

High-voltage direct current (HVDC) systems — Guidebook to the specification and design evaluation of A.C. filters

National foreword

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TECHNICAL REPORT



High-voltage direct current (HVDC) systems – Guidebook to the specification and design evaluation of A.C. filters

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ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS –
GUIDEBOOK TO THE SPECIFICATION AND
DESIGN EVALUATION OF A.C. FILTERS**

FOREWORD

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IEC 62001, which is a technical report, has been prepared by subcommittee 22F: Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment.

This technical report cancels and replaces IEC/PAS 62001 published in 2004. This first edition constitutes a technical revision.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
22F/180/DTR	22F/191/RVC

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

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

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

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- withdrawn,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

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

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

HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS – GUIDEBOOK TO THE SPECIFICATION AND DESIGN EVALUATION OF A.C. FILTERS

1 Scope

This technical report deals with the specification and design evaluation of a.c. side harmonic performance and a.c. side filters for high-voltage direct current (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.

The scope of this technical report 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 Power Line Carrier (PLC) and radio interference spectra.

The bulk of the document 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 Clause 20. Other unusual applications, such as series filters, which use conventional technology but are only employed in very specific circumstances, are discussed in Clause 13.

The term “technical report” or “report” used in this document 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 report defines the technical basis for a contract between two parties, who in this document 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.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60076-6:2007, *Power transformers – Part 6: Reactors*

IEC 60099-4:2004, *Surge arresters – Part 4: Metal-oxide surge arresters without gaps for a.c. systems*

IEC/TR 61000-3-6, *Electromagnetic compatibility (EMC) – Part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems*

IEC 61000-4-7, *Electromagnetic compatibility (EMC) – Part 4-7: Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto*

IEC 61803:1999, *Determination of power losses in high-voltage direct current (HVDC) converter stations*

3 Outline of specifications of a.c. filters for HVDC systems

3.1 General

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. AC 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 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 % to 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 (see IEC/TR 60919-1 (2005), IEC/TR 60919-2 (2008), IEC/TR 60919-3 and [65, 66, 68])¹⁾ 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.

1) The figures in square brackets refer to the Bibliography.

In general, this technical report 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 the majority of HVDC schemes to date. The discussions herein of aspects such as provision of technical information, allocation of risks and so on therefore apply principally to such an all-inclusive approach. If the alternative approach of specifying and purchasing equipment item by item were adopted, then these aspects of the document would have to be reconsidered in the context of the particular scheme, although the purely technical content of the document would still be applicable.

Most 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 Annex A.

3.2 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.
- It is unlikely that there is 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

technical report 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. It is to be:

- a demonstration by calculation of performance parameters, using the specified data,

or

- a 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.

3.3 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.

3.4 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.

3.5 Technical data to be supplied by contractor

At the tender stage of an HVDC project, the bidders are normally required to supply technical data regarding their proposed designs to the customer. This data is used by the customer in order to qualify the proposed design technically and to allow comparisons to be made between competing bidders. The 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.

3.6 Alternative proposals by bidders

The customer should recognise that bidders for an HVDC project will have accumulated an extensive 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.

4 Permissible distortion units

4.1 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 described below.

- 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 clause attempts to provide the background information necessary, and to give recommendations on the different approaches available to the customer.

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

However, due to:

- the powerful calculation tools now available,
- the recent refinements in harmonic influence assessment methods as it is stated in IEC/TR 61000-3-6 (2008) and in [40, 41],
- 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 clause 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 high voltage (HV) and extra-high voltage (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 subclauses and annexes.

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.

4.2 Voltage distortion

4.2.1 General

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

4.2.2 Voltage distortion – Definitions of performance criteria

Individual harmonic distortion, D_n (in %):

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

where

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

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

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

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

where

N is the maximum harmonic order considered.

Total arithmetic harmonic distortion, D :

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

4.2.3 Voltage distortion – Discussion and recommendations

The individual (D_n) and total harmonic distortion (THD) are widely accepted indices of voltage distortion in a.c. networks, while the total arithmetic harmonic distortion (D) is controversial, even though it has been used in a number of HVDC schemes [42, 43], 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 *Permissible Distortion Limits Section 3* accepted within IEC (see IEC/TR 61000-3-6 (2008) and IEEE [58]) and is therefore the criterion recommended in this technical report.

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 13.2.2).

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 8.1.6 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.

4.2.4 Voltage distortion – Determination of limits

4.2.4.1 General

Most major utilities have their own harmonic standards including rules to control the harmonic emission from individual disturbing loads. Generally, the setting of these standards has to a considerable degree been influenced by experience gained with a range of harmonic induced problems and the measures taken to resolve them. They therefore tend to be empirical and conservative in form as they are rarely based on a detailed study and understanding of system behaviour. Where a large HVDC installation is planned, 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.

4.2.4.2 Voltage distortion – Determination of limits without detailed studies

One way to guide the determination of the voltage distortion limits is to refer to existing schemes for which acceptable performance has been experienced. The following ranges of specified limits were taken from CIGRÉ surveys [42, 43] 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. AC filter installations designed according to these limits have generally performed satisfactorily. But, without detailed studies, engineering judgement has to be exercised in order to adapt the limits set for other projects to the specific characteristics of the 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 [42, 43] 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.

4.2.4.3 Voltage distortion – Determination of limits with detailed studies

Determining suitable distortion limits by means of detailed studies requires more work at the specification stage but is likely to result in a cheaper 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.

CIGRE has published a technical paper on limitation of harmonic distortion for MV and HV power systems [44] based on electromagnetic compatibility. Clause B.1 of this technical report summarises the basic principles and concepts outlined in the CIGRE 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.

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

- the determination (by calculation) of the ratio of the harmonic voltage at the point of connection to the harmonic voltage at the main HV, MV or LV substations in the area. This should be done over the whole frequency range considered and for all anticipated normal network configurations and load levels. The harmonic penetration depth into the network is likely to be frequency dependent as discussed earlier;
- the measurement of actual harmonic voltage levels at the point of connection and at the main HV, MV or LV substations in the area (see 4.2.4 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 [44] can be adopted.

Reference [44] 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 megavolt-amperes (MVA) rating of the installation and the network supply capability at the point of common coupling.

The method described in [44] takes into account the presence of important disturbing installations in the vicinity of the considered substation and gives summation coefficients dependent on the harmonic order for computation of total harmonic levels. It also gives some guidelines for application in practical situations (pre-existing level, unrealistically low emission limits, etc.). The harmonic load flow studies should also try to identify amplification or resonance situations which may cause remote harmonic voltage problems that are not evident at the HVDC connection bus. These remote effects are controlled by applying appropriate coefficients for the particular harmonics in the individual emission limits applied at the HVDC connection bus.

The indicative values of planning levels for harmonic voltage given in Clause B.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 B.3 in order to keep an equivalent contribution for the HV or EHV levels to the LV and MV compatibility levels shown in Table B.2.

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.

4.2.5 Voltage distortion – Pre-existing harmonic levels

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

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

Harmonic measurements in the area of the HVDC system installation will indicate the aggregate harmonic levels produced by all sources, both within the HV and EHV system and coming from the MV and LV systems. Analysis of the measurement results combined with the simulation results will be helpful to segregate the two contributions. Indeed, the pre-existing harmonic contributions from all the individual distorting loads in LV and MV systems and other unknown sources cannot be assessed easily otherwise. The planning levels proposed in Clause B.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 B.3, 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.

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. 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.

