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TECHNICAL REPORT

colour inside

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

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

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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

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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.

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1) The figures in square beackets 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 expertize, 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 %):

$$D_n = \frac{U_n}{U_1} \times 100\,\% \tag{1}$$

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):

$$\text{THD} = \sqrt{\sum_{n=2}^{N} D_n^2} \tag{2}$$

where

N is the maximum harmonic order considered.

Total arithmetic harmonic distortion, D:

$$D = \sum_{n=2}^{N} D_n \tag{3}$$

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 tortional oscillation of the rotor elements and flexing of the turbine blades.

Fatigue in the turbine shaft and blades may result. Where a limit needs to be imposed to control these harmonic currents by the a.c. filter, the specification should indicate the maximum limit of these harmonic currents or any other harmonic currents indicated by the machine manufacturer, to be considered in the filter design (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 $_{eq}$ 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

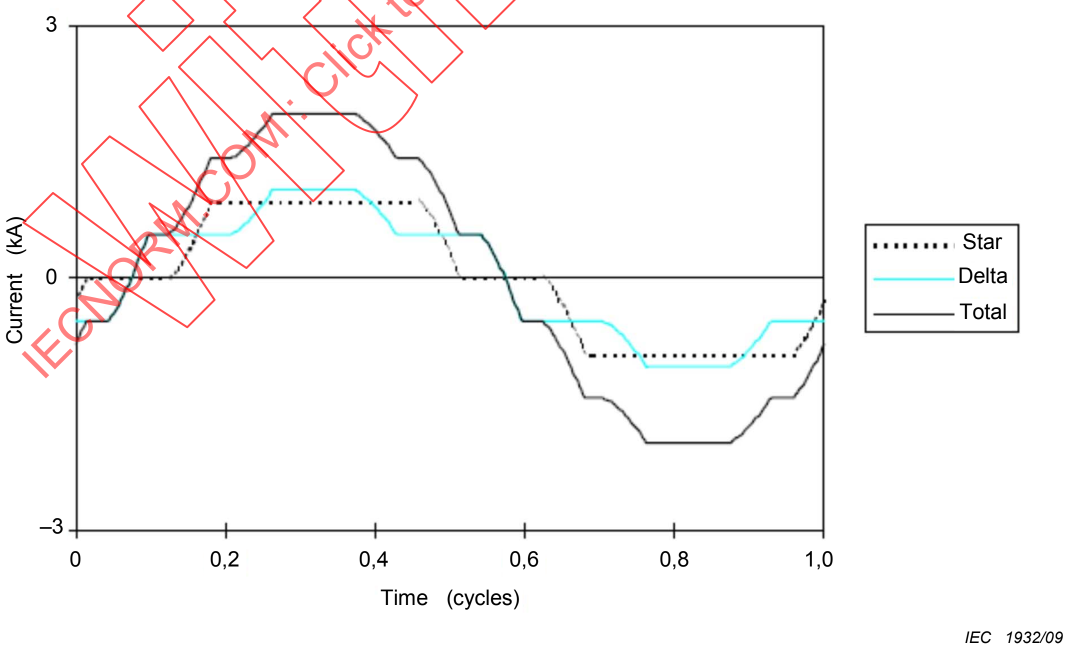
The generation of harmonics is best understood by starting to consider an idealized situation, with no asymmetries in transformer impedances or firing angle between phases, smooth d.c. current and a sinusoidal balanced a.c. voltage.

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,.. 6 k±1 are present (k is any positive integer).These are designated as “6-pulse” or “6-pulse characteristic” harmonics,
- harmonics 5,11,17,23,.. 6 k-1 are negative phase sequence,
- harmonics 7,13,19,25,.. 6 k+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,.. 12 k±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... (12 k-6)±1.



Parameters: F = 50 Hz; U_{ac} = 230 kV; U_d = 500 kV; I_d = 1 000 A; XI = 14 %; α = 15°

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.

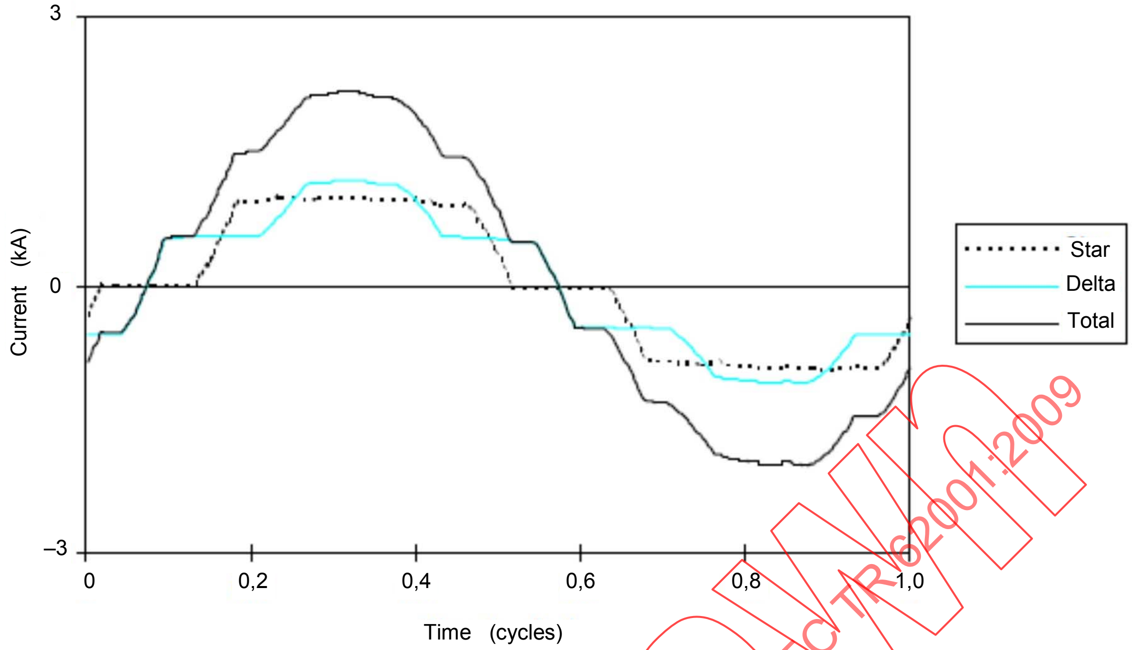
5.2.2 Realistic conditions

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.



Parameters as in Figure 1 but with:

1 % negative sequence fundamental voltage

1 % second harmonic positive sequence voltage

5 % (of Xl) leakage reactance unbalance between phases

± 0,5° 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].

