71
8.7	Operation at increased converter control angles	71
8.8	Filter switching sequence and harmonic performance	71
8.9	Demarcation of responsibilities	72
8.9.1	General	72
8.9.2	Customer	72
8.9.3	Contractor	73
9	Customer specified parameters and requirements	73
9.1	General	73
9.2	AC system parameters	73
9.2.1	Voltage	73
9.2.2	Voltage unbalance	74
9.2.3	Frequency	74
9.2.4	Short circuit level	74
9.2.5	Filter switching	75
9.2.6	Reactive power interchange	75
9.2.7	System harmonic impedance	75
9.2.8	Zero sequence data	75
9.2.9	System earthing	75
9.2.10	Insulation level	75
9.2.11	Creepage distances	75
9.2.12	Pre-existing voltage distortion	75
9.3	Harmonic distortion requirements	76
9.3.1	General	76
9.3.2	Redundancy requirements	76
9.4	Environmental conditions	76
9.4.1	Temperature	76
9.4.2	Pollution	76
9.4.3	Wind	77
9.4.4	Ice and snow loading (if applicable)	77
9.4.5	Solar radiation	77
9.4.6	Isokeraunic levels	77
9.4.7	Seismic requirements	77
9.4.8	Audible noise	77
9.5	Electrical environment	77
9.6	Requirements for filter arrangements and components	78
9.6.1	Filter arrangements	78
9.6.2	Filter capacitors	78
9.6.3	Test requirements	78

9.7	Protection of filters	78
9.8	Loss evaluation	78
9.9	Field measurements and verifications	78
9.10	General requirements	79
10	Future developments	79
10.1	General	79
10.2	New filter technology	79
10.2.1	General	79
10.2.2	Automatically tuned reactors	80
10.2.3	Single-phase redundancy	82
10.2.4	Fuseless capacitors	83
10.2.5	Active filters	84
10.2.6	Compact design	85
10.2.7	Other filter circuit components	86
10.3	New converter technology	87
10.3.1	General	87
10.3.2	Series commutated converters	87
10.3.3	PWM voltage-sourced converters	88
10.3.4	Transformerless converters	90
10.3.5	Unit connection	91
10.4	Changing external environment	91
10.4.1	Increased pre-existing levels of harmonic distortion	91
10.4.2	Developments in communication technology	92
10.4.3	Changes in structure of the power supply industry	92
10.4.4	Focus on power quality	93
Annex A (informative)	Alternative type of procurement procedure	94
Annex B (informative)	Formulae for calculating the characteristic harmonics of a bridge converter	95
Annex C (informative)	Definition of telephone interference parameters	97
C.1	General	97
C.2	Criteria according to European practice	97
C.3	Criteria according to North American practice	98
C.4	Discussion	99
Annex D (informative)	Equivalent frequency deviation	101
Annex E (informative)	Reactive power management	102
E.1	HVDC converter reactive power capability	102
E.1.1	Steady-state capability	102
E.1.2	Temporary capability	104
E.2	Converter Q-V control near switching points	105
E.3	Step-change in voltage on switching a filter	106
Annex F (informative)	Voltage sourced converters	108
F.1	General	108
F.2	Two-level converter with PWM	108
F.3	Three-level converter with PWM	110
F.4	Multi-level converters	111
F.5	Modelling of VSCs for harmonic filtering purposes	112
Bibliography		114

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	31
Figure 3 – Comparison of harmonic content of current waveform under idealized and realistic conditions	32
Figure 4 – Typical variation of characteristic harmonic magnitude with direct current	36
Figure 5 – Single tuned filter and frequency response	42
Figure 6 – Double tuned filter and frequency response	44
Figure 7 – Triple tuned filter and frequency response	45
Figure 8 – 2nd order damped filter and frequency response	47
Figure 9 – 3rd order damped filter and frequency response	47
Figure 10 – C-type filter and frequency response	48
Figure 11 – Double tuned damped filter and frequency response	49
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	60
Figure 19 – Example of harmonic impedances for harmonics of order 14 to 49	60
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	64
Figure 22 – Branch, sub-bank and bank definition	68
Figure 23 – Typical switching sequence	72
Figure 24 – Reactive power components	73
Figure 25 – Design principle of a self-tuned reactor using DC control current in an orthogonal winding	81
Figure 26 – Control principle for self-tuned filter	81
Figure 27 – One method of switching a redundant single phase filter	83
Figure 28 – Fuseless capacitor design compared to internal and external fused units	84
Figure 29 – Various possible configurations of series compensated HVDC converters	89
Figure 30 – Circuit and waveforms of a DC link using voltage-sourced converters	90
Figure E.1 – Capability diagram of a converter under different control strategies	102
Figure E.2 – Converter capability with $\gamma_{\min} = 17^\circ$, $\gamma_{\max} = 40^\circ$, $\alpha_{\min} = 5^\circ$, $\alpha_{\max} = 35^\circ$ and $U_{\text{dio max}} = 1,2U_{\text{dio N}}$	103
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 $d_r = 0,2\%$	105
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 $d_r = 0,2\%$	105
Figure F.1 – Simplified representation of a 2-level voltage sourced converter	109
Figure F.2 – Single-phase AC output for 2-level converter with PWM switching at 21 times fundamental frequency	109
Figure F.3 – Simplified representation of a 3-level voltage sourced converter	110

Figure F.4 – Single-phase AC output for 3-level converter with PWM switching at 21 times fundamental frequency	110
Figure F.5 – Basic operation of the MMC converters	111
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).....	113
Figure F.7 – Representation of a voltage sourced converter as a harmonic voltage source behind an inductance	113

INTERNATIONAL ELECTROTECHNICAL COMMISSION

**HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS – GUIDANCE TO
THE SPECIFICATION AND DESIGN EVALUATION OF AC FILTERS –****Part 1: Overview****FOREWORD**

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IEC TR 62001-1, 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 first edition of IEC TR 62001-1, together with IEC TR 62001-2¹, IEC TR 62001-3¹ and IEC TR 62001-4, cancels and replaces IEC TR 62001 published in 2009. This edition constitutes a technical revision.

¹ To be published.

IEC TR 62001-1 includes the following significant technical changes with respect to IEC TR 62001:

- a) Clauses 3 to 5, 7 to 9, 17, 20, Annexes A and C to E have been expanded and supplemented;
- b) Annexes C and F on the definition of telephone interference parameters and voltage sourced converters have been added.

The text of this document is based on the following documents:

Enquiry draft	Report on voting
22F/378/DTR	22F/384A/RVC

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

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts 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 publication will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

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

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

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

INTRODUCTION

IEC TR 62001 is structured in four parts:

Part 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.

Part 2 – Performance

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

Part 3 – Modelling

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

Part 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.

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 TR 62001, which is a Technical Report, provides guidance on the specifications of AC filters for high-voltage direct current (HVDC) systems with line-commutated converters and filter performance calculation.

This document 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.

The scope of this document covers AC side filtering for the frequency range of interest in terms of harmonic distortion and audible frequency disturbances. 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 line-commutated HVDC converters. The changes entailed by new technologies are also discussed.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1

specification

document which defines the overall system requirements for an AC filter and the AC system environment in which it operates

Note 1 to entry: Such a document is normally issued by utilities to the prospective HVDC manufacturers. It also ensures the uniformity of proposals and sets guidelines for the evaluation of bids.

Note 2 to entry: The term as used here does not refer to the detailed engineering specifications relating to individual items of equipment, which are prepared by the HVDC manufacturer as a result of the filter design process.

Note 3 to entry: The specification defines the technical basis for a contract between two parties: the customer (2.2) and the contractor (2.3).

2.2

customer

organization which is purchasing the HVDC converter station, including the AC filters

Note 1 to entry: The term "customer" is taken to cover similar terms which may be used in specifications, such as owner, client, buyer, utility, user, employer and purchaser, and also covers a consultant representing the customer.

2.3

contractor

organization which has the overall responsibility for delivery of the HVDC converter station, including the AC filters, as a system

Note 1 to entry: The contractor may in turn contract one or more sub-suppliers of individual items of equipment.

Note 2 to entry: The term “contractor” is taken to cover similar terms which may be used in specifications, such as manufacturer, or supplier.

Note 3 to entry: Where the context clearly refers to the pre-contract stage of a project, the word “bidder” has been used instead of “contractor”, to indicate a prospective contractor, or tenderer.

2.4

branch arm

set of components (capacitor, inductor, resistor), either in singular or interconnected arrangement, which may be isolated off load for maintenance

Note 1 to entry: In interconnected arrangement, it forms a smallest tuned filter unit.

