

Guide to the specification and design evaluation of a.c. filters for HVDC systems

ICS 29.200

National foreword

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A list of organizations represented on this committee can be obtained on request to its secretary.

Cross-references

The British Standards which implement international publications referred to in this document may be found in the BSI Catalogue under the section entitled “International Standards Correspondence Index”, or by using the “Search” facility of the *BSI Electronic Catalogue* or of British Standards Online.

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and design evaluation of a.c. filters
for HVDC systems**



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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**GUIDE TO THE SPECIFICATION AND DESIGN EVALUATION
OF AC FILTERS FOR HVDC SYSTEMS**

FOREWORD

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This PAS shall remain valid for an initial maximum period of three years starting from 2004-07. The validity may be extended for a single three-year period, following which it shall be revised to become another type of normative document or shall be withdrawn.

HOW TO USE THIS GUIDE

The principal purpose of this document is to give guidance to those responsible for:

- preparing the a.c. filtering aspects of Technical Specifications for HVDC projects,
- evaluating the proposed designs, and
- monitoring the subsequent project.

The main objective is to enable informed judgements to be made and future Technical Specifications to be written, such that the resulting a.c. filters are effective yet economical, and are not under- or over-designed.

The Guide has been written by a diverse group including engineers from various manufacturers, utilities and consultants, and the recommendations respect the interests of all parties.

This Guide can be used in different ways by different readers:

- The Guide provides sufficient instructional material so that it can be used as an introduction by those involved in HVDC technology for the first time. An initial reader can omit certain sections and concentrate on core aspects.
- An engineer preparing a Technical Specification can find the key points, which must be considered, highlighted throughout the Guide, and summarised in Section 16.
- The Guide emphasises aspects where the specified requirements can, perhaps unintentionally, have a significant impact on filter design and costs. A user issuing a Technical Specification should consider how these aspects apply to that Specification.
- For evaluating proposed designs and technically monitoring the project, a deeper understanding of many aspects will be required. This document contains guidance reflecting the accumulated knowledge of many HVDC projects, and so will be of value even to highly experienced users. It should help Customers to understand the reasons for differences among filter designs offered by Bidders.
- While making specific recommendations, it has also been necessary to provide a considerable amount of background material. Much of this information has never been brought together under one cover before, and so the Guide will provide a valuable source of reference.
- Additionally, the Guide also contains material which will be of relevance in power industry applications other than HVDC, for example in industrial filtering, switched capacitor applications and general power quality issues.

The Guide has been clearly set-out in sections, each covering specific aspects of a.c. filter design. For guidance on any particular subject, each section may be read individually. Cross-references to other sections are made where necessary.

The brief description below of the contents of each section is intended to assist the reader to use the Guide in the most appropriate way.

- For any reader, it is recommended to start with the short introductory Sections 1 and 2, which explain the justification for the production of this document and also discuss what a Technical Specification must attempt to achieve and the optional approaches regarding what should be included.

- Section 3 tackles the difficult and controversial problem of defining what harmonic distortion limits should be specified. This is a complex subject and one where it is difficult to make unambiguous recommendations, due to the vastly different local circumstances applying to different HVDC projects. The options and implications are covered in detail. However, a non-specialised reader need not go too deeply into this section before proceeding.
- In Section 4, various aspects of converter harmonic generation are discussed, concentrating on those points which could be defined in the Technical Specification, and making recommendations intended to avoid difficulties encountered in previous projects. This section contains essential introductory material.
- In Section 5, the impact of harmonic interaction across the converter is discussed. Recommendations are made as to how this phenomenon should be treated in the practical context of an HVDC project design.
- A brief review of many different a.c. filter configurations is given in Section 6, along with lists of advantages and disadvantages. As well as being of value as a reference, this information may be used in the evaluation of proposed filter solutions.
- The central question of how to calculate a.c. filter performance is treated in Section 7, which brings together various strands from other sections. The definition of a.c. system harmonic impedance is of crucial importance to the filter design, and this section shows the various options available and discusses the relative merits of each.
- The specification and design of a.c. filtering equipment is closely linked to the other main function of a.c. filters, which is to provide reactive compensation. The specified requirements on reactive compensation, and how these will influence the cost and complexity of the filter design, are covered in Section 8.
- Sections 9, 10 and 11 define how the steady-state rating, the transient rating, and the losses of a.c. filters are to be calculated, and what should be specified in this respect.
- Numerous aspects of valuable practical experience are brought together in Section 12, which discusses special areas of design not covered elsewhere in the document and what influence these aspects could have on a Specification. This section will be of value particularly to those with an in-depth knowledge of the subject
- Section 13 covers aspects of a.c. filter protection, providing sufficient information to enable an evaluation to be made of particular proposed protection schemes
- Sections 14 and 15 deal with the specialised areas of seismic design and audible noise, which in some instances can have a significant impact on the physical design, cost and layout of an a.c. filter installation.
- A summary of all the important parameters and requirements which must be specified by the Customer in a Technical Specification, is given in Section 16. This summary lists the key points which have been discussed in depth elsewhere in the Guide, and makes suitable cross-references.
- Section 17 contains a detailed description of what should be specified regarding the detailed design and testing of each item of filter equipment.
- Field measurements, and verification that the specified performance is achieved in service, are discussed in Section 18, which concentrates on those aspects which need to be clearly defined in the Technical Specification in order to avoid subsequent contractual conflict.
- Finally, the expected impacts of new technologies in the fields of HVDC converters and a.c. filters are discussed in Section 19.

In some sections, detailed background material and equations have been set aside in small Appendices.

A substantial list of references is included, in Section 20.

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1.1 General

This document is a Guide to the specification and design evaluation of a.c. side harmonic performance and a.c. 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 Technical Specifications for new HVDC projects and evaluating designs proposed by prospective suppliers.

1.2 Definitions

The term “Technical Specification” or “Specification” used in this Guide is taken to mean the document which defines the overall system requirements for the a.c. filters and the a.c. system environment in which they have to operate. 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. 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.

The Technical Specification defines the technical basis for a contract between two parties, who in this Guide will be referred to as the “Customer” and the “Contractor”.

- The “Customer” is the organisation which is purchasing the HVDC converter station, including the a.c. filters. 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.
- The “Contractor” has the overall responsibility for delivery of the HVDC converter station, including the a.c. filters, as a system, and may in turn contract one or more sub-suppliers of individual items of equipment. The term “Contractor” is taken to cover similar terms which may be used in specifications, such as Manufacturer, or Supplier.

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.

1.3 Introduction

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

HVDC converters also consume substantial reactive power, a large proportion of which must normally be supplied locally within the converter station. Shunt connected a.c. filters appear as capacitive sources of reactive power at fundamental frequency, and normally in conventional HVDC schemes the a.c. 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 a.c. filters therefore normally has to satisfy these two requirements of harmonic filtering and reactive power compensation, for various operational states and load levels. Optimisation of this design is the task of the a.c. filter designer, and the constraints under which the design is made are defined in the Technical Specification.

The a.c. filters form a substantial part of a conventional HVDC converter station. The fundamental reactive power rating of the a.c. filters (including shunt capacitors where applicable) at each converter station has

typically been in the range of 50% - 60% of the active power rating of the scheme. Together with the required switchyard equipment, the a.c. filters can occupy over half of the total land requirements of an HVDC scheme. The cost of manufacture, installation and commissioning of the a.c. 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 [Ref. 1-1, 1-2] and on the total project schedule. Once in operation, the a.c. 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 a.c. filters are specified is such as to allow the design to be optimised in terms of all the above factors, while fulfilling the essential functions of disturbance mitigation and reactive power compensation.

The scope of this Guide covers a.c. 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 PLC and radio interference spectra.

1.4 Past experience

In practice, there have been few problems of harmonic disturbance from HVDC schemes and few problems relating to a.c. filter equipment in operation. Section 12 discusses some application problems, while analyses of some filter reactor failures may be found in Ref. 1-3. Further information on experience with existing a.c. filter schemes is available through the "HVDC Users' Group".

This past experience indicates that designs in general have been at least adequate. However, it is not obvious to what extent this satisfactory experience might indicate that a.c. filters in some instances may have been over-designed, and that a more economical design might have been possible.