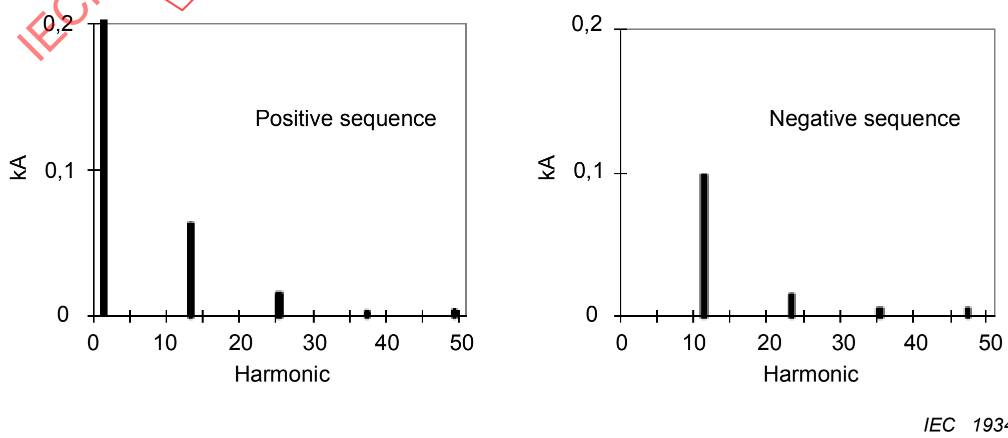


Figure 3a – Harmonic content of current waveform in Figure 1 (idealized conditions)

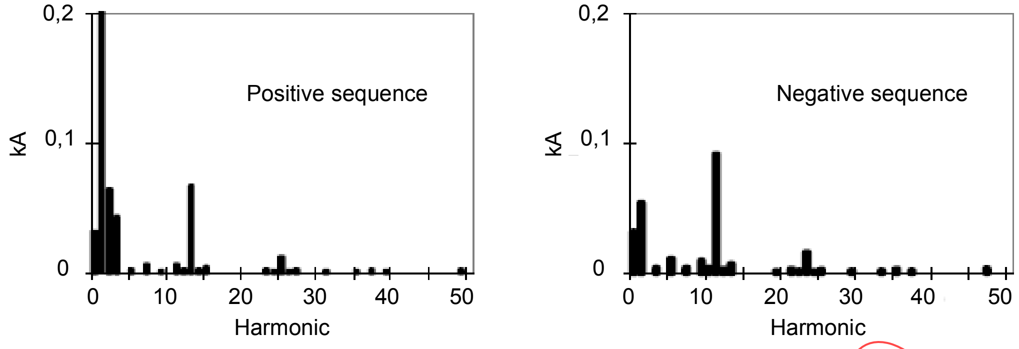


Figure 3b – Harmonic content of current waveform in Figure 2 (realistic conditions)

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.

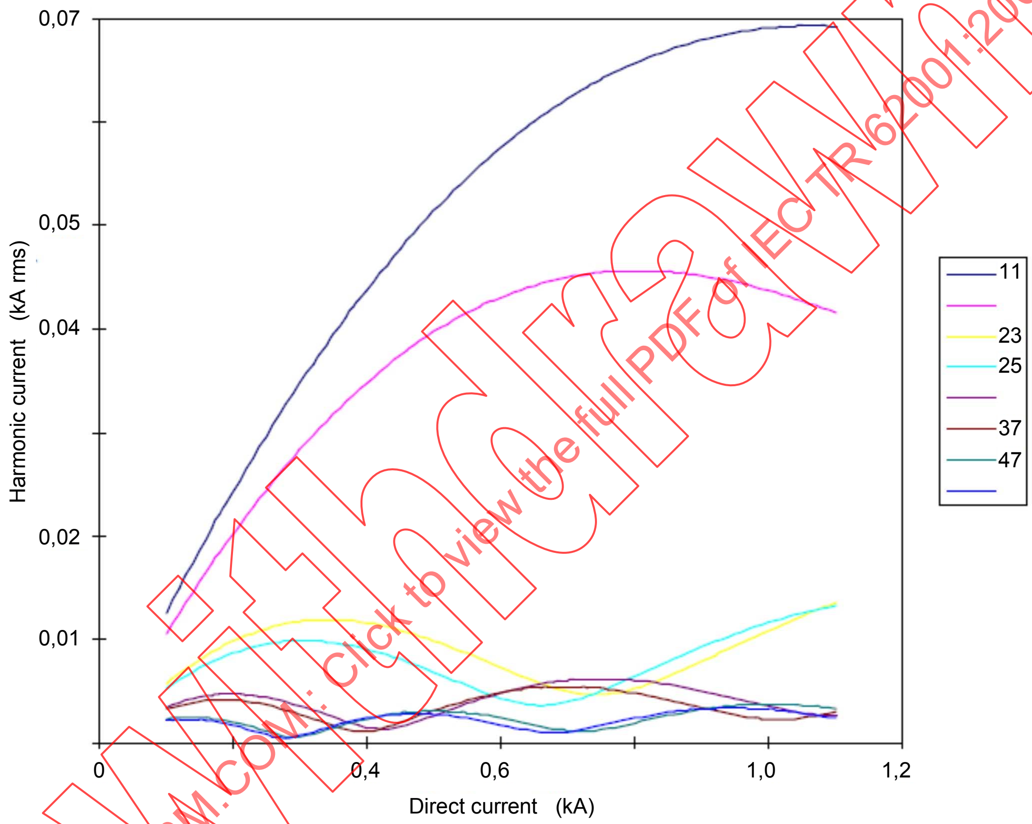
5.3.5 Harmonic generation for different d.c. power ranges

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.



IEC 1936/09

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,.. (12 k-6)±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 6 k -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 VAR[2] 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).

a) 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.

b) 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.

c) 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.

d) 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

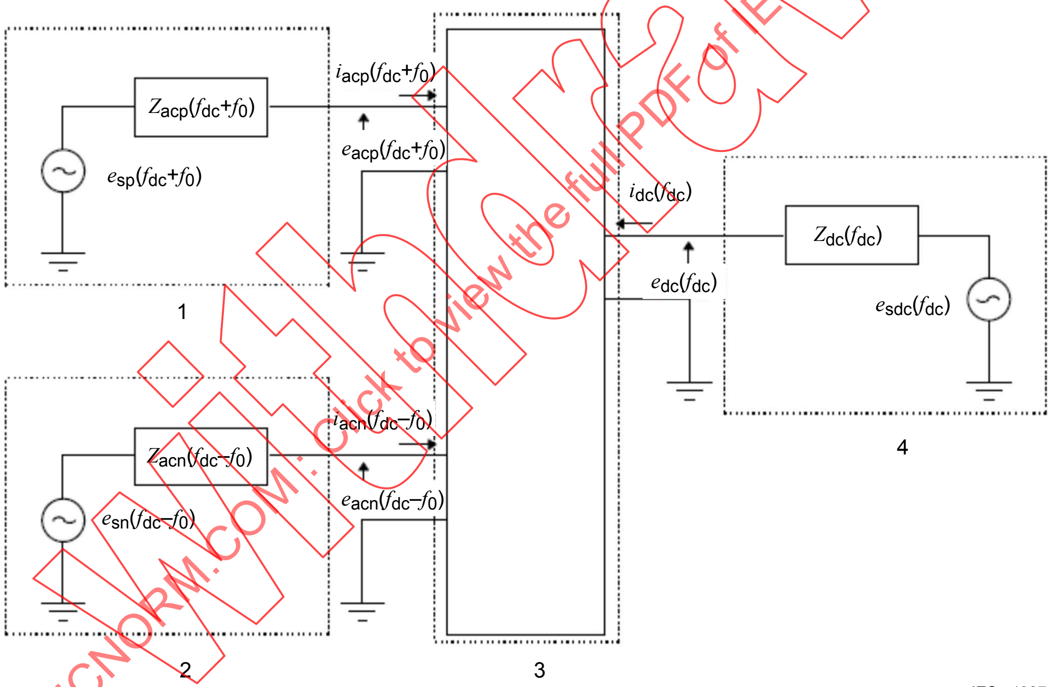
[c] d.c.

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.



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-case conditions.) On the other hand, a prescriptive specification which asks for proof of adequate filter design by calculation, and gives detailed requirements on how harmonic performance is to be calculated, but which omits specific mention of harmonic interaction phenomena, may leave the customer vulnerable.