SEE: Figure 22

2.5

sub-bank

one or more branches which can be switched (connected or disconnected) on load for reactive power control

Note 1 to entry: The switch does not necessarily need to have fault clearing capability.

SEE: Figure 22

2.6

bank

one or more sub-banks which can be switched together by a circuit breaker

SEE: Figure 22

3 Outline of specifications of AC filters for HVDC systems

3.1 General

When installing an HVDC converter station in an AC system, the way in which it may affect the quality of power supply in that system is always an important issue. One of the main power quality topics is that of harmonic performance.

The AC side current of an HVDC converter has a highly non-sinusoidal waveform, and, if allowed to flow in the connected AC system, might produce unacceptable levels of distortion. AC side filters are therefore required as part of the total HVDC converter station, in order to reduce the harmonic distortion of the AC side current and voltage to acceptably low levels.

HVDC converters also consume substantial reactive power, a large proportion of which is normally supplied locally within the converter station. Shunt connected AC filters appear as capacitive sources of reactive power at fundamental frequency, and normally in conventional HVDC schemes the AC filters are used to compensate most or all of the reactive consumption of the converter. Additional shunt capacitors and reactors may also be used to ensure that the desired reactive balance is maintained within specified limits under defined operational conditions.

The design of the AC filters therefore normally has to satisfy these two requirements of harmonic filtering and reactive power compensation, for various operational states and load levels. Optimization of this design is the task of the AC filter designer, and the constraints under which the design is made are defined in the specification.

The AC filters form a substantial part of a conventional HVDC converter station. The fundamental reactive power rating of the AC filters (including shunt capacitors where

applicable) at each converter station has typically been in the range of 50 % to 60 % of the active power rating of the scheme. Together with the required switchyard equipment, the AC filters can occupy over half of the total land requirements of an HVDC scheme. The cost of manufacture, installation and commissioning of the AC filter equipment is significant, being typically in the approximate range of 10 % of the total station costs. In addition, the filter design studies can be extensive and may have an impact on many other aspects of station design (see [1, 2, 3]²) and on the total project schedule. Once in operation, the AC filters will continue to have a major importance due to requirements for switching, maintenance, component spares, and reliability.

It is therefore important that the way in which the requirements for the AC filters are specified is such as to allow the design to be optimized in terms of all the above factors, while fulfilling the essential functions of disturbance mitigation and reactive power compensation.

In general, this document assumes that the purchase of an HVDC converter station, including AC filters, will be made on a turnkey or similar basis, such as has been the case for the majority of HVDC schemes to date. The discussions herein of aspects such as provision of technical information, allocation of risks and so on therefore apply principally to such an all-inclusive approach. If the alternative approach of specifying and purchasing equipment item by item were adopted, then these aspects of the document would have to be reconsidered in the context of the particular scheme, although the purely technical content of the document would still be applicable.

Most specifications for HVDC projects are issued in a final format after definition of the details of the project by the customer and possibly consultants. An alternative approach which has recently been used is discussed in Annex A.

3.2 Boundaries of responsibility

Before a specification enters into the detail of AC filter design requirements, it should first clearly define the boundaries of responsibility between customer and contractor.

In this respect there are two extreme approaches.

- c) The customer defines an AC system impedance, distortion limits and other performance criteria to be satisfied by calculation, the calculation method, and the parameters to be taken into account. The bidder, and later on the contractor, then makes studies and designs filters based on this information, and has the responsibility to prove, to the satisfaction of the customer, that the proposed filter design complies with all the specification requirements. The risk that the AC filters do not perform adequately under field conditions lies mainly with the customer.
- d) At the other extreme, the customer defines only the maximum actual measured distortion and disturbance to be permitted (or even more simply, that there are no problems of distortion or disturbance). The customer may also specify field tests to confirm that the defined limits are not exceeded. The bidder, and later on the contractor, then has full responsibility for determining the AC system impedance, defining all relevant parameters, and designing AC filters which will perform in practice within the limits specified by the customer (or proposed as reasonable by the contractor) and withstand all actual operating conditions. Most risks in this case lie with the contractor.

For a customer with relatively little in-house study capability, approach b) might appear attractive. However, there are several disadvantages to b), as follows.

- It implies that at the tender stage, several prospective contractors will all have to make extensive studies of AC system impedance and local harmonic limit requirements. This will be expensive and difficult to achieve during a short tender period. Therefore, these

² Numbers in square brackets refer to the Bibliography.

studies should be conducted by the customer or his consultant during the longer period which is usually available before issue of the specification.

- As the contractor has to assume risks, there will be a corresponding impact on pricing.
- The customer may have to decide between completely different designs offered by bidders working on quite different assumptions about the AC system.
- There are significant practical difficulties in proving compliance during verification tests.
- There is unlikely to be any overall financial gain, as the customer will eventually pay for studies done by the bidder/contractor as part of the overall contract price.

In practice, most specifications adopt an approach which lies somewhere between these two extremes. For example, the customer may provide some information about the AC system configuration, maximum and minimum short-circuit powers, and expected future expansion, but not a full definition of AC system harmonic impedance.

The decision on where to place the boundary of responsibility will depend on the strategy of each individual customer and on the information and resources available to the customer. This document does not recommend a particular approach, but rather provides the detailed information necessary to guide decisions in this respect.

It is, however, strongly recommended that this overall question is carefully considered by the customer at an early stage, and that the boundaries of responsibility and delivery are clearly defined in the specification according to the customer's decision. The more detailed technical requirements of the specification should then follow in accordance. Failure to make a clear definition of responsibility, and to ensure that the detailed requirements of the specification are in accordance with the general definition of responsibility, creates risks of contractual conflict, delay and possible unsatisfactory performance of the AC filters.

Most essentially, the specification defines whether the criterion by which the filter performance is to be judged as satisfactory is to be:

- demonstration by calculation of performance parameters, using the specified data, or
- measurement in the field after commissioning, or
- a combination of the above.

Demonstration by calculation ensures that the worst-case conditions can be taken into account, but allows scope for erroneous data or calculation methods. Measurement in the field may be considered as the definitive proof of correct design, but it may not be possible to make measurements under the most onerous environmental and AC and DC system conditions for which the design has been made. Also, the impact of pre-existing harmonic distortion in the AC system is taken into account, by measuring pre-existing harmonic levels with the HVDC converters blocked (and with AC filters both connected and disconnected).

A combination of demonstration by calculation followed by eventual field measurement therefore provides the customer with the greatest assurance that the filter performance will be satisfactory.

The specification should also define the contractor's responsibility for considering the interaction of the AC filters with the HVDC converter controls, and the possible resonance of the filters with the AC system.

3.3 Scope of studies

Depending on the boundaries of responsibility discussed above, some system studies may be required to be conducted by the customer prior to issuing the specification, or may be the responsibility of the bidder and later the contractor. Such studies related to the AC filters would normally cover

- AC system reactive power requirements,
- AC system impedance measurements or calculations,
- pre-existing harmonic levels,
- inductive co-ordination for telecommunication lines near affected AC lines.

The extent of system studies required to be conducted by the bidder and the contractor should be made clear in the specification. A minimum set of studies will always be required to ensure that the filters perform adequately and that they withstand all defined electrical and environmental conditions.

These essential studies would normally comprise the following:

- a) reactive power supply and control;
- b) low-order resonance with AC system;
- c) AC filter performance;
- d) AC filter steady-state rating;
- e) AC filter transient rating, overvoltage and insulation co-ordination;
- f) AC filter losses;
- g) AC filter protection;
- h) AC filter circuit breaker duties;
- i) AC filter discharge requirements;
- j) those parts of the control and dynamic performance studies which are affected by the AC filters, and analyse the integrated operation of the AC and HVDC systems;
- k) those parts of the audible noise study which are affected by the AC filters;
- l) those parts of the RAM (reliability, availability and maintenance) study which are affected by the AC filters.

However, further performance and rating studies may be of interest to assist the planning of economic and flexible operation, and to define recommended procedures in the event of outages, maintenance or unusual operational situations. Such studies might cover, for example, performance and rating under outage contingencies not required by the specification, or with wider limits of reactive power interchange than specified. These situations might be of considerable interest to operation planners, and have an economic value. The possible need for such additional studies should be considered by the customer and, if desired, included in the scope of studies required in the specification.

Of the essential design studies, some would normally be conducted in full by the bidder as part of the tendering process (at least a), c), d), and j) of the above list). Others might be omitted or minimized during the tendering stage, and estimates made based on the bidder's previous experience. During the detailed design stage, all essential studies would be conducted in full by the contractor.