One of the fundamental problems in specifying a.c. filters is that some of the essential design data is not readily available. The harmonic impedance of the a.c. system is of paramount importance to the design, and yet is difficult to measure or calculate for all operational conditions, both at present and during the future operational life of the scheme. The level of existing harmonic distortion to be considered is another factor which is difficult to measure or predict, as is the extent to which existing or future telecommunication systems may be affected by harmonic currents flowing in the a.c. network. The tolerance to harmonics of existing and future equipment such as motors and electronic loads, connected to the power system itself, is also difficult to evaluate.

Other factors affecting the filter design have, in the past, been difficult to calculate accurately with the available tools. Most prominent of these is the effect of the harmonic interaction between the a.c. and d.c. sides of the converter which, while well understood in theory, has been difficult to incorporate consistently into the design process.

One important aspect of the filtering scheme is the eventual ease of operation. Complex switching schemes with several different types and sizes of a.c. filter bank may fulfil rigorous requirements on performance and reactive power exchange, but the practical consequences and costs of lifetime operation should also be considered.

Historically, there has been a wide variation in the content and requirements of Technical Specifications of a.c. filters for different HVDC projects. There have developed several near-standard types of specification, associated with certain utilities and consultants, but even these are adapted to suit individual projects.

1.5 Objectives

In preparing this Guide, CIGRÉ Working Group 14.30 has attempted to:

- examine previous a.c. filter specifications and consider relative merits,
- consider field experience and draw conclusions,
- review results of previous and current CIGRÉ work on voltage and current limits, on a.c. system modelling, and on a.c./d.c. harmonic interaction and consider how the recommendations resulting from this work can usefully be incorporated in future specifications for HVDC projects,
- take note of other relevant work in CIGRÉ and the IEEE,
- examine how particular aspects of specification can have a significant influence on the design and costs,
- look forward to the likely impact of new technologies, both in the HVDC field and in related areas such as telephone technology,
- make recommendations based on all of the above,
- provide information to facilitate reasoned decisions in the preparation of future Technical Specifications and the evaluation of prospective designs.

In doing so, the Working Group sought to bring together the experience, and consider the interests, of all sectors of the HVDC community and to produce a Guide which, while primarily intended for the use of utilities and consultants, will be of interest to all parties.

1.6 Approach

The Guide attempts to review all possible aspects to be covered in a specification and the subsequent design evaluation, and to give a more detailed analysis of critical or contentious points.

The technical background to each subject area is described briefly, and reference made to further sources of information, in order to provide the background and context for the decisions to be made.

Where it is possible to make clear recommendations, these are given in the Guide. In other instances, where there may be different ways to approach some aspect, then the different approaches and their consequences are described. The intention in such instances is to enhance awareness of the implications of different possible approaches.

The Guide gives a comprehensive treatment of most aspects of the subject. This does not imply that a Technical Specification needs to mention all the aspects included in this Guide. In some circumstances a simple and open Specification may be preferable. However, while preparing any Specification, those responsible should at least be aware of, and consider, all the points discussed in this Guide. In the eventual design evaluation phase, most of the material included in this Guide will be of relevance.

New technologies which are currently being introduced into HVDC systems will, where applied, substantially alter many aspects of a.c. filter design. Foremost of these are the series compensated converter, the automatically continuously tuned reactor, and active filters.

To introduce throughout this Guide the radically different approaches which such new technologies require, would have led to a clumsy presentation. Instead, the bulk of the Guide concentrates on the “conventional” a.c. filter technology and current-source line-commutated HVDC converters. Discussion of the changes entailed by new technologies is treated exclusively in Section 19. Other unusual applications, such as series filters, which use conventional technology but are only employed in very specific circumstances, are discussed in Section 12.

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Appendix 2.1 Alternative type of procurement procedure

2.1 General

A Technical Specification has several essential purposes:

- Primarily its objective is to define the technical features of the equipment to be purchased. In doing so, it may define in detail many aspects of the equipment design, or may restrict itself to describing the system conditions, the main constraints under which the equipment must perform, and the performance requirements.
- It will attempt to enforce uniformity of certain aspects of design both within the converter station and with the rest of the a.c. system.
- It will ensure compatibility among all aspects of HVDC system operation, such as a.c. filtering, reactive power control, and converter controls.
- Finally, a Specification issued for tender purposes will attempt to provide a basis on which competitive designs can be fairly evaluated and compared both technically and economically.

Aspects of a Technical Specification which are poorly written can have a severe negative impact on a project, possibly leading to:

- overdesign or underdesign
- different interpretations by different Bidders
- long-running discussions
- re-design during the project
- wasting of time and consequent project delays
- contractual and legal conflict

There is therefore a strong incentive for those preparing Technical Specifications to eliminate these risks by stating precise and unambiguous definitions of the requirements, based on a sound technical knowledge.

In general, this Guide assumes that the purchase of an HVDC converter station, including a.c. filters, will be made on a turnkey or similar basis, such has been the case for practically all HVDC schemes to date. The discussion 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 Guide would have to be reconsidered in the context of the particular scheme, although the purely technical content of the Guide would still be applicable.

Most Technical 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 Appendix 2.1.

2.2 Boundaries of responsibility

Before a Technical Specification enters into the detail of a.c. filter design requirements, it should first clearly define the boundaries of responsibility between Customer and Contractor.

In this respect there are two extreme approaches:

- a) The Customer defines an a.c. 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 a.c. filters do not perform adequately under field conditions lies mainly with the Customer.

- b) At the other extreme, the Customer defines only the maximum actual measured distortion and disturbance to be permitted (or even more simply, that there must be 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 a.c. system impedance, defining all relevant parameters, and designing a.c. 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 a.c. system impedance and local harmonic limit requirements. This will be expensive and difficult to achieve during a short tender period. It is therefore recommended that these studies should be conducted by the Customer or his consultant during the longer period which is usually available before issue of the Technical 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 a.c. 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 Technical Specifications adopt an approach which lies somewhere between these two extremes. For example, the Customer may provide some information about the a.c. system configuration, maximum and minimum short-circuit powers, and expected future expansion, but not a full definition of a.c. 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 Guide 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 Technical 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 a.c. filters.

Most essentially, the Specification must define 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 a.c. and d.c. system conditions for which the design has been made. Also, the impact of pre-existing harmonic distortion in the a.c. system must be taken into account, by measuring pre-existing harmonic levels with the HVDC converters blocked (and with a.c. 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 Technical Specification should also define the Contractor's responsibility for considering the interaction of the a.c. filters with the HVDC converter controls, and the possible resonance of the filters with the a.c. system.

2.3 Scope of studies

Depending on the boundaries of responsibility discussed above, some system studies may require to be conducted by the Customer prior to issuing the Technical Specification, or may be the responsibility of the Bidder and later the Contractor. Those such studies related to the a.c. filters would normally cover:

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

The extent of system studies required to be conducted by the Bidder and the Contractor should be made clear in the Technical 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:

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

2.4 Scope of supply

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

- site preparation
- civil and mechanical structures
- earthing
- fencing
- interface with a.c. 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, performance, etc., should also be clearly stated.

2.5 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 Technical 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:

- method and assumptions for filter performance calculations
- criteria and assumptions for steady-state filter rating, and for transient stresses and rating calculations

as well as the following specific areas where clarity is important:

- 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.)
- 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.)
- 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 Technical 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.

2.6 Alternative proposals by Bidders

The Customer should recognise that Bidders for an HVDC project will have a great deal of 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.

It is therefore recommended that Technical 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.

Appendix 2.1

Alternative type of procurement procedure

In the most usual process of procurement, the detailed Technical Specification as discussed in this Guide is established prior to the tender stage. An alternative approach is to issue an “open” specification, and during discussions with the various Bidders find the optimal solution for the specific project. (As an example, the European Union directives define different procurement procedures and one of these is the so called 'EU Negotiated Procedure'.) For this procedure an inquiry document is sent to the Bidders with an open specification. After receiving the Bidders' proposals the Customer starts the evaluation process, which is more complicated due to the open specification.

During the negotiation process the goal is to find the optimal solution and base the final Specification on this. This final Specification would not differ much from a Specification prepared prior to a tender phase with respect to the content; however, several advantages are gained:

- The specific requirements will probably be more optimised for the project.
- During the negotiations a common understanding of the various aspects of the Specification is established between the Customer and the Bidders. This should result in less need for clarification after the contract is signed.