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

For unusual conditions during short periods of time (less than 1 h), the IEEE 519-1992 [58] recommends that the limits may be exceeded by 50 %.

IEC/TR 61000-3-6 (2008) 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 519-1992. These may be associated with specific harmonic impedance loci.

4.2.7 Treatment of interharmonic frequencies

In the case of an HVDC link connecting two 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 Hz and 60 Hz, or may be nominally identical but differ at times by up to 1 Hz or 2 Hz).

This additional generated distortion will be at frequencies which are harmonics of the fundamental frequency of the remote a.c. system, and will be transferred across the link by the mechanisms described in Clause 6. This transfer may be thought of as harmonic penetration or transition from one 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.

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 60 Hz system.

Of interest here is how the distortion effects resulting from such interharmonics should be taken into account in the performance criteria. If the various formulae for definition of harmonic performance, as given in this clause, 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 [58].

IEC/TR 61000-2-1 (1990) [26] discusses interharmonic sources and some possible effects. IEC/TR 61000-3-6 (2008) 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 inter-harmonic distortion. This may be by modification of the various specified definitions of harmonic performance criteria to encompass significant interharmonics generated by the converter, or by a specific interharmonic limit which may need to be related to preventing interference with ripple control equipment or to control of flicker.

4.3 Distortion limits pertaining to the HV and EHV network equipment

4.3.1 HVAC transmission system equipment

Setting harmonic emission limits as described above to meet the compatibility requirements in the network will usually also ensure a safe harmonic level for the HV and EHV network equipment. However, when very relaxed limits may otherwise be permissible, 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 [62] which defines the maximum acceptable RSS of the 3rd, 5th and 7th harmonics at buses where transformers are connected.

4.3.2 Harmonic currents in synchronous machines

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

One way to specify the filter requirements to control the possibility of overheating is to require that the equivalent negative phase sequence component I_{2eq} (as defined in Clause B.2) of the harmonic current flowing in the machine, together with the expected level of actual negative sequence current, be less than the negative phase sequence component operating capability of the machine as specified by IEC 60034-1 (2004) [1] 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 casings.

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 (IEC/TR 60919-3 (2009)).

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.

4.3.3 Nearby HVDC installations

An existing HVDC system in the vicinity of the new HVDC installation should be reviewed. Such an HVDC system was most probably designed without sufficient allowance for such a new installation. The presence of the new HVDC station will affect significantly the network impedance seen from the existing installation and constitutes a new harmonic source. In this situation, the design report of the existing installation, including all the HVDC system data and design assumptions, 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.

4.4 Telephone interference

4.4.1 General

Telephone interference is a common concern related to the harmonic distortion produced by HVDC systems. A survey [43] 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 subclause reviews the most common criteria used to define limits of telephone interference for HVDC systems, with typical criteria ranges, and gives some guidelines for the determination of limits.

4.4.2 Causes of telephone interference

Clause B.3 provides a brief overview of the basic telephone interference mechanism, sufficient to understand the recommendations of this technical report. A flow-chart describing the process is also shown in Clause B.5. More detailed information is available in references [40, 41].

4.4.3 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 Clause B.4, which also gives indicative values used in previous HVDC projects.

4.4.4 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 [44]. 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 [41]. 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 8.1.6 on the system conditions under which telephone interference parameters should be calculated.

4.4.5 Telephone interference – Determination of limits

4.4.5.1 Telephone interference – Determination of limits without detailed studies

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 Clause B.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. 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 subclause. Additional indicative values on balanced IT for HV and EHV transmission lines are provided by the IEEE Standard 519-1992 [58]:

- 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 will probably 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 [43], 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.

4.4.5.2 Telephone interference – Determination of limits with detailed studies

For major HVDC projects or where the telephone interference might be an important concern, it is strongly recommended to perform an inductive co-ordination study. Such a study will likely result in an optimal filter design relative to telephone interference, reduce the overall cost of

the installation and avoid an inadvertent situation with regard to complaints from the telephone companies. The inductive co-ordination process is described in the earlier mentioned references.

The first step involves the calculation of a range of equivalent disturbing current reflecting different levels of telephone interference. The evaluation of such a range will allow the appropriate limits to be specified to the equivalent disturbing level for which the incremental cost of improving the filtering is equal to the incremental saving in mitigation required in the telephone lines. This requires the preliminary estimation of both the cost of mitigation measures and the cost of improved filtering being gathered from telephone companies and HVDC system manufacturers respectively. In practice this data may prove to be difficult to obtain at this stage. Optional design limits, covering a range appropriate to the available cost estimation, could be specified in order to guide selection of the optimal limit by the bidder as part of the design.

An equivalent disturbing current limit can be expressed as a set of I_{eq} values specific to every HV or EHV transmission 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.

4.4.6 Telephone interference – Pre-existing harmonic levels

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

For the reason indicated previously in 4.2.4, measurements within the HV or EHV system 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.

4.4.7 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.

4.5 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.

5 Harmonic generation

5.1 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 Clause 3. 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 clause therefore identifies the important aspects which affect the calculation of harmonic generation.

5.2 Converter harmonic generation

5.2.1 Idealized conditions

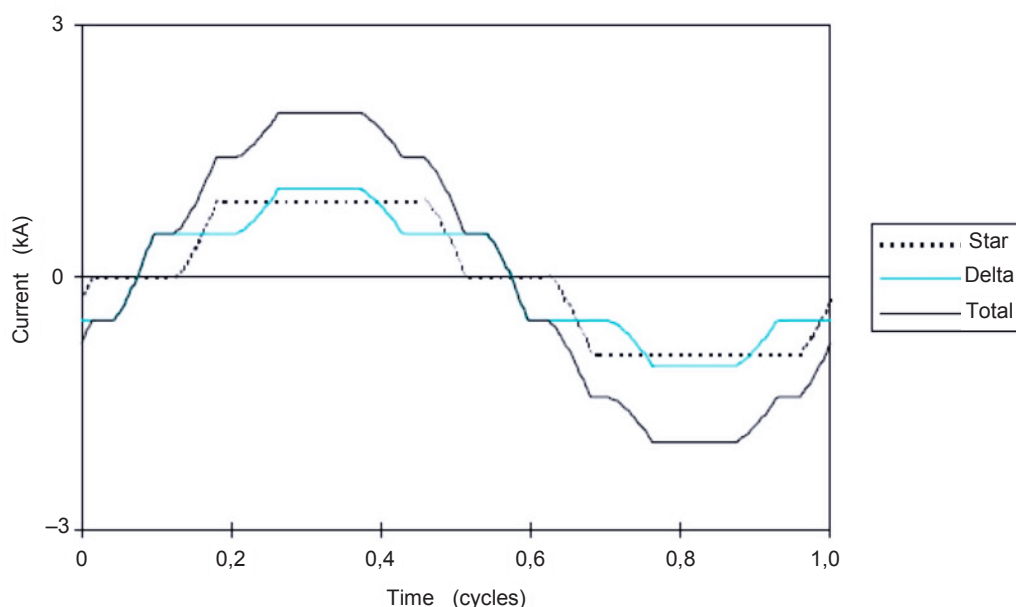
The generation of harmonics is best understood by starting to consider an idealized situation, with no asymmetries in transformer impedances or firing angle between phases, smooth d.c. current and a sinusoidal balanced a.c. voltage.

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

Formulae for the calculation of converter harmonics are readily available in textbooks and standards (IEC/TR 60146-1-2 (1991)). One such formula is given in Annex C.