The recommended approach is for the customer to state explicitly that all phenomena relating to the harmonic interaction between a.c. and d.c. sides of the converter, and between the two converter stations, must be taken into account in the filter design and calculation of harmonic performance and component rating. At the tender stage, bidders should be asked to indicate which calculation methods and computer tools will be used to analyze harmonic interaction. If the bidder, or later the contractor, believes that harmonic interaction will have a negligible impact on the filter design, performance and rating, or that margins in the design are sufficient to take into account harmonic interaction phenomena, then he should be asked to demonstrate this by calculation.

The customer should however be aware that to make a correct analysis of harmonic interaction, the contractor requires having adequate information about those aspects of the a.c. system which lies outside his scope. Information on the harmonic impedance of the a.c. network, on pre-existing distortion, on levels of negative sequence component, and on possible coupling from parallel a.c. lines to the d.c. line, must be supplied by the customer. In addition, the customer must provide realistic forecasts of future changes to, and expansion of, the a.c. system. If full information on these points is not available to the customer, then the customer should be prepared to share the risks associated with lack of data with the contractor and to allow judgments based on the contractor's previous experience.

7 Filter arrangements

7.1 Overview

There are various possible circuit configurations which can prove suitable for a.c. side filters in HVDC converter stations. This clause reviews these designs to give background information on the advantages and disadvantages of particular filter types.

Only shunt connected filters are considered in this section, series filters being discussed in 13.4.3.

The comments on particular filter designs apply to HV and EHV connected filters and equally to LV connected filters, for example tertiary connected filters.

The choice of the optimum filter solution is the responsibility of the contractor and will differ from project to project. The design will be influenced by a number of factors which may be specified by the customer:

- specified harmonic limits (current injection, voltage distortion, telephone interference factors),
- a.c. system conditions (supply voltage variation, frequency variation, negative phase sequence voltage, system harmonic impedance),
- switched filter size (dictated by voltage step limit, reactive power balance, self-excitation limit of nearby synchronous machines, etc.),
- environmental effects (ambient temperature range),
- converter control strategy (voltage and overvoltage control, reactive power control),
- site area (limited switch bays),
- loss evaluation criteria,
- availability and reliability requirements.

Reviews of previous HVDC schemes [42] can indicate typical filter solutions for particular schemes but this can only act as a guide or a starting point; only detailed study will produce an optimum design.

Different filter configurations will possess certain advantages and disadvantages when considering the above factors. The purpose of this clause is to provide designers and planners of HVDC schemes with a review of the advantages and disadvantages associated with a number of widely used filter configurations. As only the filter design and performance aspects are considered, additional equipment such as surge arresters, current transformers and voltage transformers are omitted from the circuits shown. In HV and EHV applications surge arresters are normally used within the filters to grade the insulation levels of the equipment. The protective level and energy absorption capability of these arresters will be the subject of detailed transient studies, as discussed in Clause 11.

7.2 Advantages and disadvantages of typical filters

The following general points apply to all the different filter configurations described and compared below.

Filter earthing: For HVDC applications the filter neutral is normally solidly earthed on systems above 66 kV and sometimes 110 kV. On low voltage systems, the filter neutral may be earthed or unearthed depending on local requirements. Alternatively the neutral of the filter may be earthed through a reactor.

Position of reactor: In the figures shown in the following sections, the reactor is connected at the neutral end of the circuit, although in practice the reactor can be connected at either the HV side or neutral side of the circuit.

- If connected on the HV side of the circuit, the reactor is exposed to short circuit currents in the event of an earth fault on the capacitor bank. This will require the reactor to be rated for the calculated short circuit current and a suitable type test performed, thus adding to overall reactor costs. However, this arrangement allows capacitor unbalance protection schemes to be installed at the neutral terminal which minimises their design costs.
- If the reactor is connected at the neutral side of the circuit, it is not exposed to large short circuit currents and hence the design can be simpler and the need for a costly type test is removed. However, the capacitor unbalance scheme now requires high voltage current transformers or voltage transformers which adds to costs.
- The location of the reactor may also influence the Transient Recovery Voltage (TRV) developed across circuit breaker contacts when clearing faults between a line side reactor and the capacitor bank. In some cases, line side reactors have been prohibited due to adverse effects on the breaker TRV.

7.3 Classification of filter types

Many terms are employed to classify filters and in this clause the following terms are used.

a) Tuned filters

These are filters tuned to a specific frequency, or frequencies. They are characterized by a relatively high Q (quality) factor, as in Equation (4), i.e. they have low damping. The resistance of the filter may be in series with the capacitor and inductor (more usually it is simply the loss of the inductor), or in parallel with the inductor, in which case the resistor is of high value. Tuned filters are also referred to as narrow band-pass filters. Examples of tuned filters are discussed later in this clause and include single (e.g. 11th) double (e.g. 11/13th) and triple (e.g. 5/11/13th) tuned types.

b) Damped filters

These are filters designed to attenuate more than one harmonic, for example a filter tuned at 24th harmonic would cover 23rd and 25th harmonics. Damped filters always include a resistor in parallel with the inductor which produces a damped characteristic at frequencies above the tuning frequency. Normally a low resistor value is chosen to give high damping, however the choice will depend on the need to meet performance requirements, achieve a sufficiently low resistive impedance of high frequencies and avoid unacceptable losses at fundamental frequency. Damped filters are alternatively referred to as broad band-pass filters. If they are also intended to have a highly damped characteristic at frequencies above the tuned frequency, they may also be referred to as high pass (HP) filters. Examples of damped filters are discussed later in this clause and include single tuned damped high pass (e.g. HP12) and double tuned damped high pass (e.g. HP 12/24).

c) Filter "order"

The expression "order" refers to the order of the terms in the transfer function of the filters, as follows:

- 1st order is a simple C or R-C circuit, i.e. a shunt capacitor.
- 2nd order is a L-C circuit, i.e. a tuned filter (Figure 6) or damped filter (Figure 9).
- 3rd order contains an additional capacitor bank, i.e. a double tuned filter (Figure 7) or damped filter (Figure 10).

The order of a filter is sometimes used to clearly define the type of filter being considered, e.g. a 2nd order damped high pass (as in 7.5.1.1) or a 3rd order damped high pass (7.5.1.2).

7.4 Tuned filters

7.4.1 Single tuned filters

The single tuned filter is the simplest filter topology, consisting of a reactor connected in series with the capacitor bank. Figure 6 shows the circuit arrangement and the impedance/frequency response for a typical 11th harmonic tuned filter.

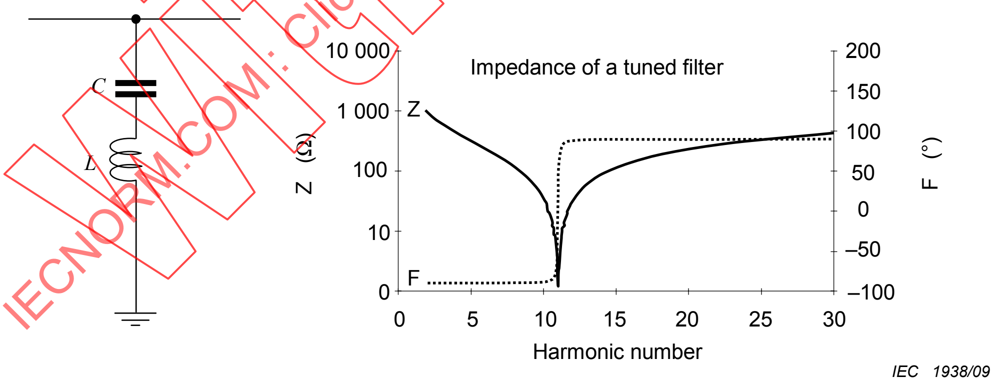


Figure 6 – Single tuned filter and frequency response

By choosing the capacitance (C) and inductance (L) to achieve a series resonance at one specific harmonic order, a very low impedance path, limited only by the resistance (r) in the reactor, is created for one harmonic current. That is,

$$2\pi f_0 nL = \frac{1}{2\pi f_0 nC} \qquad (4)$$

giving

$$n = \frac{1}{2\pi f_0 \sqrt{LC}} \tag{5}$$

where

f_0 is the fundamental frequency;

n is the harmonic order.