In the open specification some information related to the a.c. filtering must be included. This would comprise the parameters that are known and fixed, such as a.c. system parameters and environmental parameters. The requirements on harmonic distortion and filter design could be open. A starting point for these parameters could also be defined in order to make a first evaluation of the proposals; however, there should be an opening for alternatives/options in order to visualise the consequences of different requirements. These consequences are discussed throughout this Guide, and they are typically related to cost, lay-out or operation.

This “open” specification approach, however, has some disadvantages:

- The procurement period will be considerably extended compared to that for a normal tender package.
- In the process of optimising the design, all the Bidders have to do costly and time-consuming detailed studies of various design options, which represents wasted effort for all but the successful Bidder. The Bidders are acting in effect as unpaid consultants.
- The Customer's engineering personnel must have a high level of competence, and must expend more time and effort than normally required, in order to evaluate multiple options offered by several Bidders. Alternatively, the Customer may need to engage an experienced consultant to do this work on his behalf.
- Some essential main parameters of the project may not be decided until late in the procurement process, which could result in delayed licensing and approval by the relevant authorities.

In this Guide, the term “Technical Specification” refers to the final definition of the Customer's requirements for a defined project, whether determined by the conventional approach or by this alternative negotiated approach.

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3.1 General

The performance objective of the a.c. 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:

- 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.
- The harmonic current circulating in the a.c. lines can, by induction, cause interference in adjacent communication lines and this must be limited to an acceptable level.
- 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 Technical Specification normally defines permissible harmonic distortion limits, which must be respected by the a.c. filter designer. The definition of suitable criteria for setting such limits is a complex and controversial subject, which must be addressed by any Customer installing a new HVDC scheme. This Section 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 [Ref. 3-1, 3-2, 3-3, 3-4],
- the growing concern of the utilities and their customers about power quality,
- the trend towards cost reduction through optimisation of equipment design,

it is recommended that appropriate specification studies be conducted in order to develop harmonic limits tailored to the particular characteristics of the HVDC scheme and the connected a.c. network.

This section describes the different indices used to control the adverse harmonic effects and discusses the considerations that must be 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:

- voltage distortion limits
- limits pertaining to HV and EHV network equipment
- telephone interference limits
- 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 a.c. filters for HVDC stations, and so this aspect is discussed in some depth in the following sections and Appendices.

A Customer should understand that it is not necessary or desirable to include in the Technical Specification all of the distortion limits discussed in this section. 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.

3.2 Voltage distortion

The main requirements for a.c. 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 a.c. 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 a.c. system. (The validity of this approach is discussed further below).

This sub-section describes the most common indices used to control voltage distortion and gives some guidelines for the determination of suitable limits.

3.2.1 Voltage distortion - Definitions of performance criteria

v Individual harmonic distortion, D_n (in %)

$$D_n = \frac{U_n}{U_1} \cdot 100\% \quad (3-1)$$

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

v Total harmonic distortion, THD (also called **Deff** or **voltage distortion factor**)

$$THD = \sqrt{\sum_{n=2}^N D_n^2} \quad (3-2)$$

where :

- N is the maximum harmonic order considered

v Total arithmetic harmonic distortion, D

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

3.2.2 Voltage distortion - Discussion and recommendations

The individual (D_n) and total harmonic distortion (THD) are widely accepted indices of voltage distortion in a.c. networks, while the total arithmetic harmonic distortion (D) is controversial, even though it has been used in a number of HVDC schemes [Ref. 3-6], 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 [Ref. 3-1] and IEEE [Ref. 3-5] and is therefore the criterion recommended in this Guide.

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 a.c. 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 50, 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 becomes very low with increasing frequency due to the characteristics of power transformers and loads at these frequencies (see further discussion in Section 12.2.2).

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 must 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 Section 7.1.6 on the system conditions under which total harmonic distortion should be calculated. The range of a.c. system voltages over which the distortion criteria are to be met must also be clearly defined.

3.2.3 Voltage distortion - Determination of limits

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 [Ref. 3-8]. Where a large HVDC installation is planned, it is recommended to perform a specific analysis in order to derive distortion limits which have a more rational basis and relate to the particular circumstances of the HVDC scheme in question.

3.2.3.1 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 CIGRÉ surveys [Ref. 3-6, 3-7] on a.c. harmonic filters for numerous HVDC schemes from different countries:

- specified limits on D_n are in the range of 0.5% to 1.5% (most typically 1%)
- specified limits on THD are in the range of 1% to 4% (no typical value)
- specified limits on D are in the range of 2% to 4% (most typically 4%)

(Note that 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 a.c. network representation which was specified to be used in the calculation of these indices.)

Where a Customer:

- wishes to minimise the procurement time schedule, or
- lacks the appropriate computational tools or a.c. system data, or
- where he 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. A.C. 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 a.c. 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 [Ref. 3-6, 3-7] 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 Technical 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.

3.2.3.2 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 a.c. filter design, with an optimal filter solution relative to the harmonic characteristics of the a.c. 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.

IEC has published a technical paper on limitation of harmonic distortion for MV and HV power systems [Ref. 3-9] based on electromagnetic compatibility. Appendix 3.1 of this Guide summarises the basic principles and concepts outlined in the IEC paper to ensure electromagnetic compatibility in the whole a.c.

system. Internationally recommended limits for compatibility levels of harmonic distortion in LV and MV are also described.

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 a.c. 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 must also consider the future expansion stages of the a.c. 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. [Ref. 3-10] and [Ref. 3-11] discuss many aspects of this process.

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 Section 3.2.4 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 [Ref. 3-9] can be adopted.

Reference [Ref. 3-9] 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 [Ref. 3-9] 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; examples of such amplification problems are given in [Ref. 3-12]. These remote effects are controlled by applying appropriate coefficients for the particular harmonics in the individual emission limits applied at the HVDC connection bus.

The indicative values of planning levels for harmonic voltage given in Appendix 3.1 may be used for HV networks close to load areas where the harmonic voltages from HV or EHV levels are directly transferred to the LV or MV level. These planning levels should be modified as necessary to reflect the characteristics of the particular network considered. A harmonic load flow study is necessary to assess the values of harmonic voltage within the particular EHV or HV network and the transfer to lower levels in the different network

normal operating conditions, also taking into account the foreseeable future expansion of the network. The study results will indicate the need to revise the values of Table A3.3 (Appendix 3.1) in order to keep an equivalent contribution for the HV or EHV levels to the LV and MV compatibility levels shown on Table A3.2 (Appendix 3.1).

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 a.c. 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, when two 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 must provide all the necessary data for the filter optimisation: a.c. system configurations, line data, remotely installed filters, earth resistivity, frequency dependent equivalent models at the end nodes, tolerances etc. The data must 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.

3.2.4 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. The planning levels proposed in Appendix 3.1 must then be revised according to the actual situation in order to set a realistic co-ordination between the various sources of emission.

(As an example, pre-existing harmonic levels have in some countries already exceeded the proposed planning levels of Table A3.3 in Appendix 3.1, due to low voltage apparatus e.g. television and other electronic equipment loads.)

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 transmission lines can give rise to substantial levels of third harmonic current [Ref 3-29].

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 a.c. filter installation is likely to affect the harmonic levels in its vicinity [Ref 3-27, 3-28]. It should be noted that the new a.c. filter

installation could be beneficial for the network and the utility may even consider specifying the performance of the a.c. 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.

3.2.5 Voltage distortion - Relaxed limits for short term and infrequent conditions

For unusual conditions during short periods of time (less than one hour), the IEEE Standard 519-1992 [Ref. 3-5] recommends that the limits may be exceeded by 50%.

The IEC 1000-3-6 technical report [Ref. 3-1] 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 e.g. from an equipment rating aspect.

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

3.2.6 Treatment of interharmonic frequencies

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

This additional generated distortion will be at frequencies which are harmonics of the fundamental frequency of the remote a.c. system, and will be transferred across the link by the mechanisms described in Section 5 and in Ref. 3-25. This transfer may be thought of as harmonic penetration or transition from one a.c. 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. CIGRÉ WG36.05/CC02 is currently preparing a paper concerning "Interharmonics in Power Systems".