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

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



IEC 1932/09

Parameters: $F = 50 \text{ Hz}$; $U_{ac} = 230 \text{ kV}$; $U_d = 500 \text{ kV}$; $I_d = 1\,000 \text{ A}$; $X_l = 14 \%$; $\alpha = 15^\circ$

Figure 1 – Idealized current waveforms on the a.c. side of converter transformer

The idealized current waveforms shown in Figure 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.

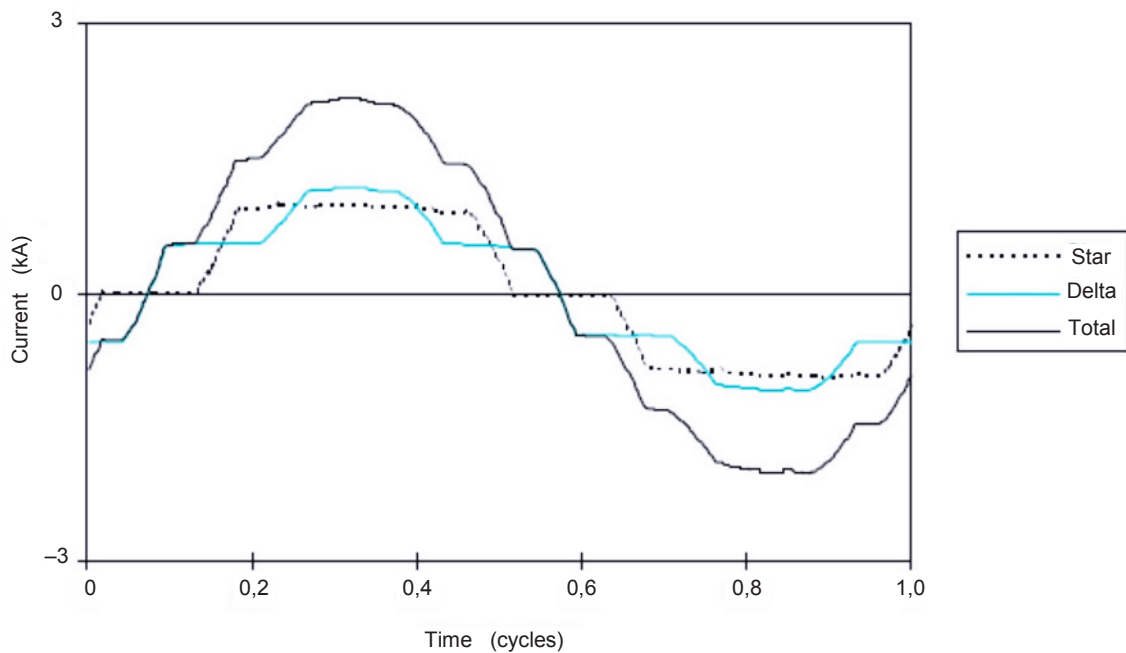
5.2.2 Realistic conditions

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 2.



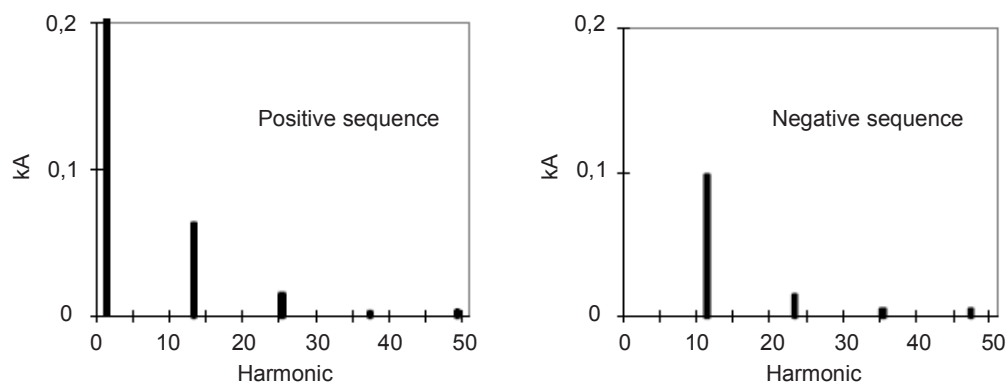
IEC 1933/09

Parameters as in Figure 1 but with:

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

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

Figure 3 compares the harmonic content of Figure 2 and the idealized harmonic content of Figure 1, and shows a small impact on the magnitude of the characteristic harmonics, and the appearance of non-characteristic harmonics of all orders. Non-characteristic harmonics are generated due to non-ideal operating conditions and have been well documented [43].



IEC 1934/09

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

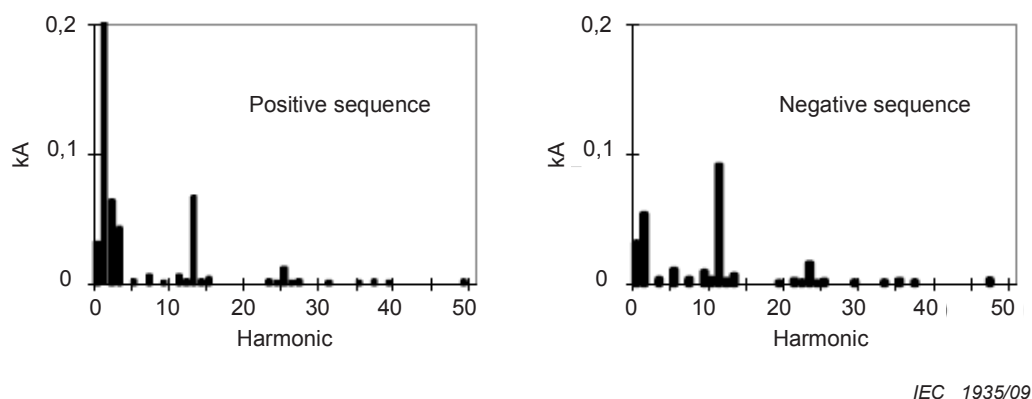


Figure 3b – Harmonic content of current waveform in Figure 2 (realistic conditions)

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

Some of the listed factors have a non-linear influence on the harmonic content in the resultant 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.

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.

5.3 Calculation methodology

5.3.1 General

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

Different methods of calculating harmonic generation may be used by different bidders. For the purposes of bid evaluation, a standard method may be defined in the technical specification if the customer wishes. However, the specification should also leave scope for the bidder to propose, as an alternative, his favored 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 Clause 6.

5.3.2 Harmonic currents for performance, rating and other calculations

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

The 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 min to be disregarded for performance calculations).

Narrower ranges of a.c. voltage or frequency, and less onerous converter operating conditions could be used for performance than for rating, for example. These aspects are discussed in more detail in the appropriate clauses (8, 10, 12 and 16).

5.3.3 Combining harmonics from different converter bridges

The most common multiple source problem is the combination of harmonics from a star-star converter with the harmonics from a star-delta converter. The best approach is to treat the 12-pulse converter as a single entity and compute the harmonics directly for the 12-pulse converter.

However, as the number of variables involved in the calculation of harmonics for a 12-pulse converter is about twice the number involved for a single 6-pulse converter, the number of operating states increases by almost a square function. If, for this reason, direct calculation of the 12-pulse harmonics is not possible with the contractor's calculation method, then the harmonics for the individual converters may be calculated separately, and combined mathematically to obtain a composite set.