By suitable choice of the Q-factor of the reactor, and thus the Q-factor of the filter, where

$$Q = \frac{2\pi f_0 nL}{r} = \frac{\sqrt{\frac{L}{C}}}{r} \tag{6}$$

the performance of the filter at and near its tuning frequency can be controlled. The filter losses will be determined by the Q values at fundamental frequency and at the tuning frequency. Note that the resistance, hence Q, of a reactor is frequency dependent. Reactor manufacturers can normally design a reactor with any desired Q-factor within a reasonable range. If an exceptionally low Q-factor is required for a single-tuned filter, a small series resistor may possibly be added.

As this type of filter deals with only one harmonic, multiple filters may be required to cater for groups of characteristic harmonics (e.g. 11th ,13th , 23rd , 25th etc.).

Because the effectiveness of the filter relies upon Equation (4) being true, it follows that if f_0 varies from nominal, the filter will no longer be tuned at the desired harmonic. Similarly, if manufactured values of C and L are not the nominal values, and this is inevitable as as-built tolerances will need to be considered, Equation (5) will no longer produce exactly the required harmonic order. However, this can be overcome by making the C and/or L value adjustable. As it is the capacitor bank which dictates reactive power generation it is preferable to maintain C constant and provide adjustment in L. This can be achieved by simple off-circuit taps on the reactor, but at increased cost, typically 10 % to 20 % and poorer reactor reliability.

As capacitance is a temperature dependent quantity, Equation (5) implies that the filter will become detuned with ambient temperature variation.

To summarize:

Advantages		Disadvantages	
1	Simple connection with only two components.	1	Multiple filter branches may be needed for different harmonics
2	Optimum attenuation for one harmonic	2	Susceptible to de-tuning effects
3.	Low loss	3	May require off-circuit tap connections
4.	Low maintenance requirements		

7.4.2 Double tuned filters

This type of filter is substantially equivalent to two parallel connected tuned filters but is implemented as a single combined filter. The reactive power rating of the combined double tuned filter would be the sum of the ratings of the two tuned filters. Figure 7 shows two typical circuit arrangements and the impedance/frequency response for a typical 11/13th filter.

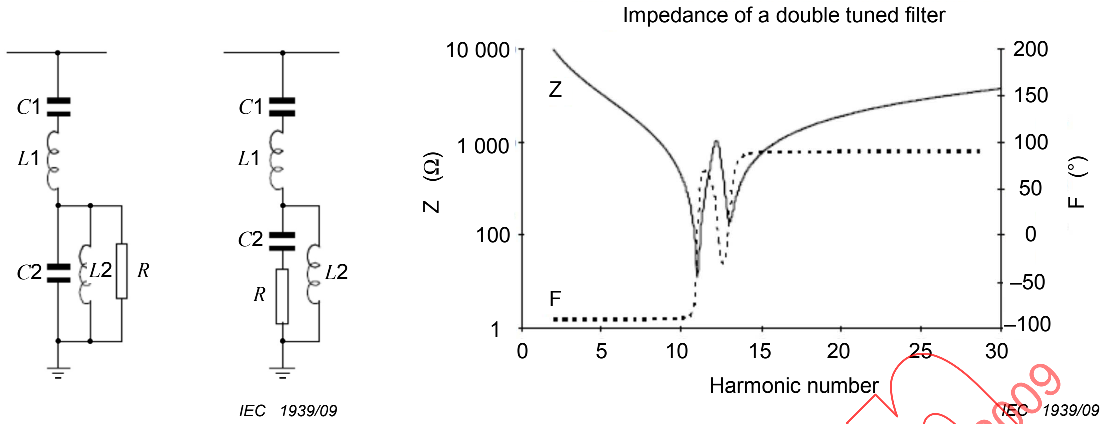


Figure 7 – Double tuned filter and frequency response

By combining two tuned filters virtually any MVAr split can be accommodated between the lower and upper frequency components. This allows the possibility of incorporating a very low MVAr rated filter, which on its own would be an un-economic design, into a larger filter to form a double tuned filter. If two single-tuned branches were used instead, there could be a minimum filter size problem due to connecting a possibly very low MVAr rated filter (as required for one of the two frequencies) on to an HV busbar. This problem can be overcome in most cases by the use of double-tuning.

There is only one HV capacitor bank C_1 and only one HV reactor L_1; the other components are operated at low voltage. The site area required for a double tuned filter will be less than for two single tuned filters, and only one set of high voltage switching apparatus is required. The protection of only one HV capacitor bank will also reduce costs.

As each switched filter can attenuate two harmonics there is more incentive to install identical filters, which has advantages in design, testing and spares costs. This also improves filter redundancy which will result in an overall increase in station reliability.

Like single tuned filters (see 7.4.1) this filter is susceptible to de-tuning due to frequency drift, ambient temperature variation and component tolerances. Off-circuit tap adjustment may be required to compensate for tolerance effects

The presence of a parallel C2 - L2 circuit will result in circulating harmonic currents, which in the case of the capacitor can exceed the fundamental current. This can make proper fusing of the C2 bank difficult, indeed most C2 banks are installed without fuses. The magnitude of such circulating currents can be controlled by lowering the Q value, i.e. increasing the resistance, of the L2 reactor or installing a resistor R in the circuit. Increased reactor resistance can be achieved by increasing the losses in the windings, e.g. by using conductors of narrower cross-section, or by increasing stray losses in structural members, or by adding additional material to induce eddy current losses.

If a resistor is used to control the circulating currents, this can be either in series with the capacitor bank C2 or connected in parallel with both C2 and L2, as shown in Figure 7.

The choice of the two tuning frequencies will affect the magnitude of these resonance currents, thus where the frequencies are widely separated, the parallel resonance currents will decrease.

An additional advantage of a double-tuned filter over two single-tuned filters with equivalent filtering at the tuned frequencies, is that better attenuation is provided at frequencies between the two tuned frequencies.

During routine bank switching or system faults the transient duty on C2 can greatly exceed its capability based on steady state rating. This may require the C2 capacitor bank rated voltage to be increased above the calculated steady state rating to withstand such transient disturbances. These transient conditions will place additional duty on the surge arresters which are used to grade the insulation of the low voltage components.

To summarize:

	Advantages		Disadvantages
1	Optimum attenuation for two harmonics	1	Susceptible to de-tuning effects
2	Lower loss than for two single tuned branches	2	May require off-circuit tap adjustment
3	Only one HV capacitor and reactor needed to filter two harmonics	3	Transient effects can determine rating of LV elements
4	Mitigates minimum filter size problem for a low magnitude harmonic	4	Complex interconnection, with 4 or 5 C-L-R components
5	Fewer branch types, facilitating filter redundancy.	5	May require two surge arresters to control insulation levels.

7.4.3 Triple tuned filters

This type of filter is electrically equivalent to three parallel connected tuned filters, but is implemented as a single combined filter. Figure 8 shows the circuit arrangement and the impedance/frequency response for a typical 12/24/36th filter.