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, e.g. 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 60Hz 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 this Section, 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 Technical Specification (as has occurred in the past) both states that the Contractor must take such interharmonics into account in his design, but also, inconsistently, defines the performance criteria in terms of “harmonics 1-50” 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 Standard 519-1992 [Ref. 3-5].

IEC 61000-2-1 Part 2 [Ref. 3-26] discusses interharmonic sources and some possible effects. IEC 61000-3-6 [Ref. 3-1] 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.

It is therefore recommended that if the proposed HVDC link connects two systems of nominally or potentially different frequencies, the Customer should take due consideration of 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.

3.3 Distortion limits pertaining to the HV and EHV network equipment

3.3.1 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, as 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 C57.12.00-1980 [Ref. 3-13] which defines the maximum acceptable RSS of the 3rd, 5th and 7th harmonics at buses where transformers are connected.

3.3.2 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 [Ref. 3-14]. 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 Appendix 3.2) 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-34.1 [Ref. 3-15] 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 a.c. 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 [Ref. 3-16].

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 satisfy 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 must also supply the Bidders with an equivalent circuit representing the generators, or include them in the overall network impedance locus.

3.3.3 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, must be provided to the Bidders for the new installation. A design constraint on the new a.c. filter will be that the rating and performance of the existing a.c. filters must not be compromised.

3.4 Telephone interference

Telephone interference is a common concern related to the harmonic distortion produced by HVDC systems. A survey [Ref. 3-7] 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 a.c. filters can be substantial. Therefore an analysis of the requirements and limits for each specific HVDC scheme is recommended.

This sub-section 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.

3.4.1 Causes of telephone interference

Appendix 3.3 provides a brief overview of the basic telephone interference mechanism, sufficient to understand the recommendations of this Guide. A flow-chart describing the process is also shown in Appendix 3.5. More detailed information is available in references [Ref. 3-2, 3-3, 3-4, 3-17].

3.4.2 Telephone interference - Definitions of performance criteria

The telephone interference performance requirements for a.c. filters are usually specified by factors calculated from the harmonic voltages and currents, with suitable weightings.

The most commonly used criteria are defined and compared in Appendix 3.4, which also gives indicative values used in previous HVDC projects.

3.4.3 Telephone interference - Discussion

One important limitation of the telephone interference criteria TIF or THFF, calculated at the HVDC converter station a.c. bus, is that they are not directly related to the telephone interference influence caused by the various lines of the a.c. network. Indeed these harmonic voltage criteria directly control only the electrostatic interference on the a.c. 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 or 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 [Ref. 3-9]. 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 a.c. 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 [Ref. 3.4]. 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 Section 7.1.6 on the system conditions under which telephone interference parameters should be calculated.

3.4.4 Telephone interference - Determination of limits

3.4.4.1 Telephone interference - Determination of limits without detailed studies

Due to a possible short time schedule, lack of computational tools, lack of network or telephone system data or if no serious interference problems are expected because of harmonic distortion, the Customer may decide to set the telephone interference limits according to the indicative values provided in Appendix 3.4. 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 a.c. transmission lines,
- earth resistivity along the a.c. transmission lines,
- length of telephone lines and mean separation from the a.c. transmission lines,
- a.c. network structure (long lines and capacitor banks can produce magnification of harmonic current, large meshed networks will likely diffuse the current lowering the individual a.c. transmission lines influence, 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 the 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 higher connection loudness loss which results in increased subscriber's sensitivity to noise [Ref. 3-18]. 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 the IEEE Std 368-1977 [Ref. 3-19] and repeated in IEEE Std 519-1992 [Ref. 3-5]:

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 a.c. 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 CIGRÉ surveys of HVDC schemes [Ref. 3-6, 3-7], those schemes which specified the IT criterion imposed limits of between 25,000 and 50,000 for the total harmonic current into the a.c. 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.

3.4.4.2 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 lines 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 optimisation: a.c. 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 a.c. 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.

3.4.5 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 Section 3.2.4, measurements within the HV or EHV system must allow for the effect that the introduction of large a.c. 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 characterise 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.

3.4.6 Telephone interference - Limits for temporary conditions

The telephone company may accept higher noise for short term conditions. Accordingly, the technical specifications of several HVDC schemes have allowed for higher telephone interference levels on the d.c. 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. It is therefore recommended that relaxed limits are specified when such short term conditions are foreseen for the HVDC system. Examples of such conditions are :

- short term duration overload conditions
- a.c. voltage outside normal continuous range
- operation at extreme frequency deviation or voltage unbalance
- infrequent a.c. network configurations
- loss of filter branches
- abnormal d.c. 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.

3.5 Special criteria

The following special conditions should also be considered when preparing the Technical Specification. Normally, they will not directly impact the limit values expressed in the Specification, or the consequent design of the a.c. 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 a.c. 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.

Appendix 3.1 Voltage distortion limits for HV and EHV networks

Utilities must control the harmonic voltage levels in their HV and EHV networks in order to keep the disturbance levels below the **compatibility levels** (defined below) for all their customers, including those in the low-voltage systems.

Each item of plant and equipment must have an **emission level** lower than, and an **immunity level** higher than, the defined compatibility level.

To achieve this, **planning levels** of harmonic distortion are specified by the utility for HV and EHV levels of the system and can be considered as internal quality objectives for the utility. There is also a trend within the utilities to guarantee a certain level of power quality for consumers at any voltage level, and planning levels can be used as power quality criteria for HV and EHV levels.

Harmonic voltages in the system are produced by the combined effect of all harmonic sources at the low voltage as well as the medium and high voltage levels. Figure A3.1 shows the harmonic voltage build up in a simple system (taking into account only the inductive reactance of the network). This figure illustrates the need for co-ordination between the different voltage levels.

From the figure, it is clear that the harmonic voltage seen at the low voltage level is the sum of the harmonic voltages over the entire system. The harmonic voltages produced at the HV or EHV level should therefore be limited to a fraction of the compatibility level defined at the LV and MV levels.

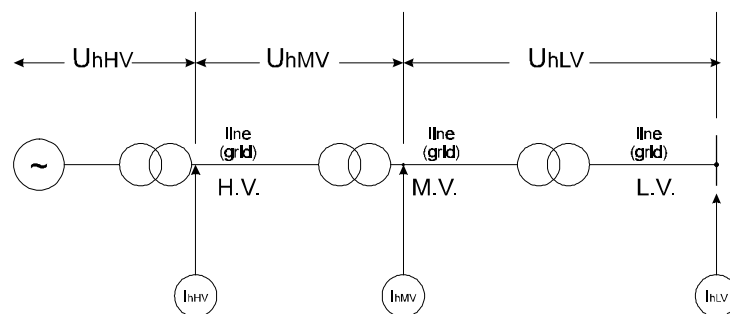


Figure 3.1
Contributions of harmonic voltages at different voltage levels in a simple network

It is also important to note that the harmonic voltages at HV and EHV levels are produced by harmonic sources from every voltage level in the system.

The above is an approximation, as real systems are not purely inductive. Capacitive paths to earth exist at the different voltage levels and resonant conditions can also occur which may lead to amplification of harmonic voltages. In addition the structure of networks is more complex than shown, with usually several MV or LV sub-networks.

Recommended limits for HV or EHV networks

The two main standard organisations, IEC and IEEE, give recommendations on voltage distortion for electrical power systems. They both recommend different distortion limits for distribution and transmission systems recognising the greater impact of harmonics with increasing transmission system voltage.

As a general observation, recommended limits are lower for IEEE compared to IEC. IEC also proposes different values according to the type of harmonic and the frequency to reflect the results of measurements in power systems and to allow for different effects on sensitive equipment.

IEEE

The voltage distortion limits recommended by IEEE 519-1992 are shown in the Table A3.1

Bus Voltage at PCC	Individual voltage distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69 kV to 161 kV	1.5	2.5
161 kV and above	1.0	1.5

Note: High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

Table A3.1
Voltage distortion limits from IEEE 519-1992

IEC

A considerable amount of work has been completed recently by IEC/IEEE/CIGRE/CIRED/UIE/UNIPED committees on the subject of harmonic compatibility levels for a.c. systems. Based on this work, IEC has issued a technical report [Ref. 3-1] on assessment of emission limits for distorting loads in MV and HV power systems. This technical report outlines principles which are intended to be used as the basis for determining the requirements for connecting large distorting loads to public power systems.