For converters in the same pole, the 12-pulse characteristic harmonics and non-characteristic harmonics (excluding the theoretically canceled harmonics) may be calculated as the sum of the largest magnitude of the harmonics of the individual converters. The theoretically cancelled harmonics are calculated as the largest difference in magnitudes of the harmonics of the individual converters. For these it is important to take into account possible manufacturing differences between the two converter types, in particular, the expected variation in the transformer reactance and the expected variation in voltage ratio between the star and delta winding designs. The average firing angle error between the two groups must also be considered.

For converters in separate poles, it is important to take into account the slightly different operating conditions pertaining to the two poles due to d.c. current unbalance between poles.

particularly if extended d.c. neutral current operation is permitted. This will result in differences in magnitude and phase angle between the harmonics generated in the two poles.

In general, with the exception of the treatment of theoretically cancelled harmonics, it is normal to assume that the harmonics from each converter at a bus add arithmetically. This assumption will result in net harmonic currents which are greater than those which can be expected to occur in practice. However, when it can be shown that as part of a consistent set of operating conditions, the phase relationship between harmonics is relatively well defined, it may be advantageous to take account of this relationship in calculating the total harmonics. In particular, if it can be shown that there is a completely random phase displacement between harmonics from two or more sources, then a RSS sum may be considered.

5.3.4 Consistent sets

The terms “consistent” and “non-consistent” sets are frequently used, and often misunderstood. A “consistent set” of harmonic currents consists of harmonics generated at a single, realistically feasible operating condition. Many such consistent sets will be calculated within a typical harmonic generation computer program, considering each of the very many combinations of variables. However, if all the asymmetries of a realistic converter are to be considered, it is clearly impractical to then calculate the filter circuit for each of these many fully consistent sets of harmonics.

A “non-consistent” set is a combination of worst-case harmonic values taken from a range of converter operating conditions, that is, the set of harmonics where the magnitude of any individual harmonic in the set would not be exceeded for any of the possible operating conditions represented by the set. The total harmonic generation represented by a non-consistent set can never occur in reality, but it does eliminate the need to solve the harmonic flow for each of many consistent sets, all of which may be covered by one non-consistent set. The disadvantage is that its use can result in overly pessimistic values of parameters which sum the influence of all harmonics, for example TIF, THD or rating quantities.

An intermediate concept is that of a “quasi-consistent” set. This implies that one or more major variables, such as d.c. current, are in a single state, but that other minor variables, such as commutating reactance and firing angle may be varied within their complete scope.

Alternatively, a non-consistent set could be statistical in nature, that is, the magnitude of selected harmonics in the set could be exceeded for some specified percentage of time. This is not normal procedure, however, and would have to be specifically approved by the customer.

5.3.5 Harmonic generation for different d.c. power ranges

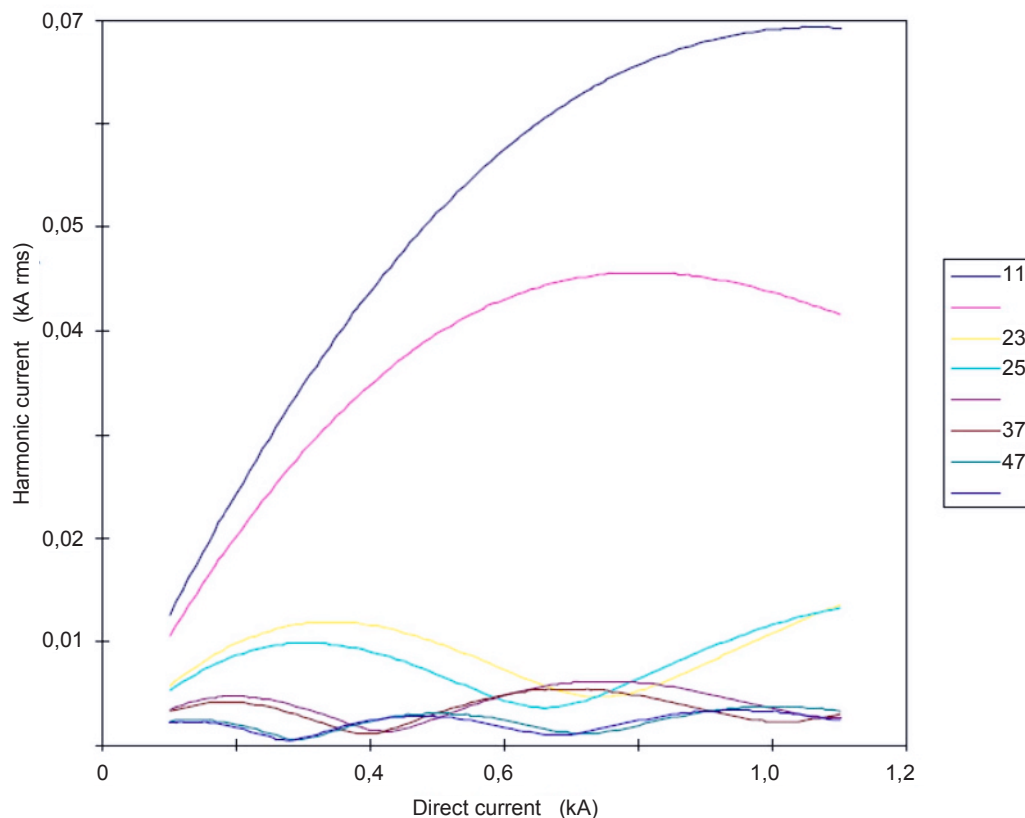
For most HVDC converter stations, as d.c. power transfer increases, additional a.c. filters are connected, both to mitigate the increased harmonic generation and to compensate reactive power. There is, therefore, usually a range of d.c. power for which a given set of a.c. filters may be connected. Within this range, those filters must perform adequately and not suffer overload, and so must be designed for the worst set of harmonic currents which can occur within the given range of d.c. power. It would not however normally be economical to design the filters to deal with harmonic currents corresponding to a higher d.c. power level, as in reality further branches would then be connected, reducing the duty on each filter.

To obtain an economical design, therefore, the harmonic currents must be calculated separately for each angle of power at which a distinct set of a.c. filters may be connected.

As shown in the plots of Figure 4, the magnitude of the generated harmonic currents, particularly at higher orders, can be cyclic and does not increase uni-directionally with d.c. power. Within each d.c. power range therefore the worst-case set of harmonic currents (for performance or for rating) may occur at any level. Most usually, it is at the maximum power within the range, that is just before switching in the next filter branch, as both performance and rating are often dominated by the 11th and 13th harmonics, which increase monotonously for most of the usual power range. However, for say a 24/36th filter, the worst-case harmonic

generation may be at an intermediate point in the d.c. power range, corresponding to a local maximum in the harmonic generation curve.

The filter designer will therefore be required to calculate the harmonic generation at a number of intervals throughout the complete d.c. power range. Initially, quasi-consistent sets of harmonics at steps of say 5 % or 10 % of d.c. power may be adequate, but later in the design process, as filter switching points are determined, the harmonic generation at these specific points must be calculated, and in some cases at finer intervals in between. Conversely, however, some intermediate steps may be eliminated if it becomes clear that the worst case is just before switching-in the next filter.



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Figure 4 – Typical variation of characteristic harmonic magnitude with direct current

Alternatively, to minimize design effort, a non-consistent set of harmonics may be derived by taking the highest value of each harmonic that occurs anywhere in the given power range. This is a cautious approach. If the customer does require non-consistent sets to be used for calculation then this must be stated in the technical specification, but normally there is no reason to do this and the contractor should be allowed to use consistent or quasi-consistent sets if he wishes.