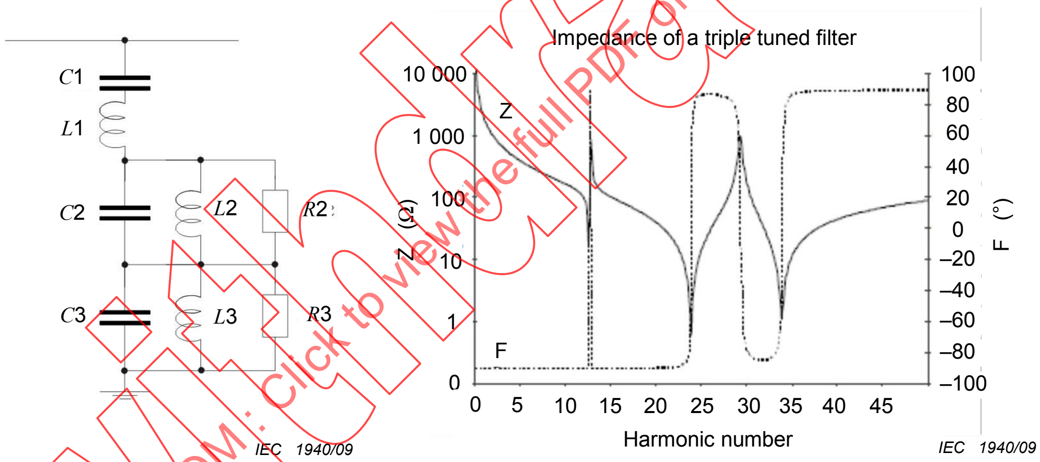


Figure 8 – Triple tuned filter and frequency response

Although a complex filter, this arrangement can provide a suitable method of incorporating filtering at three harmonics. This can be either three characteristic harmonics to control harmonic performance (e.g. 12/24/36th) or may be two characteristic harmonics plus one non-characteristic harmonic (e.g. 3/12/24th) to prevent resonance problems.

The use of triple tuned filters could improve the operational requirements for reactive power control. This would be of particular importance at low load conditions where a shunt reactor may have been required to off-set a 3rd harmonic filter. Such minimization of reactive power generation may be important to avoid self-excitation of nearby generators. Where low levels of TIF and IT are specified, these filters may achieve the required performance levels. As they are similar in nature to double tuned filters, their merits and drawbacks are as described in 7.4.2.

	Advantages		Disadvantages
1	Optimum attenuation for three harmonics	1	Susceptible to de-tuning effects
2	Lower loss than for three single tuned branches	2	May require off-circuit tap adjustment
3	Only one HV capacitor and reactor needed to filter three harmonics	3	Transient effects can determine rating of LV elements

4	Mitigates minimum filter size for low magnitude harmonic(s)	4	Complex interconnection, with 7 or 8 C-L-R components.
5	Fewer branch types, facilitating filter redundancy.	5	Two or three surge arresters may be required to control insulation levels.

7.5 Damped filters

7.5.1 Single tuned damped filters

7.5.1.1 2nd order damped filter (high pass filter)

In this filter topology a damping resistor R is connected in parallel with the series reactor L. Figure 9 shows the circuit arrangement and the impedance/frequency response for a damped filter, with a minimum impedance at 11th harmonic.

For a damped filter where the resistor is in parallel with the reactor, the degree of damping may be defined in terms of quality factor Q, or alternatively as a damping factor m, defined respectively as

$$Q = \frac{R}{\sqrt{L/C}} \qquad \text{or} \qquad m = \frac{L}{R^2 C}$$

(note that this is the inverse of the definition of Q-factor for a filter where the resistance is in series, as in 7.4.1, - the logic being that in both cases Q is a measure of the sharpness of tuning.)

The figure illustrates the effect of choosing a high quality factor Q (Curve Z_1) or low Q (Curve Z_2). Note the transition between capacitive and inductive impedance, i.e. the phase angle = 0° does not occur exactly at the point of minimum impedance. At very high frequencies the phase angle will fall to near zero, i.e. the filter impedance becomes the resistor value (R).

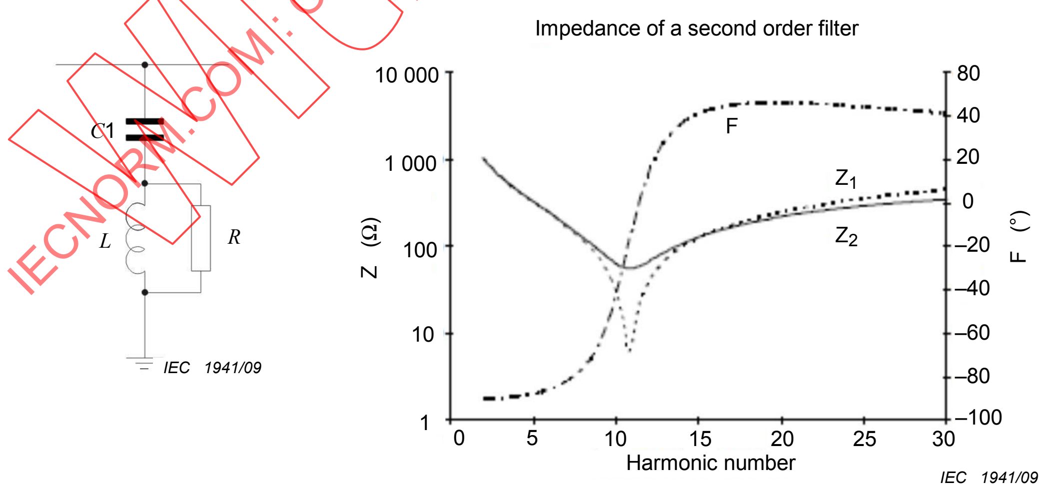


Figure 9 – 2nd order damped filter and frequency response

The presence of the resistor broadens out the frequency response of the filter which introduces two beneficial effects. The filter is now less sensitive to the de-tuning effects of frequency drift, ambient temperature variation and component tolerance effects. Also, by choice of R, the filter response can cover a number of harmonics, e.g. 11th and 13th could be attenuated by one damped filter. However the attenuation achieved by a damped filter may be less than that achieved by two tuned arms of the same total rating, e.g. an 11th and a 13th single tuned filter. Thus a larger installed MVAr rating of filter may be required to achieve the same level of harmonic performance. By adding the resistor, filter losses have been increased both at harmonic frequencies where it is needed and at fundamental frequency where it is not. These higher losses can be prohibitive if the cost of losses are high, especially for a filter designed to attenuate the 11th and 13th harmonics.

Advantages	Disadvantages
1 Provides attenuation over a spectrum of harmonics	1 May require larger installed MVAr rating than multiple tuned branches
2 Relatively insensitive to de-tuning effects.	2 Higher losses than tuned filters

7.5.1.2 3rd order damped filter

In this topology an auxiliary capacitor (C2) is connected in series with the resistor to act as a blocking impedance, as shown in Figure 10. The main application of such a filter would be at low harmonic orders where the losses in a 2nd order filter resistor would be unacceptable. The impedance/frequency response of such a filter at 3rd harmonic is shown in Figure 10.