This work uses the concept of compatibility levels as a basis for electromagnetic compatibility (EMC) of a system. The electromagnetic compatibility is the ability of a device, equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment. The electromagnetic compatibility level is the specified disturbance level in a system which is expected to be exceeded only with a small probability , this level being such that electromagnetic compatibility should exist for most equipment within the system.

Experimental values for the harmonic voltage normally obtained in the vicinity of disturbing equipment, were used within IEC to define the compatibility levels for LV and MV systems [Ref. 3-20]. The **compatibility** levels for harmonic voltages in LV and MV systems are given in Table A3.2. These compatibility levels are reference values for co-ordinating the emission and immunity of equipment which is part of, or supplied by, a supply network in order to ensure the EMC in the whole system (including both network and the connected equipment).

The IEC report [Ref. 3-1] also gives indicative values of **planning** levels for harmonic voltage in HV and EHV systems; see Table A3.3. This table reflects harmonic patterns obtained from measurement results on several MV-HV networks [Ref. 3-20 (note 1)]. It may be considered typical for a.c. networks situated in normal load areas. However, the planning levels will be different from case to case depending on network structure and circumstances. These levels should be modified as necessary to reflect the characteristics of the particular network considered.

Note that the original table does not consider explicitly EHV networks, but the general practice is not to differentiate between HV and EHV. Bearing in mind the meaning of “planning levels”, such a difference would have little significance. It was proposed [Ref. 3-9] not to change the table but to consider HV values as HV-EHV values. However not enough measurement results are available yet to validate those HV-EHV values, particularly for EHV power systems.

ODD HARMONICS NON MULTIPLE OF 3		ODD HARMONICS MULTIPLE OF 3		EVEN HARMONICS	
Order h	Harmonic voltage (%)	Order h	Harmonic voltage (%)	Order h	Harmonic voltage (%)
5	6.0	3	5.0	2	2.0
7	5.0	9	1.5	4	1.0
11	3.5	15	0.3	6	0.5
13	3.0	21	0.2	8	0.5
17	2.0	>21	0.2	10	0.5
19	1.5			12	0.2
23	1.5			>12	0.2
25	1.5				
>25	0.2 + 1.3(25/h)				

Total harmonic distortion (THD) : 8%

Note : LV refers to $U_N < 1$ kV;
MV refers to $1 \text{ kV} < U_N \leq 35$ kV

Table A3.2

Compatibility levels for harmonic voltages (in percent of the nominal voltage) in LV and MV power systems [Ref. 3-1]

ODD HARMONICS NON MULTIPLE OF 3		ODD HARMONICS MULTIPLE OF 3		EVEN HARMONICS	
Order h	Harmonic voltage (%)	Order h	Harmonic voltage (%)	Order h	Harmonic voltage (%)
5	2.0	3	2.0	2	1.5
7	2.0	9	1.0	4	1.0
11	1.5	15	0.3	6	0.5
13	1.5	21	0.2	8	0.4
17	1.0	>21	0.2	10	0.4
19	1.0			12	0.2
23	0.7			>12	0.2
25	0.7				
>25	0.2 + 25/2h				

Total harmonic distortion (THD) : 3%

Note : HV refers to $35 \text{ kV} < U_N \leq 230$ kV;
EHV refers to $U_N > 230$ kV.

Table A3.3

Indicative values of **planning** levels for harmonic voltages in HV and EHV power systems [Ref. 3-1]

Appendix 3.2 **Harmonic current in generators**

One definition of an equivalent negative sequence current I_{2eq} for a six pulse converter, is as follows [Ref. 3-21, 3-22] :

$$I_{2eq} = \sqrt{\sum_n \left[\sqrt{\frac{6n}{2}} \cdot (I_{6n+1} + I_{6n-1}) \right]^2} \quad (3-4)$$

where :

n	is an integer
I_{6n+1} and I_{6n-1}	are harmonic currents flowing into the synchronous machine armature winding.

For twelve pulse converters, only the terms with n equal to an even number will give any significant contribution to the sum in the above equation.

It should be noted that alternative formulae have been developed for use in some HVDC projects, in consultation with the generator manufacturers. It is recommended that the generator manufacturer should be asked to specify a suitable formula to calculate the effective harmonic current flow in the machines. Acceptable limit values for the calculated parameter should be agreed between the Customer and the generator manufacturer.

Appendix 3.3

Causes of telephone interference

Harmonic currents flowing in any conductor of a power transmission line create a magnetic field inducing harmonic voltages and currents in nearby installations. The induced voltage in the telephone lines is related to the harmonic current in the transmission line conductors and the mutual coupling impedance Z_m . The term Z_m is mainly dependent on the frequency, the earth resistivity, the length of exposure and the distance between transmission line and telephone line routes. The mutual impedance should be calculated with the help of computer programs because of the complexity involved in solving Carson's equations, however the Dubanton equations [Ref. 3-23] give satisfactory results over an extensive range of frequencies, separation distances, and earth resistivities. The following equation gives the longitudinal induced voltage on one telephone line conductor :

$$V_{cn} = \sum_{j=1}^{j=k} (I_{jn} \cdot Z_{m_{jn}}) \quad (3-6)$$

where :

V_{cn}	is the longitudinal voltage at harmonic n
n	is the harmonic order
j	is the conductor number
k	is the number of conductors on the transmission line
I_{jn}	is the phasor current in the conductor j at harmonic n
$Z_{m_{jn}}$	is the mutual impedance between conductor j and telephone circuit at harmonic n

The distance between the transmission line conductors is generally small compared to the distance to the telephone lines, and consequently the mutual impedance is nearly identical for each conductor. In such cases the induced voltage due to balanced (positive or negative sequence) components of the transmission line currents is comparatively low, compared to the residual component, due to the cancellation of the individual conductor contributions.

Modern telephone systems generally still use cables to transmit the electric signal from the communication centre to the subscribers. Such a cable consists of many twisted metallic conductor pairs protected by a shield. One pair is usually assigned to an individual subscriber. Cables may also be used to transmit information between communication centres. The harmonic voltage is induced on each conductor of a pair *along* the exposed section and is therefore called the *longitudinal voltage*. For these pairs, the resulting interference voltage, which is applied to the telephone set, is the *difference* between the longitudinal voltages of each conductor of the pair and is known the *transverse voltage* or *metallic mode voltage*. The ratio between the longitudinal and resulting transverse voltages is called the *balance* of the circuit.

The two main characteristics of the telephone system which contribute to reduce telephone interference are the shielding and the balance. The mechanical shield also acts as an electromagnetic shield and is very effective at higher frequencies. The balance depends on the earth capacitance unbalances of cables and the terminal equipment unbalances and therefore worsens with increasing frequency. The telephone companies are responsible for maintaining their telephone system in good condition and usually meet certain minimum standards on balance and shielding.

Open-wire communication systems are still in operation in many locations. These systems are very similar to cable systems except that there is no shield and consequently no shielding effect, and their balance is generally lower.

The sensitivity of the human ear varies with frequency and standard weighting curves have been developed to reflect this frequency dependence of the ear, the response of the telephone receiver and other factors, and so to establish the effective noise level of the individual harmonics. In countries following European practice, *psophometric weighting* is commonly used, while the *C-message weighting* curve is more in use in countries following North American practice, the difference between the two being quite slight. Figure A3.1 shows the two curves.