Although d.c. power (or current) range is most usually used to create sets of harmonics, other deterministic factors such as d.c. voltage or firing angle could be used to group the harmonics in other operating modes such as:

- reactive power control using d.c. voltage adjustment,
- reduced voltage operation.

5.4 Sensitivity of harmonic generation to various factors

5.4.1 Direct current, control angle and commutation overlap

The magnitude of the characteristic harmonics produced by the converter are principally dependent on d.c. current, control angle, and commutation overlap. These dependencies are non-linear and cyclic but are well defined. The commutation overlap is itself a function of current, voltage and control angle, as well as the commutating reactance, and so the relationship can be expressed in different ways. Variations of the magnitudes of several characteristic harmonics is shown in Figure 4. The curves are based on the assumption of ideal d.c. current on the d.c. side of the converter and balanced perfectly sinusoidal voltages on the a.c. side of the converter.

As the converter control angle affects the waveshape of the converter current, both directly and through its impact on the overlap angle, it has a very significant influence on the harmonic generation. In general, higher control angles result in higher harmonic generation (although this may not be true in all circumstances, due to consequential impacts on currents and voltages, and cyclical variations of harmonic magnitudes).

If the operation strategy of the converter envisages higher than normal control angles, for reasons of reactive power balance, then these must be taken into account in the calculation of sets of harmonic currents. Such operation may be required at certain times for reasons related to the a.c. system operation (to be requested in the technical specification if required), or may be associated with filter switching points and apply only to certain d.c. power ranges (normally at the discretion of the contractor).

The magnitude of non-characteristic harmonics is also affected by these parameters, as well as by the various asymmetries discussed below.

5.4.2 Effect of asymmetries on characteristic harmonics

The asymmetries which give rise to non-characteristic harmonics do influence the magnitude of the characteristic harmonics for any given operating condition but the effect is of relatively low magnitude. Using the same methods as used for the calculation of non-characteristic harmonics, the worst-case values of the characteristic harmonics under the most pessimistic combination of asymmetries can be calculated. Using these worst-case values for the filter design may lead to slight over dimensioning, if this worst-case combination does not occur in reality. It is however a cautious approach and is recommended. Care must therefore be taken in the wording of the technical specification, so that it is clear that the calculation of characteristic as well as non-characteristic harmonics must take account of all asymmetries.

5.4.3 Converter equipment parameter tolerances

The technical specification should require the contractor to include in the calculation of non-characteristic harmonic currents all possible variations of converter equipment parameters, such as commutating reactance, transformer winding ratios, and firing angle variation.

It is unlikely that firing angle accuracy or transformer winding ratio differences can be improved, and so the filter designer must simply use the actual values.

The commutation reactance unbalance is due to manufacturing tolerance of converter transformer leakage impedance, so that it is a controllable value to some extent. In designing the converter transformers, the contractor may compare the higher cost of the converter transformer caused by tighter manufacturing tolerance with the possible lower cost of the filters caused by lower non-characteristic harmonic currents. Close dialogue with the transformer designer is recommended [26].

5.4.4 Tap steps

The converter transformer tap settings affect the converter voltage, current and control angle, and therefore the harmonic generation. Within a 6-pulse valve group, the tap settings for the three phases normally result in virtually identical voltages for the three phases and so it is not usual to consider any difference among phases when calculating harmonic generation.

Between the star-star and star-delta 6-pulse valve groups, the tap-changers are normally synchronized. There is therefore no impact on harmonic generation, but the technical specification should require that out-of-step protection is installed.

Possible differences in tap setting between the transformers of the two poles of a bipolar HVDC scheme will depend on the operating strategy of the scheme and whether tap-step synchronization between poles is installed. If differences can exist, then the technical specification should require that they are taken into account in the calculation of converter harmonic generation.

5.4.5 Theoretically cancelled harmonics

Sometimes a distinction is made between “theoretically cancelled” and other non-characteristic harmonics. The “theoretically cancelled” harmonics are of orders $5, 7, 17, 19, \dots (12k-6)\pm 1$, that is, harmonics which are characteristic of each 6-pulse valve group but which are mutually cancelled in an idealized 12-pulse converter. In reality, incomplete cancellation occurs due to small differences between the two 6-pulse valve groups.

If non-characteristic harmonics are calculated on a 12-pulse basis using a suitable algorithm, then the worst-case values of the “theoretically cancelled” harmonics will be automatically calculated.

If however, calculation is made on the basis of individual 6-pulse groups, then the technical specification should require that the values of commutating reactance, and control angle deviation used for the two groups should be at the opposite extremes of the feasible ranges, unless the contractor can guarantee that the difference between the mean values of these parameters for the two groups will be less than a certain value. This will ensure that the most pessimistic value of “theoretically cancelled” harmonics is derived.

5.4.6 Negative and zero phase sequence voltages

Negative sequence voltage at the converter a.c. bus results in the introduction of harmonics of order $6k-3$ where k is any positive integer, i.e. harmonics 3, 9, 15 etc. The most significant is the 3rd harmonic. The amount of negative sequence component which is specified for the converter a.c. bus is very important. With a negative sequence voltage of greater than about 1 %, it is possible that the 3rd harmonic current produced by the converter is so high that a very expensive 3rd harmonic filter is required. In some instances it may be more economic to improve the voltage balance in the a.c. system, for example by adding transpositions to circuits, if applicable, than to specify a large voltage unbalance increasing the cost of converter filtering.

As negative phase sequence voltage generally varies over time, rarely reaching its extreme values, it may be acceptable to use a smaller value of negative phase sequence voltage for performance calculations (e.g. 1 %) than for rating (e.g. 2 %). This should be carefully considered by the customer when preparing the technical specification, as the implications for cost of a 3rd harmonic filter could be considerable.

It should be noted that if a converter station is connected electrically close to a generating station, then the negative sequence voltage at that point should be considerably lower than is assumed throughout the rest of the system. This may eliminate the need for a third harmonic filter, and so the technical specification should consider this aspect carefully.

As zero sequence voltage is not transferred through the converter transformer (due to the unearthed star or delta thyristor valve winding connection), zero sequence voltages at the converter a.c. bus do not directly influence the generation of non-characteristic harmonics.

5.4.7 Converter transformer saturation

For long distance transmission systems, fundamental frequency currents on the d.c. system induced from parallel a.c. transmission are important, and cross the converter to give a.c. side direct current and positive sequence second harmonic. Both of these can result in d.c. current flow in the valve winding of the converter transformer. The resultant shift towards single sided saturation results in the generation of a broad spectrum of harmonics in the magnetizing current on the a.c. side of the converter transformer. Also d.c. or extremely low frequency current flow through the neutral of the transformers resulting from stray d.c. current from nearby electrodes or possibly geo-magnetically induced currents can result in a similar shift in magnetizing characteristics and increased harmonic generation.

The technical specification should require that the contractor be responsible for calculating any such harmonic currents from the converter transformer due to any of the causes stated, and should take account of such harmonics in the a.c. filter design.

5.4.8 Harmonic interaction across the converter

Due to harmonic interaction across the converter, positive or negative sequence harmonic voltages at the converter a.c. bus result in the generation of non-characteristic harmonic currents at two harmonics down or two harmonics up. For example a 4th harmonic positive sequence voltage at the converter will result in the generation of 2nd harmonic negative sequence currents. Similarly a 4th harmonic negative sequence voltage will result in the generation of 6th harmonic positive sequence currents. Currents at additional harmonics are also present but the magnitudes are less than these dominant harmonics. The effects above are cumulative; i.e., the presence of one harmonic on the a.c. side results in a harmonic on the d.c. side which in turn may result in another harmonic on the a.c. side.