3.4 Scope of supply

The specification should make clear the scope of supply with regard to AC filtering as with all aspects of the HVDC scheme. In addition to supply of the main AC filter components, the responsibility for supply of the following should be defined:

- site preparation;
- civil and mechanical structures;
- earthing;
- fencing;
- interface with AC switchyard;

- control, measuring, monitoring and protection;
- switching equipment;
- cabling;
- spare parts;
- special test equipment required for commissioning and maintenance;
- erection, commissioning and testing;
- in-service performance measurements.

Any requirement for guarantees concerning, for example, capacitor failure rates, measured filter losses and performance, should also be clearly stated.

3.5 Technical data to be supplied by contractor

At the tender stage of an HVDC project, the bidders are normally required to supply technical data regarding their proposed designs to the customer. This data is used by the customer in order to qualify the proposed design technically and to allow comparisons to be made between competing bidders. The specification should define carefully exactly what technical data is to be supplied, otherwise there is a risk that the information supplied by different bidders will not show possible weaknesses in design or will not enable fair comparisons to be made. Aspects where particular attention should be paid include the general aspects:

- 1) method and assumptions for filter performance calculations;
- 2) criteria and assumptions for steady-state filter rating, and for transient stresses and rating;
- 3) calculations as well as the following specific areas where clarity is important:
 - a) harmonic currents generated by converters (the specification should define under exactly what conditions these are to be stated. It should preferably request harmonic currents at several critical conditions or power levels and under any special operation conditions);
 - b) impedance characteristics of filters (the specification should request information on impedance at and near tuned frequencies, under conditions of detuning, and across the whole spectrum of interest);
 - c) performance parameters to be stated at defined operation conditions (for example, at full load and at intermediate loads immediately prior to switching-in an additional bank).

After contract award and during the design and procurement stage of the project, the contractor will normally produce technical study reports and other documents covering aspects of the filter design (performance, rating, circuit diagrams, protection, insulation co-ordination, layout, reliability and availability evaluation), and equipment specifications for the individual items of filter equipment. The specification (or another part of the agreement between customer and contractor) should make clear whether these are to be approved by the customer, and if so, define an adequate procedure which allows time for examination of such material by the customer, possible subsequent modification, and approval, within the intended project time-schedule.

3.6 Alternative proposals by bidders

The customer should recognize that bidders for an HVDC project will have extensive accumulated experience and expertise, and furthermore that they are continually developing new techniques and equipment technologies. Consequently, it is always possible that a bidder may be able to propose a filtering solution which is advantageous to the customer, but for some reason falls outside the strict boundaries which may have been set by the specification.

Therefore, specifications should always leave open the possibility for the bidder to propose an alternative solution, in addition to the solution which expressly satisfies the specified requirements.

4 Permissible distortion limits

4.1 General

The performance objective of the AC filter design is to limit the adverse effects of both the individual harmonics and of the total harmonic distortion of the voltage and current waveform, at both the HVDC connection bus and in the surrounding network.

These possible adverse effects are as follows.

- a) The waveform distortion can cause increased heating and higher dielectric stresses in both the utility's and other customers' equipment as well as malfunction of electronic equipment.
- b) The harmonic current circulating in the AC lines can, by induction, cause interference in adjacent communication lines and this should be limited to an acceptable level.
- c) Induced voltages may cause problems because of risk to human safety or malfunction of adjacent communication, signalling and protection equipment.

In order to mitigate such adverse effects, the customer's specification normally defines permissible harmonic distortion limits, which need to be respected by the AC filter designer. The definition of suitable criteria for setting such limits is a complex and controversial subject, which will be addressed by any customer installing a new HVDC scheme. Clause 4 attempts to provide the background information necessary, and to give recommendations on the different approaches available to the customer.

A common procedure for the determination of limits has often been to set the values according to references in international literature, without detailed preliminary studies of the particular location. This approach requires a minimal amount of studies and allows a short time schedule. The disadvantage is that it requires conservative limits to be imposed in order to ensure that there are no adverse effects of excessive distortion and telephone interference, which may require high additional cost for corrections and/or mitigation.

However, due to

- the powerful calculation tools now available,
- the recent refinements in harmonic influence assessment methods as stated in IEC TR 61000-3-6 and in [4, 5],
- the growing concern of the utilities and their customers about power quality, and
- the trend towards cost reduction through optimization of equipment design,

appropriate specification studies should be conducted in order to develop harmonic limits tailored to the particular characteristics of the HVDC scheme and the connected AC network. Clause 4 describes the different indices used to control the adverse harmonic effects and discusses the considerations that are accounted for in the definition of the indices and in the determination of the limits. Ranges of limits adopted for existing schemes are provided as well as general guidelines. The detailed methods recommended for the determination of specific limits are referenced.

The definition of permissible limits is discussed below under four headings:

- 1) voltage distortion limits;
- 2) limits pertaining to the HV and EHV network equipment;
- 3) telephone interference limits;

4) special criteria.

The limitation of telephone interference through the application of weighted indices has in the past had a substantial influence on the nature, size and cost of AC filters for HVDC stations, and so this aspect is discussed in some depth in 3.4 and Annex C.

A customer should understand that it is not necessary or desirable to include in the specification all of the distortion limits discussed in Clause 4. Some indices apply only in certain situations; others represent alternative approaches to the definition of distortion. The customer should consider carefully the requirements of his particular scheme, and select those distortion indices and limits which are relevant to his needs.

4.2 Voltage distortion

4.2.1 General

The main requirements for AC filter performance specification are generally related to the permissible voltage distortion, this being a directly measurable quantity at the point of connection. The intention is that by limiting the voltage distortion, the harmonic currents injected into the AC system by converters and the resulting voltages elsewhere should also be limited to levels that will ensure service quality to the utility and to all connected customers of the AC system (the validity of this approach is discussed further below).

Subclause 4.2 describes the most common indices used to control voltage distortion and gives some guidelines for the determination of suitable limits.

4.2.2 Voltage distortion – Definitions of performance criteria

Individual harmonic distortion, D_n (in %), is calculated as follows:

$$D_n = \frac{U_n}{U_1} \cdot 100\% \quad (1)$$

where

U_1 is the line to neutral nominal fundamental frequency system voltage (RMS);

U_n is the n -th order harmonic line to neutral voltage appearing at the bus under consideration.

Total harmonic distortion, THD (also called D_{eff} or voltage distortion factor), is calculated as follows:

$$D_{\text{eff}} = \sqrt{\sum_{n=2}^N D_n^2} \quad (2)$$

where

N is the maximum harmonic order considered.

The total arithmetic harmonic distortion, D , is calculated as follows:

$$D = \sum_{n=2}^N D_n \quad (3)$$

4.2.3 Voltage distortion – Discussion and recommendations

The individual (D_n) and total harmonic distortion (THD) are widely accepted indices of voltage distortion in AC networks, while the total arithmetic harmonic distortion (D) is controversial,

even though it has been used in a number of HVDC schemes [6, 7], instead of, or as well as, the THD. The THD corresponds to the power of the harmonics and is therefore more closely related to the severity of the disturbance in terms of heating effects. The total arithmetically added distortion (D) does not correspond to any physically verifiable disturbance, although it is an indicator of the maximum possible deviation of the waveform from a sinusoid and of the maximum possible harmonic voltage peak levels. Furthermore, the THD is well accepted within IEC (see IEC TR 61000-3-6 [8] and IEEE Std 519-1992 [9]) and is therefore the criterion recommended in this document.

The harmonic voltages used in the definition of harmonic distortion are generally those of the highest value in any phase. This is not an issue when using the conventional calculation method, as the harmonics produced by HVDC converters are assumed to be either positive or negative sequence and so are equal in all phases, and the AC system impedance is assumed balanced. The zero sequence current generation of the HVDC converters is very low and there are no reported problems related to this as a cause of zero sequence harmonic voltage. However, in real systems, the harmonic voltage magnitudes will be different in the three phases due to asymmetries in the network and non-ideal harmonic generation conditions. Analysis of harmonic performance using a three-phase model of transmission lines would generally show differences among the three phase distortion parameters.

The maximum harmonic order considered, N , is normally set to 49, as the magnitude of the current generated by the HVDC systems decreases with frequency and the harmonic voltages transferred to the lower voltage levels generally become very low with increasing frequency due to the characteristics of power transformers and loads at these frequencies.

In the formula for definition of voltage distortion, some customers prefer to use the worst-case value from the range of system operating voltages as voltage reference (U_1), rather than the nominal system voltage (that is, the value of voltage, consistent with the converter harmonic generation used in the calculation, for which the highest percentage distortion is calculated. This will generally be the minimum voltage from the applicable range). The argument for this approach is that it more truly expresses the actual percentage distortion occurring in reality. Whichever reference voltage is to be used for the definition of voltage distortion, it needs to be stated clearly in the specification in order to avoid different interpretations by different bidders, and because it may appreciably affect the filter design.