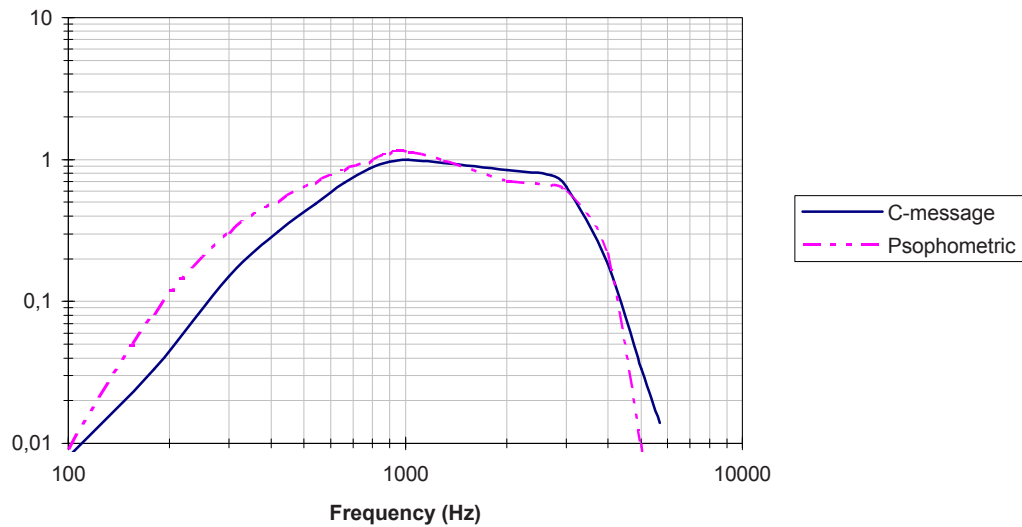


Figure A3.1
C-message and psophometric weighting factors

Using these weighting factors, the total weighted metallic noise level is given by :

$$V_m = \sqrt{\sum_{n=1}^{n=N} (V_{cn} \cdot K_n \cdot B_n \cdot C_n)^2} \quad (3-7)$$

where :

- V_m is the metallic mode weighted voltage
- V_{cn} is the longitudinal induced voltage
- N is the maximum order of harmonic to be considered
- C_n is the psophometric or the C-message weighting factor of harmonic n
- K_n is the telephone circuit shielding factor at harmonic n
- B_n is the telephone circuit balance at harmonic n

The CCITT [Ref. 3-24] has specified the acceptable e.m.f. level of the noise at the line terminals of the subscriber's set to be a maximum of 1 mV.

Within ANSI/IEEE, the circuit noise is defined relative to 1 picowatt in 600 ohms, i.e., relative to an applied voltage of 24.5 μ V, and is expressed in dB above this level. The communication industry has determined performance thresholds for metallic mode C-message weighted noise on normal business or residential lines. A noise level of 20 dBrc (0.245 mV) is considered fully acceptable, however 30 dBrc (0.775 mV) is considered unacceptable in most cases. Higher noise levels are generally accepted for open-wire systems.

All the relevant information on the telephone system, including the route of the telephone lines, should be requested from the telephone company at an early stage of the project. References [Ref. 3-2, 3-3, 3-4, 3-24] describe the whole inductive co-ordination process with many of the details. Even though some of these references concern the d.c. transmission lines, the process is the same for both cases. These references also describe the concept of the equivalent disturbing current as a simplified method to calculate the total weighted metallic noise level in telephone lines and to specify telephone interference limits. This method is recommended for the specification of telephone interference limits for HVDC systems. It is therefore possible, for any HVDC project, to calculate the telephone interference level for each exposure with acceptable accuracy and to assess the extent of telephone interference influence related to a particular specified limit.

Appendix 3.4

Definition of telephone interference parameters

The definitions of the most commonly used telephone interference performance criteria are given below, together with typical values of performance limits. The criteria are presented in two main categories; the ones which are commonly in use in countries following European practice and those which are commonly in use in countries following North American practice.

Criteria according to European practice

v **Telephone harmonic form factor, THFF :**

$$THFF = \sqrt{\sum_{n=1}^{n=N} \left(\frac{U_n}{U} \cdot F_n \right)^2} \quad (3-8)$$

where:

U_n is the component at harmonic n of the disturbing voltage
 N is the maximum harmonic number to be considered

U is the line to neutral total rms voltage and calculated by $U = \sqrt{\sum_{n=1}^{n=N} U_n^2}$

$F_n = p_n n f_o / 800$
 p_n is psophometric weighting factor
 f_o is fundamental frequency (50 Hz).

The required limit of THFF for HVDC schemes is typically around 1%.

v **Equivalent disturbing current I_p** is defined , according to CCITT, by :

$$I_p = \frac{1}{p_{800}} \cdot \sqrt{\sum_f (h_f \cdot p_f \cdot I_f)^2} \quad (3-9)$$

where :

I_f is the component at frequency f of the current causing the disturbance
 p_f is the psophometric weighting factor at frequency f
 h_f is a factor which is function of frequency and which takes into account the type of coupling between the lines concerned. By convention $h_{800} = 1$.

For practical cases, the preceding formula can be expressed as two components, the balanced and the residual equivalent disturbing currents of a three phase line, in the following way :

balanced component:
$$I_{pe} = \frac{1}{16} \cdot \sqrt{\sum_{n=1}^{n=N} (n \cdot p_n \cdot I_n)^2} \quad (3-10)$$

where :

I_n is the balanced component of the current in the phase conductors at harmonic n
 n is the harmonic order
 N is the maximum harmonic number to be considered
 h_f is set equal to $f/800$ Hz and is accordingly replaced by $n/16$ in the above equation.
 This frequency weighting is suitable for interference caused by earth capacitance unbalance of the telephone cable.

and :

$$\text{residual component : } I_{rpe} = \frac{1}{16} \cdot \sqrt{\sum_{n=1}^{n=N} (n \cdot p_n \cdot I_{rn})^2} \quad (3-11)$$

where :

I_{rn} is the residual current (sum of the zero phase-sequence components) at harmonic n

The equivalent disturbing current has been used for few projects but there is no published information on specified limits. However reference [Ref. 3-4] provides some indicative figures for a typical transmission line, based on the Finnish experience. The figures are :

$$7 \text{ A} < I_{pe} < 20 \text{ A}$$

$$1 \text{ A} < I_{rpe} < 3 \text{ A}$$

Criteria according to North American practice

v Telephone interference factor, TIF :

$$TIF = \frac{\sqrt{\sum_{n=1}^{n=N} (U_n W_n)^2}}{U_1} \quad (3-12)$$

where :

U_n is the single frequency rms voltage at harmonic n
 N is the maximum harmonic number to be considered
 U_1 is the fundamental line to neutral voltage (rms)
 $W_n = C_n 5 n f_0$ is the single frequency TIF weighting at harmonic n
 C_n is the C-message weighting factor
 n is the harmonic order
 f_0 is the fundamental frequency (60 Hz)

The strict definition of TIF uses the line to neutral total rms voltage in the denominator, but the above definition is widely used in the HVDC field for specification of performance requirements for AC filters. The error introduced by using the fundamental voltage in the denominator is very small for typical values of THD in HV and EHV power systems.

Typical requirements of TIF are between 15 and 50.

v IT product :

$$IT = \sqrt{\sum_{n=1}^{n=N} (I_n W_n)^2} \quad (3-13)$$

where :

I_n is the single frequency rms current at harmonic n
 N is the maximum harmonic number to be considered
 $W_n = C_n 5 n f_0$ is the single frequency TIF weighting at harmonic n

Typical requirements of IT are between 15,000 and 50,000 at the HVDC converter station a.c. bus.

v **Equivalent disturbing current :**

$$I_{eq} = \sqrt{\sum_{n=1}^N (H_n \cdot C_n \cdot I_n)^2} \quad (3-14)$$

where :

I_n	is the effective disturbing current at harmonic n (generally corresponding to residual mode current)
N	is the maximum harmonic number to be considered
C_n	is the C-message weighting factor
H_n	is the weighting factor normalised to reference frequency (1000 Hz) that accounts for the frequency dependence of mutual coupling, shielding and communication circuit balance at harmonic n

Where the balanced mode harmonic currents are expected to contribute significantly to the induced noise, they must be included in the calculation of I_{eq} . The effective disturbing current is then specified as :

$$I_n = \sqrt{(I_{rn})^2 + (K_b \cdot I_{bn})^2} \quad (3-15)$$

where :

I_{rn}	is the total residual mode current at harmonic n
I_{bn}	is the balanced mode current at harmonic n
K_b	is the ratio of balanced mode coupling to the residual mode coupling at reference frequency

The equivalent disturbing current has rarely been used as telephone interference requirement for an a.c. line feeding an HVDC system. In one instance of its application, limit values in the range 150 - 800 mA were specified. The equivalent disturbing current concept has also been used for d.c. transmission lines for which past experience has indicated that values in the 0.1 to 1.0A range are typical for normal operation.