A further factor which must be taken into account is harmonic current, or ripple, on the d.c. side. Harmonic currents on the d.c. side are transferred to the a.c. side as two harmonics, namely, a positive sequence harmonic one harmonic up from the d.c. side harmonic and a negative sequence harmonic, one harmonic down. Ripple in the d.c. current normally consists of harmonics of order $12k$, where $k=1,2,..$ plus possibly the second harmonic.

The harmonic current flow on the d.c. side is normally under the control of the contractor. However, under situations where the specification is being prepared for a single converter, then the technical specification must specify the harmonics present in the d.c. current waveform due to the remote converter.

Harmonic interaction across the converter is analyzed and discussed in detail in Clause 6.

5.4.9 Back-to-back systems

A special case of harmonic interaction across the converter (see also Clause 6) occurs in back-to-back HVDC systems [49]. In back-to-back systems, particularly those with low values of smoothing reactance, d.c. side harmonics are an important consideration. Back-to-back systems with low reactance or no smoothing reactors can introduce harmonics of one a.c. system frequency into the other. If the fundamental frequencies of the two a.c. systems are the same, then harmonics due to the remote system can add or subtract from the harmonics due to the adjacent system, depending on the difference in phase angles of the two converter a.c. bus voltages. To establish a single set of harmonics which take into account both effects, it is often assumed that the harmonic phase displacement exhibits a random characteristic and an RSS sum of the harmonics may be considered to be appropriate for performance type calculations. For rating considerations, the pessimistic assumption is often made that the two frequencies are identical and result in harmonics which are in phase. In this case, the magnitude of the harmonics would be added arithmetically to obtain an equivalent current.

When the fundamental frequencies of the two a.c. systems are not the same, then currents can be generated at frequencies which are not harmonics of the adjacent system frequency. Although the frequencies are not harmonics, they must still be considered in the filter design.

A further possible source of interaction has been observed on at least one existing back-to-back scheme. If the a.c. lines connected to the two sides of a back-to-back converter station share the same tower or route for a significant distance, then inductive coupling will occur, resulting in the presence of non-synchronous harmonics in both a.c. systems, or interharmonics if the frequencies of the two systems are not identical.

5.5 Externally generated harmonics

The filter design must take into account other harmonic sources both within the station and external to the station.

Within the station, one possible additional harmonic source would be controllable reactive compensation equipment, such as a static VAR² compensator (SVC) (even if it has its own filters). The technical specification should require that any such source is to be taken into account when calculating both a.c. filter performance and rating, and design of the filtering for both HVDC and SVC should be co-ordinated.

Outside the station, other harmonic sources such as other HVDC converters, SVCs, rectifier type loads, controllable a.c. drives, arc furnaces, power transformers, corona from a.c. lines, consumer equipment etc. can result in a significant harmonic presence. The effect of harmonic sources from outside the station for considerations of filter performance is discussed in 8.1.6. Such sources must be considered for the purpose of filter rating (see 10.2.2). The technical specification must therefore clearly identify such external sources. The customer and contractor should be aware that this is an area where considerable disruption and dispute can occur if a filter is eventually damaged while in operation, due to harmonics generated externally to the converter station.

6 Harmonic interaction across converters

6.1 General

In order to facilitate the analysis of harmonic generation by an HVDC converter, simplifying assumptions are often made. Typically, the HVDC converter is regarded as a generator of harmonic currents, with an infinite internal impedance. Such an assumption is reasonably valid for practical purposes for most harmonics, and is the basis of the calculation methods described in Clause 4.

The customer should be aware however, that such a simplified approach has limitations, and can lead to incorrect analysis and design in some circumstances. In practice, the converter is a link between the a.c. and d.c. side harmonic systems, and the a.c. side harmonic currents may be strongly influenced by the harmonic impedance and harmonic current flows on the d.c. side.

This is particularly true for low-order harmonics, and it is strongly recommended that the analysis of third harmonic distortion and filtering requirements should take into account the a.c./d.c. side harmonic interaction. At the 11th and 13th harmonics, the interaction effect can also be significant. At higher frequencies, although interactions occur, their practical impact on filter design and harmonic performance will normally be negligible.

The following subclauses attempt to give the customer an overview of the interaction phenomena, focusing on practical implications for a.c. filter design. The technical specification should make it clear that such phenomena have to be taken into account, and the customer should be able to address the subject in his evaluation of the bidders' designs.

² VAR = Volt-Ampere Reactive.

A detailed treatment of this subject will be available in a CIGRÉ Technical Brochure [49] prepared by CIGRÉ working group 14-25.

6.2 Interaction phenomena

The a.c. voltage and current wave-forms can be considered to be composed of positive, negative and zero sequence components of the fundamental frequency along with positive, negative and zero sequence components of other frequencies. The d.c. side wave-forms can similarly be expressed as a d.c. component plus a broad spectrum of other frequencies. The conversion process involved in the conventional bridge connected converter establishes a well defined relationship between frequencies on the a.c. side of the converter and frequencies on the d.c. side.

In general the relationship is governed by several simplified rules listed below from a) to d).

- The ungrounded star and delta transformer connections on the valve side of the converter transformers preclude the transfer of zero sequence frequencies from the a.c. side of the converter transformers to the d.c. side. Zero sequence coupling is limited to second order capacitive transfer effects.
- Any given positive sequence frequency greater than fundamental on the a.c. side of the converter is converted to a dominant frequency on the d.c. side which is lower in frequency than the a.c. side frequency by an amount precisely equal to the fundamental frequency of the a.c. side of the converter. For a.c. side positive sequence frequencies less than fundamental, the resultant d.c. side frequency is the complement of the a.c. side frequency.
- Any given negative sequence frequency on the a.c. side of the converter is converted to a dominant frequency on the d.c. side which is greater in frequency than the a.c. side frequency by an amount precisely equal to the fundamental frequency of the a.c. side of the converter.
- Any given frequency on the d.c. side of the converter is converted to two dominant frequencies on the a.c. side. A positive sequence frequency is created which is greater than the d.c. side frequency by an amount precisely equal to the fundamental frequency of the a.c. side of the converter. If the d.c. side frequency is greater than the a.c. side frequency, a negative sequence frequency is also created which is less than the d.c. side frequency by an amount precisely equal to the fundamental frequency of the a.c. system. If the d.c. side frequency is less than the a.c. side fundamental frequency, then instead of a negative sequence frequency, a second positive sequence frequency is generated at a value precisely equal to the a.c. side fundamental frequency less than the d.c. side frequency.

Table 1 provides a summary of the dominant frequencies involved in any interaction.