Refer also to the discussion in 7.1.6 on the system conditions under which total harmonic distortion should be calculated. The range of AC system voltages over which the distortion criteria are to be met needs also to be clearly defined.

4.2.4 Voltage distortion – Determination of limits

4.2.4.1 General

Most major utilities have their own harmonic standards including rules to control the harmonic emission from individual disturbing loads. Generally, the setting of these standards has to a considerable degree been influenced by experience gained with a range of harmonic induced problems and the measures taken to resolve them. They therefore tend to be empirical and conservative in form as they are rarely based on a detailed study and understanding of system behaviour. Where a large HVDC installation is planned, a specific analysis should be performed in order to derive distortion limits which have a more rational basis and relate to the particular circumstances of the HVDC scheme in question.

4.2.4.2 Voltage distortion – Determination of limits without detailed studies

One way to guide the determination of the voltage distortion limits is to refer to existing schemes for which acceptable performance has been experienced. The following ranges of specified limits were taken from CIGRE surveys [6, 7] on AC harmonic filters for numerous HVDC schemes from different countries:

- a) specified limits on D_n are in the range of 0,5 % to 1,5 % (most typically 1 %);

- b) specified limits on THD are in the range of 1 % to 4 % (no typical value);
- c) specified limits on D are in the range of 2 % to 4 % (most typically 4 %).

These figures refer to distortion due to the HVDC converter and do not include other pre-existing distortion. They also generally refer to worst normal operating conditions of the HVDC system, in comparison to more extreme conditions which determine the component ratings. When considering such values as used in former projects, it is also vital to take into account the AC network representation which was specified to be used in the calculation of these indices.

Where a customer

- 1) wishes to minimize the procurement time schedule, or
- 2) lacks the appropriate computational tools or AC system data, or
- 3) anticipates no serious consequences from the harmonic distortion,

then the customer may set distortion limits based on such indicative values taken from experience of existing systems. AC filter installations designed according to these limits have generally performed satisfactorily. But, without detailed studies, engineering judgement has to be exercised in order to adapt the limits set for other projects to the specific characteristics of the AC system to which the HVDC system is to be connected. Therefore, the determination of performance requirements for a particular HVDC scheme based on past experience from existing schemes should take into consideration the following aspects:

- local regulations on harmonic limits;
- voltage levels (stricter limits are usually recommended for higher voltage levels);
- proximity of load areas;
- proximity of generators;
- other harmonic sources in the vicinity;
- pre-existing level of harmonic distortion;
- network structure (long lines and capacitor banks can produce magnification of harmonic voltage at remote locations, large meshed networks will be likely to transfer a lower level of harmonic to the load areas, etc.).

The CIGRE surveys [6, 7] give many details on the existing installations which may be helpful for this task. The limits adopted should be on the conservative side to prevent the consequences of excessive distortion which, should it occur, may ultimately lead to restrictions on the operation of the HVDC transmission. However, there is also a risk that this approach may lead to a design which in practice is unjustifiably expensive.

In view of this, it is suggested that the cost sensitivity of the filter design is investigated by asking for an alternative filter design based, for example, on 1,5 or 2 times the basic specification limit. The cost reduction, if significant, is indicative of the need to perform more detailed studies before the choice of a final design.

The specification could also allow the bidders to propose alternative designs (in addition to the main proposals), which, while possibly exceeding the specified limits under some circumstances, nevertheless offered substantially simpler and more economical filters.

4.2.4.3 Voltage distortion – Determination of limits with detailed studies

Determining suitable distortion limits by means of detailed studies requires more work at the specification stage but is likely to result in a cheaper AC filter design, with an optimal filter solution relative to the harmonic characteristics of the AC system, and avoid an unnecessarily complex filtering scheme which may impose undue constraints on the HVDC system design and operation. The methodology can be applied to respect either IEEE or IEC

recommended limits. CIGRE has published a technical paper on limitation of harmonic distortion for MV and HV power systems [10] based on electromagnetic compatibility.

One objective of the limitation of harmonic emission in HV and EHV systems is to keep the disturbance levels below the compatibility levels (with a non-exceeding probability of 95 %) in the low-voltage systems. To achieve this goal, the utility has to co-ordinate the emission limits of equipment in the different parts of the AC system in the most economical way. The utility has therefore to take into consideration all the possible emission sources, both existing and future, and their frequency dependent coefficient of transfer to the other voltage levels. It should also consider the future expansion stages of the AC network.

Usually, a widespread programme of harmonic measurements is performed to gather data for this task. Such an exercise should result in the determination of suitable planning levels for the HV and EHV system and rules for the connection of disturbing loads that are generally valid over the whole network.

Such a study gives a base for the establishment of rational harmonic emission limits for the connection of HVDC systems. For such large disturbing loads, it is worthwhile to perform additional studies to adapt the planning levels to the particular circumstances at the point of connection on the network. The following studies are recommended:

- The determination (by calculation) of the ratio of the harmonic voltage at the point of connection to the harmonic voltage at the main HV, MV or LV substations in the area. This should be done over the whole frequency range considered and for all anticipated normal network configurations and load levels. The harmonic penetration depth into the network is likely to be frequency dependent as discussed earlier.
- The measurement of actual harmonic voltage levels at the point of connection and at the main HV, MV or LV substations in the area (see 4.4.5 for further details).

The results should be analysed following the general co-ordination principles to determine appropriate emission limits.

Such evaluation of sources of harmonic emission and analysis of the network, to establish suitable planning levels, may require an enormous amount of work for a large meshed network and furthermore, it is difficult to plan for the future addition of harmonic sources and the evolution of the network. Where no standards and practices have been previously developed by the utility or where detailed knowledge of network harmonic characteristics is not known, the method described in [10] can be adopted.

Reference [9] gives a simplified method to determine the emission limits of a particular HVDC installation for HV and EHV systems. It proposes simple rules to share the permissible harmonic voltage emission between the various users of the power system. For most large HVDC installations, the allowed limits are shared according to the MVA rating of the installation and the network supply capability at the point of common coupling.

The method described in [10] takes into account the presence of important disturbing installations in the vicinity of the considered substation and gives summation coefficients dependent on the harmonic order for computation of total harmonic levels. It also gives some guidelines for application in practical situations (pre-existing level, unrealistically low emission limits, etc.). The harmonic load flow studies should also try to identify amplification or resonance situations which may cause remote harmonic voltage problems that are not evident at the HVDC connection bus. These remote effects are controlled by applying appropriate coefficients for the particular harmonics in the individual emission limits applied at the HVDC connection bus.

It is important to note here that the limits so defined are related to the particular network conditions, and this should be considered in the design of the AC filters. As an example, a stricter limit, defined to control an amplification problem, may correspond to a limited part of the total harmonic impedance locus computed at the point of coupling. Similarly, the

important harmonic sources are in the vicinity, the emission limit is shared among them but then the impedance locus for each should assume that the filter installation of the other is present. When these aspects are significant, multiple emission limits coupled to different harmonic impedance loci may be provided to the bidders.

The following alternative approach would in principle be possible, but up to now has not been used for any HVDC scheme. Where the network is of moderate size, the customer could consider providing the bidders with the complete network data set. The harmonic voltage contribution limit from the HVDC converter could then be individually defined at all the different MV or LV buses. With this approach, the customer provides all the necessary data for the filter optimization: AC system configurations, line data, remotely installed filters, earth resistivity, frequency dependent equivalent models at the end nodes, tolerances, etc. The data should also consider the future evolution of the network. This approach would require more work for the bidders, and they would possibly have to develop additional computer tools, but it would avoid the above mentioned inconsistencies. It would also entail considerable effort by the customer to prepare all the necessary data, and lengthen the time required for the tendering process. Unless the bidder defined exactly how each component in the network should be modelled, each bidder could derive different harmonic impedances, depending on the representation used for network components, in particular loads, transformers and transmission lines.

4.2.5 Voltage distortion – Pre-existing harmonic levels

Measurements of the actual pre-existing harmonic levels are important to complement the simulation studies. They are often needed for the following reasons:

- to characterise pre-existing harmonic levels, including statistical characteristics;
- to determine harmonic source characteristics;
- to validate simulation models.

Harmonic measurements in the area of the HVDC system installation will indicate the aggregate harmonic levels produced by all sources, both within the HV and EHV system and coming from the MV and LV systems. Analysis of the measurement results combined with the simulation results will be helpful to segregate the two contributions. Indeed, the pre-existing harmonic contributions from all the individual distorting loads in LV and MV systems and other unknown sources cannot be assessed easily otherwise.