Discussion:

The American and European definitions are very similar. Indeed, the C-message and psophometric weighting factors of Figure A3.1 are nearly identical. Except for these factors, the TIF and THFF differ only by a constant ratio of 4000 (that is, $5 n f_0$ versus $n f_0 / 800$).

Similarly, the American I_{eq} concept is a variation of the European I_p where the reference frequency and the weighting factor are changed to the American standard. The IT can be considered as a special case of I_{eq} for which the H_n factor is linear with frequency and normalised at 1000 Hz. For this special case, the ratio between IT and I_{eq} is 5000.

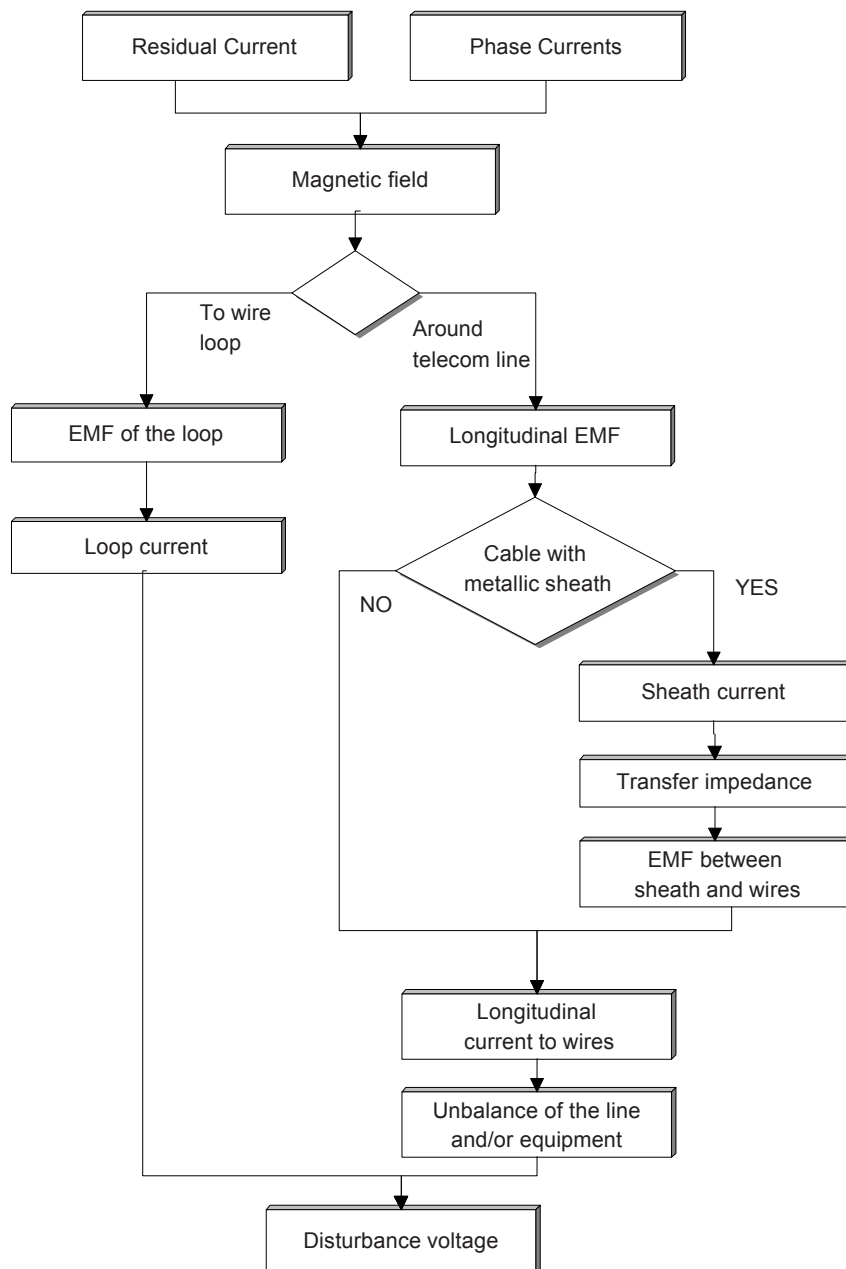
The linear frequency dependence assumption for H_n is generally considered adequate for standard telephone cable systems and typical exposure characteristics. However the IT concept is conventionally calculated with balanced mode harmonic currents only. The I_{eq} concept has the advantage of considering both balanced modes and residual mode induction and may be set to fit the needs of a particular project, where the linear frequency dependency assumption is not considered valid (due to high soil resistivity for example), by defining a H_n factor which reflects the particular project characteristics [Ref. 3-2, 3-3].

The TIF and THFF factors are dimensionless quantities that are indicative of the waveform distortion and not the absolute amplitude.

The definitions of TIF and THFF above, are as stated in [Ref. 3-6] and use as a reference the *total voltage* derived as the root-mean-square sum of the fundamental and all harmonics. However, most HVDC Technical Specifications use instead the *nominal fundamental frequency* voltage, or the *actual fundamental frequency voltage relevant to the operating conditions*. Whichever is intended to be used should be stated clearly, for the reasons discussed in Section 3.2.2

The maximum harmonic order to consider for the calculation should be higher than that for the calculation of harmonic voltage distortion because of the relative weight of the higher harmonic orders and the coupling characteristics. Theoretically, up to 5000 Hz should be considered but in practice many technical specifications have asked for only up to the 50th harmonic (see Section 12.2.2)

Appendix 3.5
The coupling mechanism from power-line current to telephone disturbance voltage.



4. HARMONIC GENERATION

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Appendix 4.1 Formula for calculating the characteristic harmonics of a 12-pulse converter

4.1 General

The design of the a.c. filters requires a knowledge of the harmonic currents which are generated by the converters. These currents must be calculated by the Contractor, using his knowledge of the converter equipment and its interaction with the connected a.c. and d.c. systems.

The information to be included in the Technical Specification regarding harmonic generation will depend on the overall division of responsibility between Customer and Contractor, as discussed in Section 2. If the performance of the a.c. 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 must be clearly expressed in the Technical Specification. Important aspects to include are indicated below.

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

4.2 Converter harmonic generation

4.2.1 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 d.c. current and a sinusoidal balanced a.c. voltage.

Idealized phase current waveforms on the a.c. side of converter transformers of a line-commutated 12-pulse bridge are shown in Figure 4.1. 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 [Ref. 4-1, 4-2, 4-3, 4-4, 4-5]. One such formula is given in Appendix 4.1.

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,.. $(12k-6) \pm 1$.

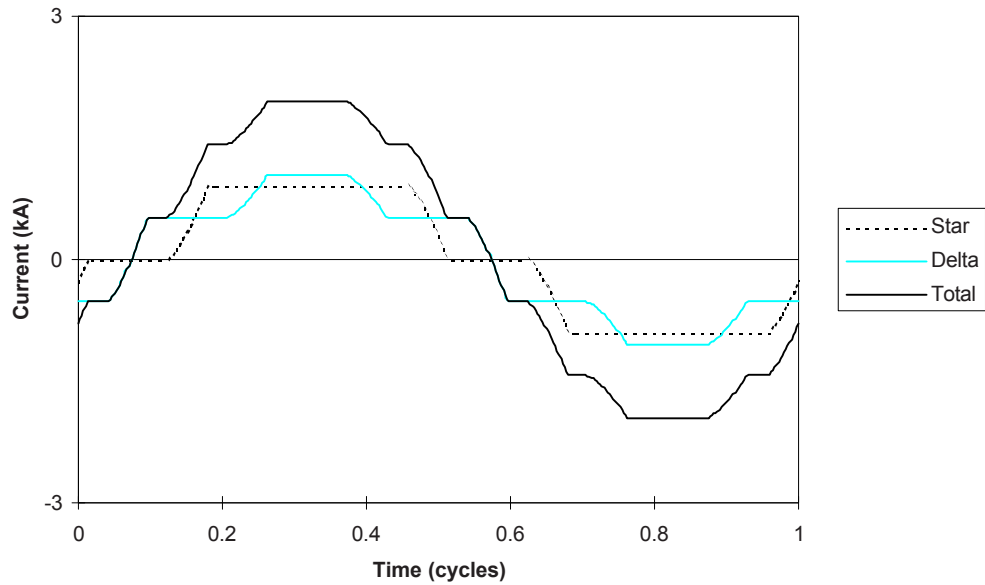


Figure 4.1

Idealized current waveforms on the a.c. side of converter transformer

Parameters:
 $f = 50$ Hz
 $U_{ac} = 230$ kV
 $U_d = 500$ kV
 $I_d = 1000$ A
 $X_l = 14\%$
 $\alpha = 15^\circ$