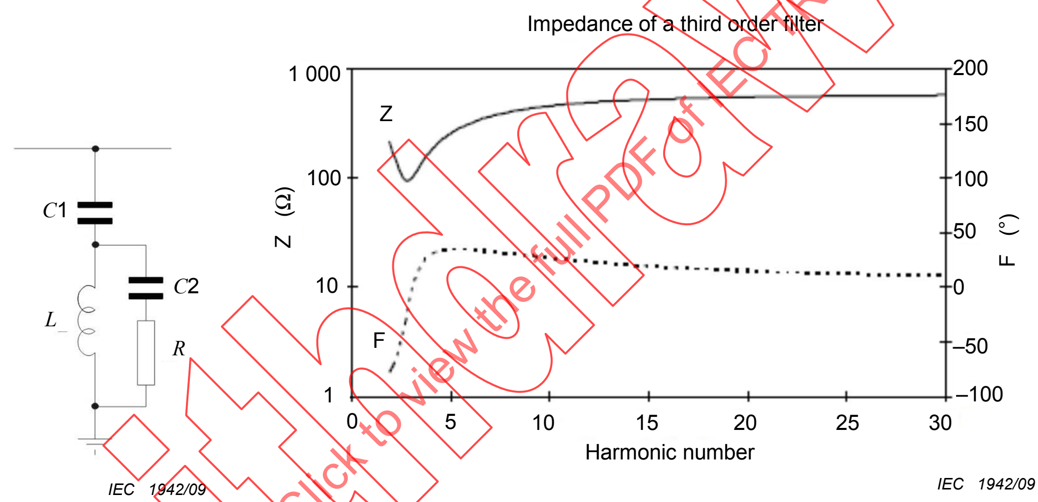


Figure 10 – 3rd order damped filter and frequency response

At fundamental frequency C2 has a high impedance, thus reducing fundamental losses in the resistor as current preferentially flows through the reactor. At higher frequencies, as the impedance of bank C2 decreases, harmonic current flows through R providing the required damping. The choice of C2 is essentially economic as the reduced power dissipation, hence cost, of the resistor plus reduced capitalized losses must cover the costs of the C2 bank.

The presence of the C2 bank slightly degrades the filter admittance characteristic, thus a slightly larger MVAr rating may be needed to maintain performance. To summarize, the comments in 7.5.1.1 apply, plus:

Advantages	Disadvantages
As 7.5.1.1 plus:	As 7.5.1.1 plus:
1 Lower fundamental frequency losses in the resistor than 2nd order damped design.	1 Slightly poorer performance compared with 2nd order damped design.
	2 More complex filter, with four C-L-R components.

7.5.1.3 C-type filter

In this topology an auxiliary capacitor (C2) is connected in series with the reactor and is tuned to form a fundamental frequency bypass of the resistor. Figure 11 shows the circuit arrangement and the impedance/frequency response for a typical 3rd harmonic filter.

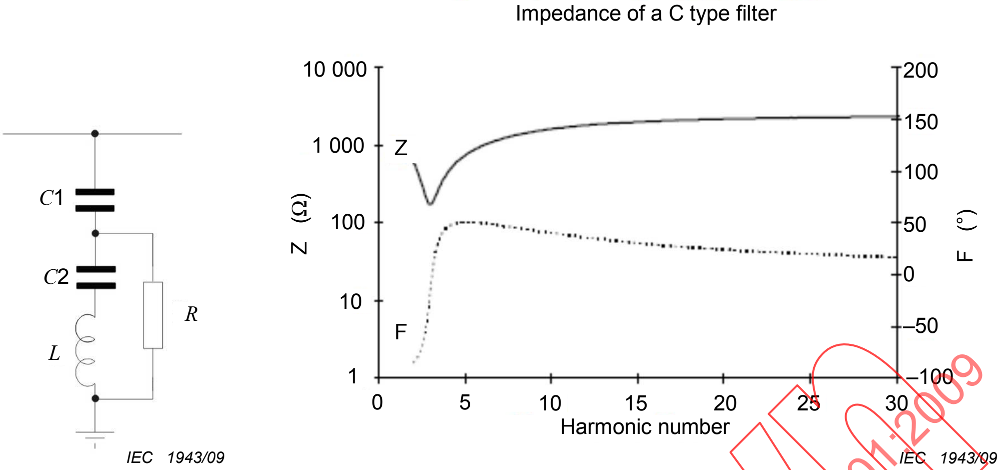


Figure 11 – C-type filter and frequency response

By creating a tuned filter C2-L within a 2nd order filter, virtually all fundamental current is excluded from the resistor. At frequencies above fundamental, harmonic current flows through R achieving the desired damping. However, as C2-L is a tuned filter, de-tuning can occur due to variations in L or C values from the rated values. However, in this case the effect of de-tuning is to increase the resistor rating rather than degrade overall filter performance.

The presence of the C2 capacitor has a small effect on the impedance characteristic.

To summarize:

	Advantages		Disadvantages
	As 7.5.1.1 plus:		As 7.5.1.1 plus:
1	Negligible fundamental frequency loss in resistor	1	Resistor rating is susceptible to de-tuning effects.
		2	May require off-circuit tap adjustment
		3	More complex filter, with four C-L-R components
		4	Slightly poorer performance compared with 2nd order damped design.

7.5.2 Double tuned damped filters

This type of filter is electrically equivalent to two parallel connected 2nd order damped filters but implemented as a single combined filter. Figure 12 shows the circuit arrangement and the impedance/frequency response for a typical 12/24th filter.

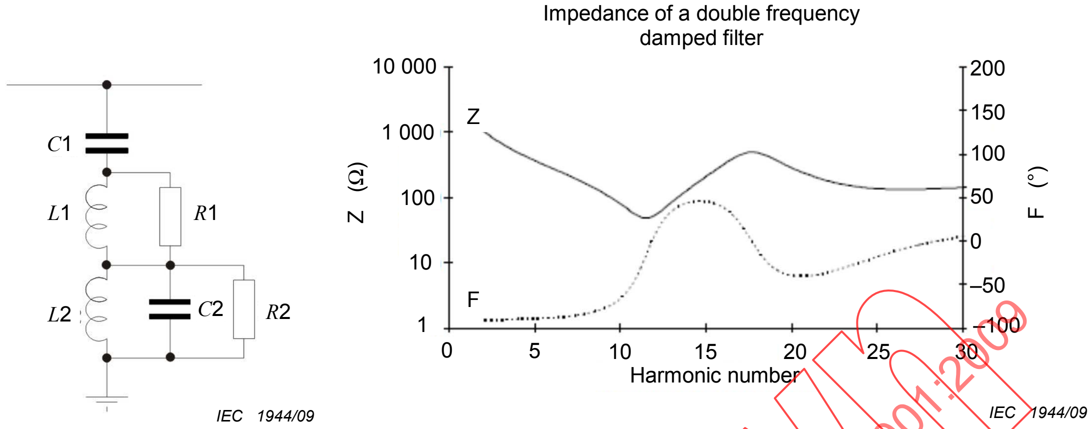


Figure 12 – Double tuned damped filter and frequency response

This filter offers a considerable degree of control over the frequency response, allowing changes in MVAr split between low and high frequencies, and changes in the damping achieved across the range. The design has the same advantages as the double tuned filter whilst being less sensitive to de-tuning effects. However the presence of the resistors R1 and R2 will generate both fundamental and harmonic losses.

During switching or fault disturbances the loading on the LV components C2, L2, R2 can exceed their overload capability if this is based on steady state ratings. Thus particularly for C2 the rating needs to be based upon transient studies and not steady state studies.