It may also be appropriate to direct the measurements to specific operating conditions where these may affect the harmonic voltage levels. For example a high operating voltage condition may increase the harmonic contribution caused by saturation of transformers. There is also evidence that corona on EHV AC transmission lines can give rise to substantial levels of third harmonic current.

Ideally, the measurements should provide the harmonic levels, phase angle and the source impedance to characterise adequately the harmonic sources, because the introduction of a large AC filter installation is likely to affect the harmonic levels in its vicinity. It should be noted that the new AC filter installation could be beneficial for the network, and the utility may even consider specifying the performance of the AC filters at the HVDC converter with the additional aim of improving the pre-existing harmonic condition of the network at some specific harmonic order(s).

As an alternative to specifying the level of pre-existing harmonics, some utilities have requested in their specifications that the calculated harmonics produced by the HVDC converter should be increased by a margin of, say, 10 %. This is a very arbitrary approach, and while allowing a certain margin for pre-existing harmonics, is unlikely to correspond to reality.

4.2.6 Voltage distortion – Relaxed limits for short term and infrequent conditions

For unusual conditions during short periods of time (less than 1 h), IEEE Std 519-1992 [9] recommends that the limits may be exceeded by 50 %.

IEC TR 61000-3-6 does not address this issue. While it mentions that the assessment of harmonic injection from distorting loads should consider the worst normal operating conditions including those with outages that may apply for a substantial fraction of the time, it provides no limits for short term and infrequent conditions when the harmonic injection should obviously be controlled, for example from an equipment rating aspect.

Where such short term and infrequent operating conditions are possible for the HVDC system, relaxed limits should be specified, such as those suggested by IEEE Std 519-1992. These may be associated with specific harmonic impedance loci.

4.2.7 Treatment of interharmonic frequencies

In the case of an HVDC link connecting two AC systems of different fundamental frequencies, and particularly if the link is a back-to-back station, both converters may generate currents on their AC sides at frequencies other than harmonics of the fundamental (the fundamental frequencies either may be nominally different, for example 50 Hz and 60 Hz, or may be nominally identical but differ at times by up to 1 Hz or 2 Hz).

This additional generated distortion will be at frequencies which are harmonics of the fundamental frequency of the remote AC system, and will be transferred across the link by the mechanisms described in Clause 6. This transfer may be thought of as harmonic penetration or transition from one AC system to the other. As the frequencies of these transferred components lie between the converter's own harmonic frequencies, they are often termed "interharmonics". The term "non-integer harmonics" is sometimes also used.

The magnitude of these interharmonics will be low in comparison with the characteristic harmonics generated by the local converter, but may nevertheless be significant, especially as no specific filtering will generally be provided for them, other than the broad-band effect of high-pass branches.

Interharmonics may give rise to specific problems not found with true harmonics, such as interference with ripple control systems, and light flicker due to the low frequency amplitude modulation caused by the beating of a harmonic frequency with an adjacent interharmonic, for example a 10 Hz flicker due to the interaction of a 650 Hz 13th harmonic of a 50 Hz system with 660 Hz 11th harmonic penetration from a 60 Hz system.

Of interest here is how the distortion effects resulting from such interharmonics should be taken into account in the performance criteria. If the various formulae for definition of harmonic performance as given in 4.2.2 refer specifically to "harmonics", then a formal interpretation could exclude any other frequencies. A contractor could thus ignore the impact of the interharmonics in his calculation (and subsequent measurement) of the performance parameters.

The possibility of contractual conflict may arise if the specification (as has occurred in the past) both states that the contractor takes such interharmonics into account in his design, but also, inconsistently, defines the performance criteria in terms of "harmonics 1-49" or similar.

Unless it is specifically clarified, there could also be disagreement between customer and contractor about whether the term "harmonics" should include so-called "non-integer harmonics", as the term "harmonics" classically implies integral multiples of the fundamental, and is defined as such in, for example, IEEE Std 519-1992 [9].

IEC TR 61000-2-1 [11] discusses interharmonic sources and some possible effects. IEC TR 61000-3-6 considers the impact of interharmonics on low voltage systems, and

indicates the need for specific limits due to possible interference with ripple control systems, lighting flicker and other problems. It recommends a planning level of 0,2 % for individual interharmonics. Other applicable standards or guidelines may need to be taken into account.

Therefore, if the proposed HVDC link connects two systems of nominally or potentially different frequencies, the customer should take into account the possible impact of interharmonic distortion. This may be by modification of the various specified definitions of harmonic performance criteria to encompass significant interharmonics generated by the converter, or by a specific interharmonic limit which may need to be related to preventing interference with ripple control equipment or to control of flicker.

4.3 Distortion limits pertaining to the HV and EHV network equipment

4.3.1 HVAC transmission system equipment

Setting harmonic emission limits as described above to meet the compatibility requirements in the network will usually also ensure a safe harmonic level for the HV and EHV network equipment. However, when very relaxed limits may otherwise be permissible, for example due to the isolated location of the HVDC equipment in the network, then the actual harmonic emission limit may have to be set with regard to the sensitive network equipment such as shunt capacitors, cables and power transformers. Cables and capacitors can be involved in system resonance which results in high dielectric stresses or overload. Relevant standards should be consulted for the determination of the equipment capability. Particularly, attention should be given to ANSI C57.12.00 [12], which defines the maximum acceptable root-sum-square (RSS) of the 3rd, 5th and 7th harmonics at buses where transformers are connected.

4.3.2 Harmonic currents in synchronous machines

The characteristic and non-characteristic harmonic currents flowing into the stators of synchronous machines (generators and synchronous condensers) installed close to the converter stations can cause stator and rotor overheating and vibrations that could damage them. To avoid such damage, these harmonic currents should not be higher than the limits indicated by the machine manufacturer. It is, therefore, necessary that the filter specification clearly requires the filter design to control these currents, in addition to the other performance requirements.

One way to specify the filter requirements to control the possibility of overheating is to require that the equivalent negative phase sequence component I_{2eq} (as defined in B.2) of the harmonic current flowing in the machine, together with the expected level of actual negative sequence current, be less than the negative phase sequence component operating capability of the machine as specified by IEC 60034-1 [13] or similar standards.

The bidder should provide the customer with all values of harmonic currents considered in the calculation of the I_{2eq} . During the bid analysis, the customer should discuss these values with the machine manufacturer to check their adequacy as to the heating of the stator and rotor. Any further limitations that may be necessary should be discussed with the bidders.

The harmonic currents flowing into the synchronous machine stator winding will induce a pulsating air gap torque that will excite vibrations in the rotating parts of the turbine generator sets. In case of steam turbine generators, special attention should be given to the magnitude of negative sequence 5th and positive sequence 7th harmonic currents, because they will induce pulsating torque on the rotor at 6th harmonic, which may coincide with a mechanical resonant frequency involving torsional oscillation of the rotor elements and flexing of the turbine blades. Fatigue in the turbine shaft and blades may result. Where a limit needs to be imposed to control these harmonic currents by the AC filter, the specification should indicate the maximum limit of these harmonic currents or any other harmonic currents indicated by the machine manufacturer, to be considered in the filter design (IEC 60919-3).

To allow the bidder to calculate the harmonic currents flowing in the generators, the specification should give the required data, such as system configuration component models,

generator and transformer frequency dependent reactances, operating conditions to be considered, etc.

Another way to specify the filter requirements, from the point of view of the synchronous machine heating and vibration, is for the customer to undertake a study to determine the maximum permissible harmonic voltage/current at the converter bus which satisfies the worst generator criteria. This method eliminates the need to provide the single line diagram of the complete network, details of operating conditions and configurations, method of modelling, etc. The customer is then responsible for these calculations. He also supplies the bidders with an equivalent circuit representing the generators, or include them in the overall network impedance locus.

4.3.3 Nearby HVDC installations

An existing HVDC system in the vicinity of the new HVDC installation should be reviewed. Such an HVDC system was most probably designed without sufficient allowance for such a new installation. The presence of the new HVDC station will affect significantly the network impedance seen from the existing installation and constitutes a new harmonic source. In this situation, the design report of the existing installation, including all the HVDC system data and design assumptions, is provided to the bidders for the new installation. A design constraint on the new AC filter will be that the rating and performance of the existing AC filters should not be compromised.

4.4 Telephone interference

4.4.1 General

Telephone interference is a common concern related to the harmonic distortion produced by HVDC systems. A survey [7] shows that most major HVDC schemes have required telephone interference limitation. A wide range of parameters affects the influence of HVDC schemes on the magnitude of telephone interference, and so historically the limits imposed have been highly variable.