Table 1 – Dominant frequencies in a.c. – d.c. harmonic interaction

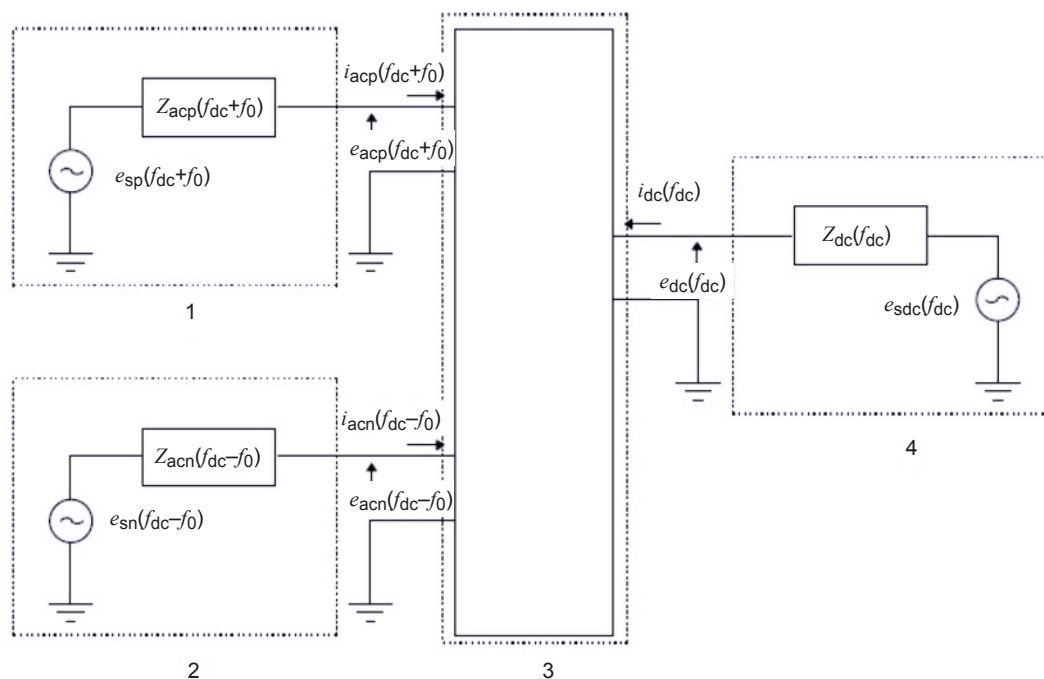
DC side frequency	AC side frequencies	
$f_{dc} > f_o$	$f_{dc} + f_o^a$	$f_{dc} - f_o^b$
$f_{dc} = f_o$	$2f_o^a$	0,0 ^c
$f_{dc} < f_o$	$f_{dc} + f_o^a$	$f_o - f_{dc}^a$
$f_{dc} = 0$	f_o^a	
f_{dc} is the interaction frequency on the d.c. side of the converter. f_o is the fundamental frequency of the a.c. side of the converter.		
^a positive sequence ^b negative sequence ^c d.c.		

The above rules are not limited to just harmonic frequencies but in general can be applied to all frequencies. Other frequencies shifted by multiples of the converter pulse number times fundamental frequency (or their complements) can also be involved in the conversion process but for the most part, their contributions to any given interaction are of second order. The relationships hold for not only steady-state conditions but can also be observed in quasi-steady state conditions as experienced under prolonged unbalance fault conditions, and even transient conditions (any phenomena lasting greater than 1 or 2 cycles.)

6.3 Interaction modeling

6.3.1 General

For any given set of a.c. and d.c. side operating conditions (a.c. voltage, d.c. voltage and current and firing angle), the d.c. converter can essentially be treated as a linear passive device similar to a three winding transformer but which transforms voltages and currents between the three networks (at three different frequencies) involved in any interaction as illustrated in Figure 5. The figure depicts the condition where the d.c. side interaction frequency is greater than the fundamental frequency of a.c. system. Representation of the other conditions is similar with the sequence and frequency of each of the networks established from the table of frequencies shown above.



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Key

- 1 a.c. positive sequence network at frequency $f_{dc} + f_0$
- 2 a.c. negative sequence network at frequency $f_{dc} - f_0$
- 3 transformation matrix transforming voltages and currents at the harmonic frequencies
- 4 d.c. network at frequency f_{dc}

Figure 5 – Equivalent circuit for evaluation of harmonic interaction with d.c. side interaction frequency greater than a.c. side fundamental frequency

The magnitude of voltages and currents which appear in any given interaction are a function of the coupling between the networks, impedances of the a.c. and d.c. networks at the respective frequencies as well as the magnitude of the driving force (or forces) which establishes the frequencies in the first place.

6.3.2 Coupling between networks

The amount of coupling from network to network is a direct function of the d.c. operating conditions and can be quantified in terms of the firing angle and overlap angle. If overlap is not considered in the analysis, the coupling network behaves as an ideal three winding transformer where the 'equivalent turns ratios' are dependent on the firing angle. The harmonic current flow into each of the three networks is a function of the 'equivalent turns ratio' and as such effectively connects each of the two a.c. networks and the d.c. network in series. Inclusion of overlap angle into the analysis is equivalent to adding leakage and magnetizing reactances to the ideal transformer.

6.3.3 Driving forces

Driving forces could originate in the a.c. systems. The driving force could be harmonic in nature resulting from the presence of harmonic generating devices such as other d.c. stations, SVC's, transformer saturation, non-linear loads etc. As well, the driving force could simply be negative sequence fundamental frequency voltage resulting from unbalanced loads in the vicinity of the d.c. converter, heavily loaded untransposed transmission lines feeding the converter or asymmetrical faults and/or 2 phase operation during single pole reclosure.

The driving force could originate in the d.c. converter itself, with harmonic currents and/or voltages driven by firing angle jitter, unbalance in commutating reactances or possibly unbalance in converter transformer turns ratios.

The third source of driving forces includes voltages and currents of the d.c. transmission network either coupled electromagnetically or electrostatically from nearby a.c. transmission or directly coupled as a result of some a.c./d.c. interaction phenomena at the remote converter. For the latter, harmonics of the remote a.c. system frequency would be involved resulting in non-harmonic interaction frequencies at the local station.

6.3.4 System harmonic impedances

The impedance of the three networks at their respective interaction frequencies play an important role in the magnitude of the voltages and currents which can appear at the converters. Series and parallel resonances can occur within each leg of the equivalent network, but also between the three legs. For example an effective series resonance could appear between the positive sequence a.c. network and the d.c. network resulting in large current flow at the respective frequencies between the two networks. To the negative sequence network, the resonance condition could appear as a parallel resonance (with a high impedance). In fact, the current flow in the positive sequence and d.c. networks could be excited by a small voltage in the negative sequence network.

6.4 Impact on a.c. filter design

6.4.1 General

Interaction will influence a.c. filter design only when the resultant harmonics are of a significant magnitude so as to affect either the a.c. filter performance or the a.c. filter rating or both.

Several are known to influence the design of a.c. filters, and are discussed in the following sub-clauses.

6.4.2 AC side third harmonic

One such set of interaction frequencies includes:

- side negative sequence fundamental frequency,
- side second harmonic,
- side positive sequence third harmonic.

The presence of a substantial component of fundamental frequency negative sequence voltage in the commutating bus voltage ($>1-2\%$) will often result in large components of positive sequence third harmonic in the a.c. side waveforms and large second harmonic components in the d.c. waveforms. Considering the two a.c. networks, current flow is limited by the series combination of the negative sequence fundamental frequency impedance and the third harmonic positive sequence impedance. With low values of net effective impedance, and a large negative sequence voltage, the negative sequence current flow and third harmonic current flow could be large. Installing a low impedance shunt connected third harmonic filter to limit the third harmonic flow into the a.c. system could actually exaggerate the amount of current flow, increasing the third harmonic current in the filter to values above the flow without the a.c. filter. This could be further compounded by resonances between the a.c. filter and the a.c. system as discussed in 8.1.6 and 13.2.1.

The second harmonic impedance of the d.c. network could also influence the design of the a.c. side third harmonic filter.