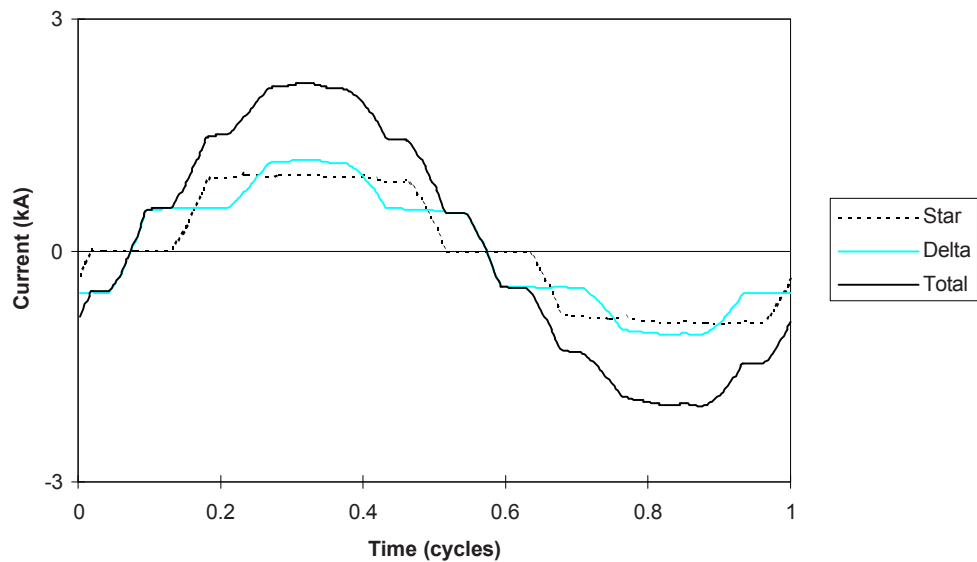


Figure 4.2

Realistic current waveforms on the a.c. side of converter transformer including effect of non-idealities

As above but with:
 1% negative sequence fundamental voltage
 1% second harmonic positive sequence voltage
 5% (of X_l) leakage reactance unbalance between phases
 ± 0.5 degree firing unbalance between star and delta groups
 50 Hz and 100 Hz components in d.c. side current

The idealized current waveforms shown in Figure 4.1 are created by the transfer of d.c. 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 d.c. current is kept constant at any given d.c. 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 a.c. side impedance, the converter is often treated as a harmonic current source in harmonic analysis.

4.2.2 Realistic conditions

The magnitude of the characteristic harmonics of the idealized waveforms described above is influenced by only the applied a.c. voltage magnitude, d.c. 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 d.c. current,
- harmonics in the a.c. voltage,
- unbalance, i.e. fundamental frequency negative sequence component, in the a.c. 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 a.c. voltages of the star-star and the star-delta valve groups due to differences in the converter transformer turns 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 d.c. current, average firing angle, average commutating reactance, are deterministic. Others, such as variations in firing angles to each thyristor valve and harmonic distortion on the a.c. buses, exhibit an almost random characteristic.

A more realistic presentation, including the influence of the above factors, of phase current waveforms on the a.c. side of the converter transformers is shown in Figure 4.2.

Figure 4.3 compares the harmonic content of Figure 4.2 and the idealized harmonic content of Figure 4.1, 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 [Ref. 4-4, 4-6, 4-7, 4-8, 4-9, 4-10, 4-11, 4-12, 4-13, 4-14, 4-15, 4-16, 4-17].

Some of the listed factors have a non-linear influence on the harmonic content in the resultant a.c. 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. A discussion of the relative impact of the above factors is included in Reference [4-6].

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 must 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.

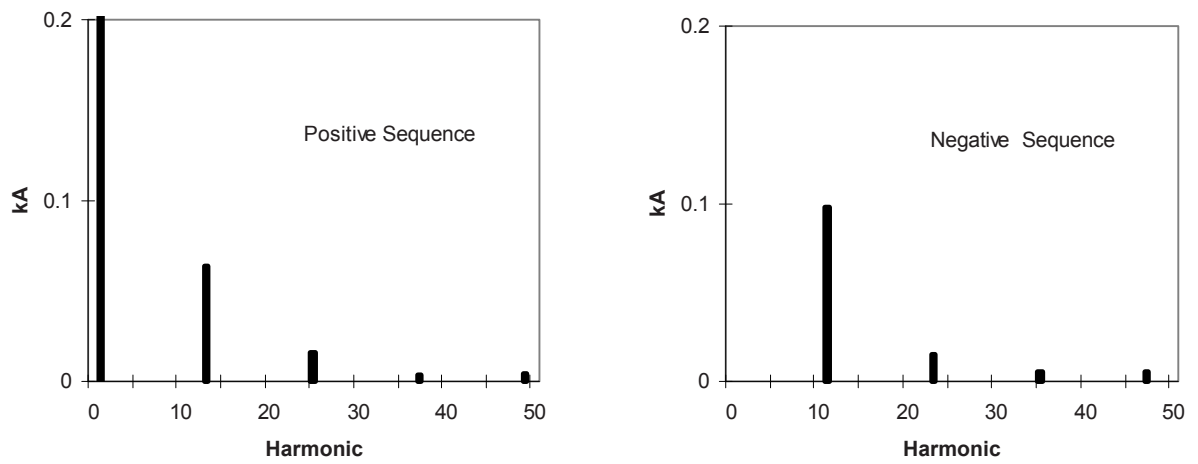


Figure 4.3 (a)
Harmonic content of current waveform in Figure 4.1 (idealized conditions)

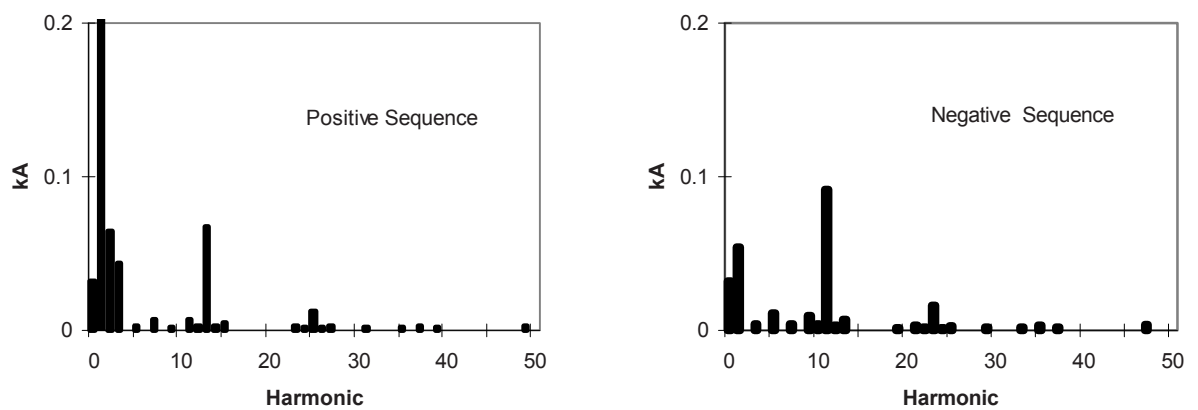


Figure 4.3 (b)
Harmonic content of current waveform in Figure 4.2 (realistic conditions)

4.3 Calculation methodology

4.3.1 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 Technical 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 must be taken into account.

In particular, the Technical 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 must 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. This aspect is discussed in depth in Section 5.

4.3.2 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 Technical 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 a.c. network voltage variation,
- the range of a.c. frequency variations, both steady-state and transient (this has a relatively minor impact, affecting only the commutating reactance),
- level of a.c. 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 a.c. bus voltage or at any operating point within the specified voltage range,
- the time for which certain conditions can exist (e.g. conditions which persist for less than say 1 minute to be disregarded for performance calculations).