The impact of the specified telephone interference indices on the complexity and cost of the AC filters can be substantial. Therefore an analysis of the requirements and limits for each specific HVDC scheme is recommended.

Subclause 4.4 reviews the most common criteria used to define limits of telephone interference for HVDC systems, with typical criteria ranges, and gives some guidelines for the determination of limits.

4.4.2 Causes of telephone interference

References [4, 5] provide a brief overview of the basic telephone interference mechanism, sufficient to understand the recommendations of this document.

4.4.3 Telephone interference – Definitions of performance criteria

The telephone interference performance requirements for AC filters are usually specified by factors calculated from the harmonic voltages and currents, with suitable weightings. The definitions of these quantities are given in Annex C.

4.4.4 Telephone interference – Discussion

One important limitation of the telephone interference criteria – telephone interference factor (TIF) or telephone harmonic form factor (THFF), calculated at the HVDC converter station AC bus, is that they are not directly related to the telephone interference influence caused by the various lines of the AC network. Indeed these harmonic voltage criteria directly control only the electrostatic interference on the AC transmission lines close to the HVDC substation.

whereas the predominant coupling mode is generally the electromagnetic interference caused by harmonic current injection.

Although controlling the voltage telephone interference factors will to some extent limit the harmonic current, and will avoid severe amplifications thus reducing the likelihood of interference, the harmonic currents injected into the network will also depend critically on the network impedance at each harmonic. Therefore, the voltage telephone interference factors should be used only for rough estimation of the telephone interference influence of a particular HVDC scheme.

The other criteria, such as IT (product of RMS current and TIF) or equivalent disturbing factor I_{eq} , based on the harmonic currents at the point of connection of the HVDC system and the network are not necessarily totally satisfactory either. Both the C-message or psophometric weighting and the coupling weighting give more predominance to higher order harmonics, and at such high frequencies the current profile along the transmission lines can be highly variable. A low harmonic current at one extremity of a transmission line does not preclude high harmonic current at the other extremity. In addition, for a meshed network or for several incoming transmission lines from different nodes, the harmonic load flow in the transmission lines is a complex function of the harmonic impedance of the network elements and the possible network configurations [10]. Amplifications are also possible at remote locations. This problem is not easily resolved considering the range of frequencies involved. Derivation of remote interference levels from a limit calculated at the HVDC converter station AC bus is therefore problematic.

Finally, the harmonic currents produced by the HVDC system are predominantly of balanced mode. The main influence of the transmission lines on telephone interference results from conversion of balanced mode currents to residual (zero sequence) currents, mainly due to the asymmetry of transmission lines [5]. The mutual impedance between balanced sequences and zero sequence modes is a function of the transmission line asymmetry, the earth resistivity and the frequency. Furthermore, the zero sequence harmonic currents circulating in the transmission lines are affected by the zero sequence impedance of the network.

The selection of appropriate limit values for whichever indices are used for a particular project depends strongly on the density and length of telephone lines in the zone of influence of the transmission lines, the soil resistivity, the separation between the power and the communication lines, the type of communication line and on the immunity of the telephone system.

Refer also to the discussion in 7.1.6 on the system conditions under which telephone interference parameters should be calculated.

4.4.5 Telephone interference – Determination of limits

4.4.5.1 Telephone interference – Determination of limits without detailed studies

The appropriate requirements for telephone interference will be highly variable from project to project compared to requirements related to voltage distortion. Therefore, the determination of performance requirements for a particular HVDC scheme based on past experience from existing schemes should be selected with care based on comparable requirements. The main parameters affecting the telephone interference influence to consider when making a comparison with previous HVDC schemes are:

- density of telephone lines close to the AC transmission lines,
- earth resistivity along the AC transmission lines,
- length of telephone lines and mean separation from the AC transmission lines,
- AC network structure (long lines and capacitor banks can produce magnification of harmonic current, large meshed networks will likely diffuse the current, lowering the influence of individual AC transmission lines, etc.),

- type and characteristics of the communication lines (cable and/or open wire).

The structure of the telephone system and the local conditions are usually the main parameters which could affect the telephone interference limits.

For example, in North America, typical factors to consider are that the subscribers of rural areas are generally located along main regional roads, the density of population increasing in the proximity of villages crossed by such roads. There are also secondary roads with usually a lower density of population. The HV transmission lines usually cross these rural areas. The telephone lines are long (up to 25 km or more) due to the sparsity of subscribers.

Long telephone lines are more subject to telephone interference because of the increased coupling and because of the lower telephone signal level which results in increased subscriber's sensitivity to noise. In hilly areas, the earth resistivity can be very high, resulting in increased mutual impedance. Joint use of poles with power distribution lines which include an earth wire may provide very low effective earth resistances, improving the shielding of telephone lines in areas of poor earth resistivity. A consultation with the telephone company is therefore recommended in order to get a picture of the relevant characteristics of the telephone structure and local conditions.

The TIF and THFF might be used as criteria for projects for which no detailed studies are performed, keeping in mind that these criteria give only a rough estimate of telephone interference influence.

The IT criterion can also be used, with the reservations concerning frequency dependency discussed in the previous section. Additional indicative values on balanced IT for HV and EHV transmission lines are provided by IEEE Std 519-1992 [9]:

- IT levels most unlikely to cause interference: up to 10 000
- IT levels that might cause interference: 10 000 to 25 000
- IT levels that probably will cause interference: in excess of 25 000

These values are per line, which will not be the same as for the complete station, if there are several AC feeders to the HVDC converter station. It is recommended that the values tabulated above should be treated with caution, and may be excessively low. In the CIGRE surveys of HVDC schemes [7], those schemes which specified the IT criterion imposed limits of between 25 000 and 50 000 for the total harmonic current into the AC network. More recent projects have also used values in this range.

It is suggested that the cost sensitivity of the filter design, compared with the cost of alternative remedial measures, is investigated by asking for an alternative filter design based, for example, on 1,5 or 2 times the basic specification limit. The cost reduction, if significant, is indicative of the need to perform more detailed studies before the choice of a final design.

4.4.5.2 Telephone interference – Determination of limits with detailed studies

For major HVDC projects or where the telephone interference might be an important concern, it is strongly recommended to perform an inductive co-ordination study. Such a study will likely result in an optimal filter design relative to telephone interference, reduce the overall cost of the installation and avoid an inadvertent situation with regard to complaints from the telephone companies. The inductive co-ordination process is described in the earlier mentioned references.

The first step involves the calculation of a range of equivalent disturbing current reflecting different levels of telephone interference. The evaluation of such a range will allow the appropriate limits to be specified to the equivalent disturbing level for which the incremental cost of improving the filtering is equal to the incremental saving in mitigation required in the telephone lines. This requires the preliminary estimation of both the cost of mitigation measures and the cost of improved filtering being gathered from telephone companies and

HVDC system manufacturers, respectively. In practice, this data may prove to be difficult to obtain at this stage. Optional design limits, covering a range appropriate to the available cost estimation, could be specified in order to guide selection of the optimal limit by the bidder as part of the design.

An equivalent disturbing current limit can be expressed as a set of I_{eq} values specific to every HV or EHV transmission line in the vicinity of the HVDC project. For long transmission lines, when the density of telephone lines varies along the line, it may be worthwhile to express the telephone interference level as a profile of I_{eq} along the transmission line. The extent of transmission lines to consider for the study depends on the penetration of harmonic currents within the network, which is dependent on the configuration of the particular network. Planning studies are therefore recommended to determine the extent of harmonic current penetration.

This approach requires the customer to provide the necessary data for the filter optimization: AC system configurations, line data, remotely installed filters, earth resistivity, frequency dependent equivalent models at the end nodes (balanced sequences and zero sequence when required), type of connection of power transformers, etc. For a meshed system with many lines, this may be impracticable, but where an HVDC station is supplied by only one or perhaps two AC feeders, the use of an equivalent disturbing current criterion may be the most accurate index of telephone interference. The approach also requires more work for the bidders, and they will possibly have to develop supplementary computer tools.

4.4.6 Telephone interference – Pre-existing harmonic levels

Two different sources of harmonic current may add to the harmonic emission from the HVDC system to contribute to the overall telephone interference level in the telephone lines. These are other sources of harmonic current within the HV or EHV system, and harmonic current flowing in the distribution lines. As with the harmonic voltage distortion, measurements of the actual harmonic current levels are important to complement the simulation studies and to assess the interference level from lines. From previous experience, interference from distribution lines is more likely to be the more significant contribution.