To summarize:

	Advantages		Disadvantages
1	Attenuation over a wide spectrum of harmonics	1	Transient effects can determine ratings of LV components
2	Only one HV capacitor and reactor needed to filter a range of harmonics.	2	Higher losses than double tuned bandpass design
3	Mitigates minimum filter size problem for a low magnitude harmonic	3	Complex interconnection, with 6 C-L-R components
4	Fewer branch types, facilitating filter redundancy	4	Additional protection requirements for resistors
5	Relatively insensitive to de-tuning effects	5	Possible additional duties on surge arresters compared to tuned filter design.

7.6 Choice of filters

From the advantages and disadvantages discussed in 7.4, the following guidelines may be summarized:

a) where system frequency varies widely, the use of damped filters would be preferred to tuned filters;

b) where there is a wide ambient temperature variation, tuned filters may give unacceptable performance. However, where off-circuit tap adjustment is provided the reactors could be re-tuned on a bi-annual basis to mitigate the variation of capacitance due to summer and winter temperatures;

c) where filters need to be tuned close to the harmonic order for optimum performance, off-circuit tap adjustment on the reactors may be required;

d) 2nd order high pass damped filters can provide the optimum solution for 11/13th and higher characteristic harmonic groups, in applications where only voltage distortion limits are applied and/or the range of system harmonic impedance is benign;

e) unless needed for low order harmonic problems, e.g., 3rd or 5th, and depending on the level of damping required, the losses in 2nd order high pass damped filters are usually of an acceptable level;

f) for low harmonic order filters where a damped characteristic is required, the C-type filter is preferred;

g) where limitation of individual harmonic current injection or IT (I_{eq}) is required tuned or double tuned filters may be needed to give the required low impedance path;

h) where limitation of voltage distortion is required either tuned or damped filters can give acceptable performance;

i) where limitation of TIF (THFF) is required, combinations of damped filters are normally required;

j) where limitation on reactive power exchange in conjunction with TIF limitation is required, double tuned or triple tuned filters may be the optimum solution;

k) for high voltage and/or low MVAr applications double tuned or triple tuned filters may provide the optimum solution;

l) where existing levels of negative phase sequence (NPS) voltage on the system are high, i.e. exceeding 1 %, 3rd harmonic filters, either tuned or C-type, may be required. If C-type filters are used, they may also provide attenuation at 5th harmonic if required, by suitable choice of the resistor value. In some schemes it may be possible to attenuate the generation of 3rd harmonic due to NPS voltage by control action.

These comments are intended as a guide, as only detailed performance and rating studies will establish an optimum solution.

8 Filter performance calculation

8.1 Calculation procedure

8.1.1 General

Filter performance calculations are central to the filter design process. Any prospective a.c. filter configuration must be first subjected to calculations to show what would be the performance under the defined conditions. However, due to other aspects to consider, such as rating, losses etc., the whole design process is iterative by nature. This means that the filter performance calculations may be made many times, with different prospective filter data, in the course of filter design for any project.

Special-purpose computer programs are required in order to conduct the required calculations efficiently, and to present the design engineer with the information to optimize the filter design. Description of which such programs are to be used by prospective contractors should be requested in the technical specification and assessed by the customer.

8.1.2 Input data

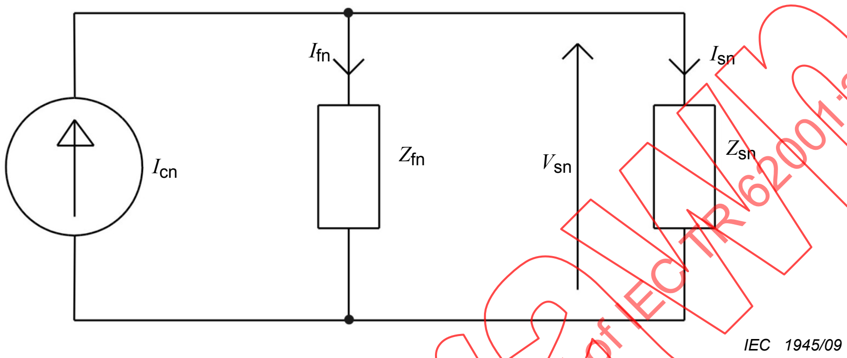
Normally, the customer defines the a.c. system harmonic impedance, voltage and frequency range, negative sequence voltage, reactive power exchange limits, operating conditions, ambient temperature range, pre-existing harmonics and the permissible distortion limits. The customer should consider possible future changes in the system.

The contractor then determines the remaining data required for performance calculations, including main circuit parameters, manufacturing tolerances and component deviations.

8.1.3 Methodology

The methodology described below is the classical calculation procedure, which does not take into account the effects of a.c.- d.c. side harmonic interaction across the converter. The reader should be aware that unless harmonic interaction phenomena are taken into account, and unless the effective impedance of the converter is adequately modeled, calculations using the classical method may give substantially misleading results, especially for low-order non-characteristic harmonics. Clause 6 discusses how such interaction may be included in the calculations.

The input data is used to construct a computer model (see Figure 13), which consists of a constant harmonic current source representing the HVDC converters, in parallel with the filters and a.c. system harmonic impedance.



Key

I_{cn} injected harmonic currents from the converter

Z_{fn} filter harmonic impedance

I_{fn} filter harmonic current

Z_{sn} a.c. system harmonic impedance

I_{sn} a.c. system harmonic current

V_{sn} a.c. system harmonic voltage

Figure 13 – Circuit model for filter calculations

The filter current may then be found from:

$$I_{fn} = \frac{Z_{sn}}{Z_{sn} + Z_{fn}} \times I_{cn} \tag{7}$$

and the harmonic voltage distortion from:

$$V_{sn} = \frac{Z_{sn} \times Z_{fn}}{Z_{sn} + Z_{fn}} \times I_{cn} \tag{8}$$

$$= \frac{I_{cn}}{Y_{sn} + Y_{fn}} \tag{9}$$

where

Y_{sn} is the a.c. system harmonic admittance;

Y_{fn} is the filter harmonic admittance.

In these equations, the harmonic current (I_{cn}) produced by the rectifier or inverter of the HVDC station must be calculated by the contractor for all harmonics (see 8.1.4). The system network harmonic impedance (Z_{sn}) is normally defined in the technical specification (see 8.3).

8.1.4 Calculation of converter harmonic currents

The conditions under which the harmonic currents generated by the converter are to be calculated for performance purposes are discussed below. (Calculation of harmonic generation and the parameters requiring consideration are described in Clause 5).

Under some extreme or rare conditions of harmonic generation, the filter performance may not be required to meet the specified limits. Therefore, depending on the nature of the particular scheme and its electrical environment, the customer may wish to consider excluding some such conditions from the calculation of filter performance. The advantage to the customer could be simpler and less expensive filters. The following aspects could be considered for exclusion:

- operation under short-time overload conditions of d.c. current (or d.c. power);
- reverse power direction for an HVDC scheme which is intended mainly for uni-directional transmission;
- reduced d.c. voltage operation, if intended only for rare and short-time use;
- extreme rare or short time a.c. voltage variations;
- extreme rare or short time levels of a.c. negative phase sequence component;
- operation with one filter bank out of service;
- unusual operating conditions or configurations.

The technical specification should be clear as to whether harmonic currents are to be calculated considering the steady state a.c. voltage range or nominal a.c. voltage. Due to the action of the converter transformer tap-changers (and assuming constant harmonic generation from the converters), the harmonic current magnitudes on the network side will vary in inverse proportion to the a.c. voltage variation. Maximum harmonic current injection from the converters may therefore occur at minimum a.c. voltage conditions.