6.4.3 Direct current on the a.c. side

A second set of interaction frequencies affecting the design of filters includes:

- side second harmonic positive sequence,
- side fundamental frequency,
- side valve winding d.c. currents.

Fundamental frequency currents on the d.c. side of the converters can be converted into positive sequence second harmonic and d.c. currents on the a.c. side of the converter. The second harmonic currents are transformed and hence appear in the a.c. network. Although d.c. currents are initially coupled into the a.c. network, with time, the a.c. side currents decay to zero and the d.c. current flow eventually ends up flowing through the magnetizing path of the equivalent circuit of the converter transformer shifting the transformer saturation characteristics. Depending on the magnitude of the shift, one-sided transformer saturation could occur resulting in the generation of second harmonic positive sequence currents due to transformer saturation. These currents could add to the second harmonics coupled by the interaction network exaggerating the current flows in the three networks.

Fundamental frequency blocking filters on the d.c. side and second harmonic shunt connected filters on the a.c. side have been used to limit the interaction effects. The design of the second harmonic filter must take into account not only the direct interaction effects but also the possible amplification resulting from interaction with transformer magnetization.

6.4.4 Characteristic harmonics

Interaction can occur at characteristic frequencies as well as low order non-characteristic frequencies.

Filtering is normally provided for the 11th and 13th harmonics creating a low impedance path in the 13th harmonic positive sequence network as well as the 11th harmonic negative sequence network. If the d.c. side impedance at the 12th harmonic is also small (as can occur on back-to-back schemes with small or no smoothing reactors), coupling can occur between the 11th and 13th networks of both a.c. systems. As a result of the coupling, 11th and 13th harmonics of both a.c. system frequencies could be evident in the respective filter waveforms.

The a.c. filters limit the impact of the interaction to the converters themselves and as a result the interaction is not normally evident in the a.c. system voltage and current waveforms. The

design of the a.c. filters however must recognize the potential for interaction with suitable allowance in the filter performance and rating (see 5.4.9).

6.5 Study methods

6.5.1 Frequency domain

Both the performance and rating calculations for filters have been carried out traditionally using frequency domain analysis and design tools. A network solution of voltages and currents are calculated for each selected harmonic and the weighted voltages and currents for each frequency are combined mathematically to establish some overall performance or rating index. Study of interaction effects requires the expansion of the single frequency network model into a multi-frequency model. The model could be the simple three frequency model described above or could be expanded to include a broad spectrum of frequencies.

With frequency domain analysis, it is possible to focus on the exact nature of a specific interaction. The a.c. system and d.c. side harmonic impedances can be readily varied within a known spread of values to establish if interaction is likely to occur. In the event that interaction can occur, the same procedure can be used to establish limiting conditions for the design including d.c. control parameters and component ratings. It can also be used to trade off d.c. design with possible a.c. and d.c. system operating restrictions.

Frequency domain analysis is for the most part limited to "small signal" analysis. For harmonic interaction analysis, this is normally valid as harmonic components are typically several orders of magnitude less than the a.c. side fundamental frequency and d.c. side d.c. components of their respective waveforms.

The main challenge involved in frequency domain analysis is the derivation of the coupling coefficients which mathematically couple the a.c. and d.c. networks. These can be derived numerically or analytically and can be set-up to include the influence of the d.c. controls.

In single frequency analysis techniques, HVDC converters are often treated as ideal harmonic current (a.c. side) and voltage (d.c. side) sources with magnitudes of non-characteristic harmonics used in the calculations based on experience from measurements on simulators or other d.c. schemes. When considering harmonic interaction, this treatment may not be completely valid. For example, the third harmonic generated by the converter is for the most part dictated by the magnitude of negative sequence voltage at the converter bus and hence an ideal third harmonic voltage source would provide a more accurate treatment in the analysis than the conventionally used current source.

6.5.2 Time domain

With the availability of digital simulation techniques approaching (or achieving) real time capability, time domain analysis is an effective tool when coupled with Fourier series or Fourier transform analysis of the voltage and current waveforms. The approach involves the simulation of a set of specific a.c. and d.c. operating conditions. Once a steady state condition is achieved, the voltage and current waveforms are recorded and analyzed for their frequency content. The waveform components are then numerically combined to obtain the traditional filter performance and rating indices. This analysis could be carried out on a continuous basis providing 'on-line' monitoring of the performance and rating indices.

The major advantage of this method is that the simulation is in fact carrying out the harmonic load flow hence there is no requirement to compute the coupling coefficients. A significant second benefit is the ability to observe sustained interaction which may be triggered by some disturbance to the network.

The major disadvantage of the time domain solution is the limit imposed on the extent of the a.c. network which can be practically represented in any given simulation. Without a detailed model, a.c. system operating conditions which may result in an interaction may not be

simulated and hence the influence of the potential interaction would not be included in the filter design.

6.6 Possible countermeasures

6.6.1 AC (and/or DC) filters

Shunt connected a.c. filters can be used to limit the impact of interaction on the a.c. system by providing a low impedance path for interaction current to flow. A low impedance at the interaction frequency results in a small corresponding voltage at the converter bus. In some instances it may be more advantageous to design the filter to introduce damping into the network. Increased damping at the interaction frequencies reduces the amplification of voltages and currents which may result from the interaction.

DC side blocking filters can be used to avoid interaction. The filters typically consist of parallel capacitor-reactor-resistor components connected in series with the d.c. converter. The filter restricts the current flow at the tuned frequency thus decoupling the d.c. network at the interaction frequency. Often this is all that is required to eliminate the interaction.

Interaction can often be avoided by selecting an appropriate value for the inductance of the smoothing reactor(s) and suitable selection of d.c. filter parameters to avoid series or parallel resonances at critical d.c. interaction frequencies. Smoothing reactors are an effective means of limiting interaction due to cross modulation effects.

6.6.2 DC control design

DC controls are an extremely cost effective way to counter harmonic interaction. They are most effective in limiting interactions induced by driving forces external to the converter at low harmonic interaction frequencies. Typical control design involves the implementation of a circuit which responds to voltage or current of one of the interaction networks at the corresponding interaction frequency. The circuit adds a small correction to the firing angle of each valve in such a way as to reduce the magnitude of the measured quantity. Changing control parameters effectively alter the gain and phase of the mathematical coefficients which couple the networks at the interaction frequencies.

6.6.3 Operating restrictions and design protections

Although undesirable, the most cost effective solution to an interaction problem may be to avoid the operating condition which results in the interaction. If the likelihood that such an operating condition could occur is extremely remote, imposing an undesirable system operating restriction may be more attractive than the expense (and possible inconvenience) associated with a large capacity low order a.c. harmonic filter. If such a strategy is adopted, it would be prudent to ensure that filter and system protections detect and respond to the interaction (should it occur) and smoothly bring the a.c.- d.c. operating conditions to a safe situation.

6.7 Recommendations for the technical specification

With regard to harmonic interaction across the converters, the main purpose of the technical specification must be to ensure that these phenomena are fully taken into account by the contractor. As the study methods and computer programs required to properly analyze harmonic interaction are different from those used in the classical harmonic analysis (such as described in Clauses 5 and 8), it is more difficult for the contractor to include analysis of such interactions in his normal design process, especially under the pressure of time and resources which occur under real project conditions.

An open and general format of specification, which does not prescribe calculation procedures and conditions but which does make the contractor responsible for verifying harmonic performance by measurement, should have the effect of forcing the contractor to take into account all phenomena which may occur in practice, including harmonic interaction. (A risk remains, however, as it is often not possible to conduct verification measurements under worst