For the reason indicated previously in 4.2.4, measurements within the HV or EHV system should allow for the effect that the introduction of large AC filter installation may have on the pre-existing harmonic current levels. The measurements should provide the harmonic levels, phase angle and the source impedance to adequately characterize the harmonic sources.

If one of the existing sources is a nearby HVDC installation, then a joint study may be required to review the filtering requirements of both installations.

4.4.7 Telephone interference – Limits for temporary conditions

The telephone company may accept higher noise for short term conditions. Accordingly, the specifications of several HVDC schemes have allowed for higher telephone interference levels on the DC side for infrequent and short-duration operating modes or conditions. One example of practice is to allow from two to three times the normal level depending on the expected frequency of occurrence and the duration. Relaxed limits should therefore be specified when such short term conditions are foreseen for the HVDC system. Examples of such conditions are

- short term duration overload conditions,
- AC voltage outside normal continuous range,
- operation at extreme frequency deviation or voltage unbalance,
- infrequent AC network configurations,
- loss of filter branches,

- abnormal DC operating conditions such as high control angles for temporary reactive power control or reduced voltage operation.

Such short term limits should be agreed with the telephone companies at the earliest possible opportunity. However, some telephone companies may be unwilling to tolerate higher noise even for such infrequent and short term events.

4.5 Special criteria

The following special conditions should also be considered when preparing the specification. Normally, they will not directly impact the limit values expressed in the specification, or the consequent design of the AC filters, as the other disturbance criteria already discussed will usually result in sufficient harmonic mitigation so that the following factors are not a problem. However, the customer should be aware of potential problems and consider the following where applicable:

- personnel safety from induced voltage on telecommunication lines;
- maloperation of telecommunication equipment (for example, telephone ringers);
- effect on data transmission and railway signalling equipment;
- effects on AC protective relaying measuring and control equipment.

Even where a possible risk may arise, these problems are usually more economically solved by applying mitigation measures to the disturbed equipment itself.

5 Harmonic generation

5.1 General

The design of the AC filters requires a knowledge of the harmonic currents which are generated by the converters. These currents are calculated by the contractor, using his knowledge of the converter equipment and its interaction with the connected AC and DC systems.

The information to be included in the specification regarding harmonic generation will depend on the overall division of responsibility between customer and contractor, as discussed in Clause 3. If the performance of the AC filters is to be guaranteed by site tests, then the customer may wish to leave all responsibility for the methods of calculating generated harmonics to the contractor. However, if the contractual requirement for adequate performance is to be proved by calculation, then the method of calculation is critical and the customer's requirements should be clearly expressed in the specification. Important aspects to include are indicated in 5.3.

In either case, the customer should be aware of the various technical factors involved, and be prepared for discussions at the evaluation stage. Clause 5 therefore identifies the important aspects which affect the calculation of harmonic generation.

5.2 Converter harmonic generation

5.2.1 Idealized conditions

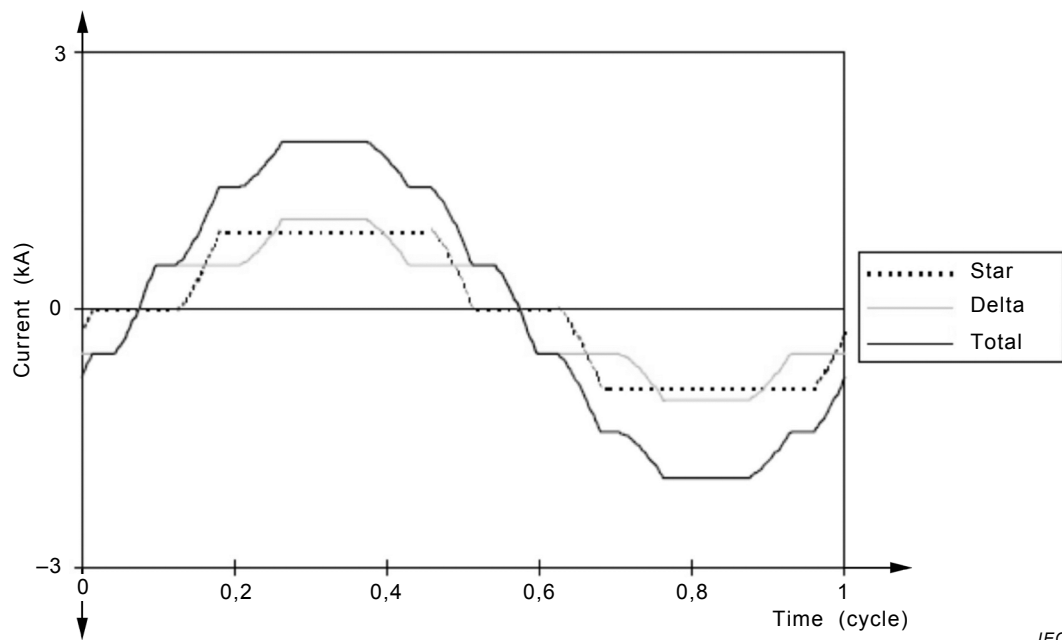
The generation of harmonics is best understood by starting to consider an idealized situation, with no asymmetries in transformer impedances or firing angle between phases, smooth DC current and a sinusoidal balanced AC voltage.

Idealized phase current waveforms on the AC side of converter transformers of a line-commutated 12-pulse bridge are shown in Figure 1. The separate traces show the current from a star-star connected transformer, the current from the star-delta connection and the sum of the two currents.

Formulae for the calculation of converter harmonics are readily available in textbooks and standards (IEC TR 60146-1-2). One such formula is given in Annex B.

Fourier analysis of the harmonic content of the idealized star-star and star-delta waveforms considering all three phases shows that:

- only harmonics 5, 7, 11, 13, 17, 19, ... $6k \pm 1$ are present (k is any positive integer). These are designated as “6-pulse” or “6-pulse characteristic” harmonics,
- harmonics 5, 11, 17, 23, ... $6k - 1$ are negative phase sequence,
- harmonics 7, 13, 19, 25, ... $6k + 1$ are positive phase sequence,
- the magnitude of each harmonic component is the same in both the star-star and star-delta waveforms,
- the angle of each harmonic component is the same in both the star-star and star-delta waveforms at harmonics 11, 13, 23, 25, ... $12k \pm 1$,
- the angle of each harmonic component is 180° out of phase in the star-star and star-delta waveforms at harmonics 5, 7, 17, 19, ... $(12k-6) \pm 1$.



IEC

Figure 1 – Idealized current waveforms on the AC side of converter transformer

Parameters:

F = 50 Hz – AC network frequency;

U_{ac} = 230 kV – AC network voltage;

U_d = 500 kV – DC voltage;

I_d = 1 000 A – DC current;

X_l = 14 % – leakage reactance;

A = 15° – firing delay angle.

The idealized current waveforms shown in Figure 1 are created by the transfer of DC current from one phase of the converter transformer to the next phase by the switching operation of the thyristor valves. In the idealized scenario under consideration, the DC current is kept constant at any given DC operating condition by the theoretically infinite smoothing reactor. For any given operating condition, the harmonic content is also therefore constant. Since the harmonic currents are constant and, under these idealized conditions, unaffected by the

connected AC side impedance, the converter is often treated as a harmonic current source in harmonic analysis.

5.2.2 Realistic conditions

The magnitude of the characteristic harmonics of the idealized waveforms described above is influenced by only the applied AC voltage magnitude, DC current magnitude, commutation reactance, and firing angle. However, in the more realistic waveform many additional factors influence the magnitudes and phase angles of harmonics. These factors include:

- the presence of ripple and fundamental frequency in the DC current,
- harmonics in the AC voltage,
- unbalance, i.e. fundamental frequency negative sequence component, in the AC voltage,
- unbalance between the firing angles of the star-star and the star-delta valve groups,
- differences in the timing of individual firing pulses to each thyristor valve,
- unbalance between the applied AC voltages of the star-star and the star-delta valve groups due to differences in the converter transformer winding ratios or taps,
- commutation reactance unbalance between converter transformer phases,
- commutation reactance unbalance between converter transformers forming 12-pulse groups.

Some of the factors above, such as DC current, average firing angle and average commutating reactance, are deterministic. Others, such as variations in firing angles to each thyristor valve and harmonic distortion on the AC buses, exhibit an almost random characteristic.

A more realistic presentation, including the influence of the above factors, of phase current waveforms on the AC side of the converter transformers is shown in Figure 2.

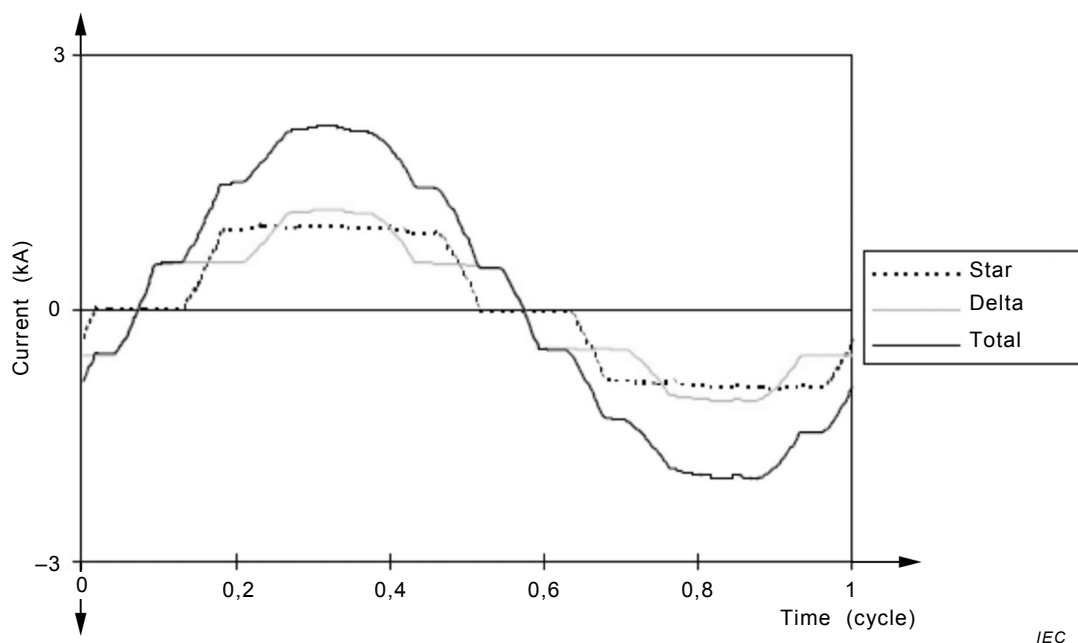


Figure 2 – Realistic current waveforms on the AC side of converter transformer including effect of non-idealities

Parameters as in Figure 1 but with:

- 1 % negative sequence fundamental voltage,

- 1 % second harmonic positive sequence voltage,
- 5 % (of XI) leakage reactance unbalance between phases,
- $\pm 0,5^\circ$ firing unbalance between star and delta groups,
- 50 Hz and 100 Hz components in DC side current.

Figure 3 compares the harmonic content of Figure 2 and the idealized harmonic content of Figure 1, and shows a small impact on the magnitude of the characteristic harmonics, and the appearance of non-characteristic harmonics of all orders. Non-characteristic harmonics are generated due to non-ideal operating conditions and have been well documented [7].

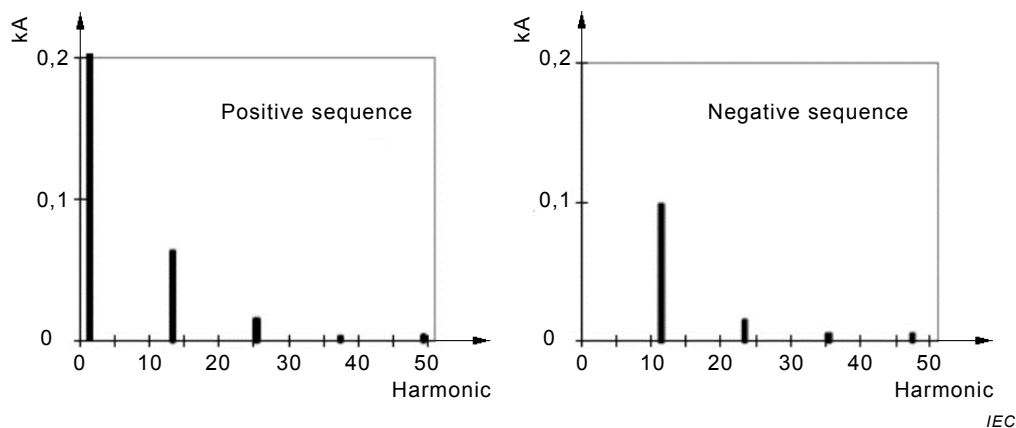


Figure 3a – Harmonic content of current waveform in Figure 1 (idealized conditions)

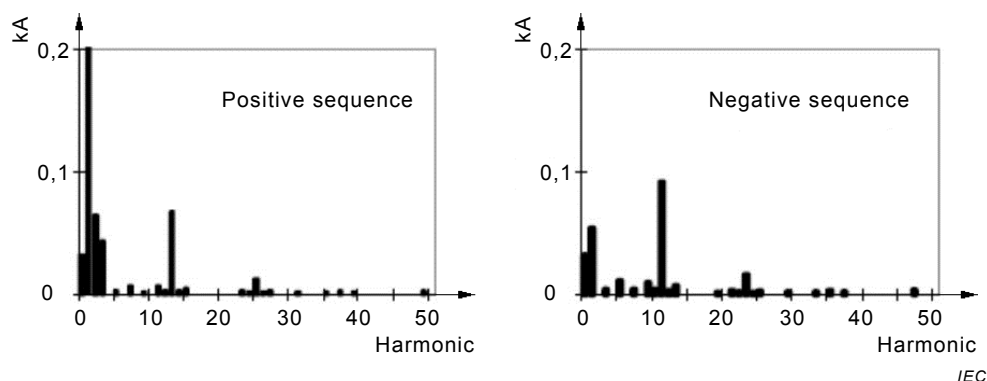


Figure 3b – Harmonic content of current waveform in Figure 2 (realistic conditions)

Figure 3 – Comparison of harmonic content of current waveform under idealized and realistic conditions

Some of the listed factors have a non-linear influence on the harmonic content in the resultant AC current waveform. The harmonic content can even be a cyclic function of some of the variables as that parameter is varied from one extreme to the other.

From the above it is evident that an analysis of the current waveform for any given operating condition will not give a reasonable definition of the level of harmonics which can be expected from a converter station. For a complete picture, the waveform should be established and the harmonic content determined for every possible operating condition, taking into account all of the factors above. A multitude of possible combinations of factors is possible, and therefore a multitude of harmonic spectra.

5.3 Calculation methodology

5.3.1 General

A typical method for calculating the harmonic currents is to construct mathematically the current waveform resulting from one particular combination of all the parameters, and then to perform a trigonometric Fourier analysis on this waveform to derive the harmonic content. One or more of the parameters is then varied within a defined range and another Fourier analysis made. This process is repeated for a very large number of combinations of all the variables. Where a parameter (such as commutating reactance) may have a random value within a range, a random choice of value may be made using for example a Monte Carlo technique. The harmonic currents resulting from each Fourier analysis are compared, and the highest values resulting from all the cases are then used.

Different methods of calculating harmonic generation may be used by different bidders. For the purposes of bid evaluation, a standard method may be defined in the specification if the customer wishes. However the specification should also leave scope for the bidder to propose, as an alternative, his favoured method, while being clear about which factors should be taken into account.

In particular, the specification should state whether statistical methods may be used to derive the values of harmonic currents due to the random differences between phases of parameters such as firing angles and commutation reactances, and if so, what level of certainty should be guaranteed. Typically it is required that the magnitude of any non-characteristic harmonic used in the calculations should not be exceeded in more than 1 % of all possible cases, or that it should not be less than 90 % of the extreme value calculated using the worst-possible combination of parameters.

The impact of harmonic interaction across the converters is not easy to take into account using such calculation methods which assume a given set of operating conditions.

5.3.2 Harmonic currents for performance, rating and other calculations

The frequency range and magnitudes of harmonic currents used in the calculations may differ depending on their ultimate application. Sets of harmonic currents used for filter rating calculations may be more onerous than other sets of harmonic currents used for the filter performance, losses or audible noise calculations.

The specification should be clear in this respect. The main factors which may differ when calculating harmonic currents for performance, or rating, or losses, etc. are:

- the range of AC network voltage variation,
- the range of AC frequency variations, both steady-state and transient (this has a relatively minor impact, affecting only the commutating reactance),
- level of AC system negative phase sequence voltage,
- levels of deviations from rated values (e.g. phase reactance tolerances),
- overload and short-time operating conditions of the converter,
- operation of the converter in reduced voltage, or high reactive power modes, if applicable,
- whether harmonic currents are to be calculated at nominal AC bus voltage or at any operating point within the specified voltage range,
- the time for which certain conditions can exist (for example, conditions which persist for less than say 1 min to be disregarded for performance calculations).

Narrower ranges of AC voltage or frequency, and less onerous converter operating conditions could be used for performance than for rating, for example. These aspects are discussed in more detail in 5.4.