To find the worst-case performance conditions which may occur in practice, the calculations should be made considering the range of a.c. voltage specified for performance calculation. However, some technical specifications in the past have requested calculation of harmonic currents only at nominal a.c. voltage, which is equivalent to a relaxation of the performance criteria. The customer should decide which approach is preferable and state this in the technical specification.

8.1.5 Selection of filter types and calculation of their impedances

During the course of the a.c. filter design for an HVDC project, various filtering solutions will be studied and the corresponding harmonic performance calculated. Different types of filters and their characteristics are described in Clause 7, including advantages and disadvantages of the respective filter type. Clause 7 also covers aspects of the choice of an optimum filter solution.

When the major features of the design have been decided, there will normally still be a need to make fine adjustments to the filter component values in order to optimize performance, rating and losses, and this process will normally entail many iterations of the performance calculation procedure.

8.1.6 Calculation of performance

Using the model (Figure 13), different sets of harmonic currents corresponding to different d.c. current (or power levels) levels are applied and individual harmonic voltages appearing across ZF are calculated, under applicable and agreed network impedance conditions. The effect of a.c. system voltage and frequency variations is considered by modifying source currents and filter impedance respectively. The calculated individual harmonic voltages are then processed, in the manner defined by customer (see Clause 4), to obtain the desired performance parameters.

For the calculation of parameters which combine all relevant harmonic orders, such as THD, TIF and THFF, there have been different approaches adopted in previous HVDC converter stations. It is unrealistic to expect that resonance between the a.c. system and the filters will occur at all or many of the harmonic frequencies simultaneously. In this respect, one of the following methods is recommended:

- THD, TIF, THFF should be calculated with a.c. network impedance connected at the two harmonics which result in the highest value of that parameter and at all other harmonics the a.c. system harmonic impedance should be considered to be an open circuit.

- when discrete impedance values/diagrams for each system configuration are available, another more sophisticated method is possible. It is to assume worst case resonance (i.e. the system configuration that is giving the highest distortion) at one or two harmonics and for the remaining harmonics to use the system condition that gave an impedance closest to that which gave the worst case resonance condition for those harmonics.

If however THD and TIF (or THFF) are required to be calculated by taking into account all harmonics under worst a.c. network conditions, then the specified limits for these parameters should be correspondingly higher.

For IT and Ipe the following simple method could be used:

- IT and Ipe could be calculated with a phase equivalent impedance modeled by a parallel connection of a resistance and a reactance. The reactance can be calculated from the fault level produced by the lines being modeled by this equivalent, and the parallel resistance can be produced by the positive sequence surge impedances of these lines. This model will not show any resonances such as occur in a real system; however, the model is a good compromise giving an average over the studied frequency range.

The calculation of performance is generally based on consideration of harmonics generated by the converter alone, i.e. neglecting the effects of pre-existing harmonics. Such a method is appropriate where either the pre-existing levels are low and/or it is difficult to define the pre-existing harmonics accurately.

However, where pre-existing distortion is known, and is significant in comparison to the permitted limits, it is recommended that the performance criteria should be defined in terms of the “total” distortion due to the converter plus pre-existing, rather than an “incremental” value of distortion due to the converter alone. This is because pre-existing distortion may change as a result of magnification (or attenuation) by the connection of the converter station a.c. filters. In this case, it is recommended that in deriving the total distortion at each harmonic, the converter and pre-existing harmonics are summed on a root-sum-square (RSS) basis unless specific data regarding their relative phase angles is available.

Careful investigations or measurements of pre-existing harmonics by the customer are necessary prior to preparation of the technical specification. A recommended practice is to model Thevenin equivalents connected to the converter busbars, representing pre-existing harmonics from the a.c. system by voltage sources behind equivalent harmonic impedances. The harmonic frequency of the voltage source should be varied over a defined range, to detect the worst case resonance conditions created by inclusion of the harmonic filter impedances.

8.2 Detuning and tolerances

8.2.1 General

Ideally, a filter would operate under conditions of perfect tuning. In reality, however, practical a.c. filters normally operate under detuned conditions to a greater or lesser extent. The technical specification should require that the following factors contributing to detuning must be taken into account in the performance calculations:

- fundamental system frequency variation,
- filter capacitance variation due to temperature variations,
- filter capacitance variation due to failed capacitor elements and ageing,
- initial mistuning of filter due to manufacturing tolerances and/or discrete taps on reactors.

Depending on the filter type (Clause 7) the different factors will influence the performance in different degree. Sharply tuned filters with high Q-value will be highly influenced by variations in the above parameters. Damped filters with low Q-value will be less influenced.

8.2.2 Detuning factors

The background to each of the factors contributing to detuning is discussed below.

a) Fundamental frequency variation

The frequency range for which the performance requirements shall be met must be given in the specification. This range may be identical to the maximum steady state frequency variation for the system, or may be lower, to exclude rare or short-term extremes.

b) Capacitance variations

The capacitance of the filter capacitors will be temperature-dependent to some extent. The ambient temperature limits for which the performance requirements shall be met must be given in the technical specification. Different temperature ranges for performance and rating calculations could be given, if the extreme values of temperature were rare and of short time duration. The variation of capacitance value versus temperature will be provided by the capacitor manufacturer. Capacitance change due to heating caused by electrical stress and solar radiation should also be taken into account.

It is usually accepted to keep a filter in operation with a few capacitor elements failed, up to a given alarm/warning level. The capacitance change corresponding to this maximum allowed number of failed elements must also be taken into consideration for the performance calculations.

It should be observed that using the approach that every filter capacitor bank may be operating with maximum number of failed elements at the same time as the temperature and the fundamental frequency are at the outer limit of specified range, a very conservative performance value is found. The probability (see 8.5) that all detuning parameters would be most critical at the same time will not be very high.

The total capacitance variation resulting from temperature variations, failed elements and ageing, must be taken into account by the filter designer.

c) Manufacturing tolerances and initial mistuning

Each component in a filter will be manufactured according to requirements on tolerances. The smaller the tolerances are, the more expensive the component will be. These tolerances must be included in the detuning factor in the performance calculations. However, to reduce the detuning factor and also relax the requirements on the tolerances, tuning facilities for the filter are often provided, the most common of which is tappings on reactors.

When reactors with tappings are used, the tolerance requirements on the capacitors can be relaxed. The contractor must assess the cost of providing reactor tappings to cover the reactor's own manufacturing tolerance, plus the range implied by the capacitor tolerances, and choose the values for both tolerances and tappings which give the overall lowest cost solution.

The maximum possible initial mistuning will correspond to half of one reactor tap step plus an allowance for the accuracy of the tuning procedure and measurement equipment. Where a long interval between retuning is required, the filters may be slightly mistuned initially in order to take into account the capacitance change during the service interval due to failures and ageing.

d) Seasonal tuning

In areas where the temperature difference between summer and winter is large, seasonal tuning of the sharply tuned branches filters should be considered. Most existing technical specifications have rejected seasonal tuning; however, seasonal tuning does offer the following advantages:

- cheaper filter,
- lower losses.

The disadvantages are the following:

- necessity of retuning every half year,
- cost of retuning (possible outage cost and labor cost).

8.2.3 Resistance variations

Variations in resistance of the resistors due to temperature changes in the resistor elements must be evaluated by the designer. The resistor elements should have very low temperature coefficient of resistance.

Additionally, the tolerance in Q-factors of reactors has to be considered, especially in the case of sharply tuned filters. The Q-factor and the tolerance will depend on the specified characteristics and the particular design of the reactor in question.

8.2.4 Modeling

To model accurately the factors contributing to detuning, these should be represented individually within the model as they occur in reality. The harmonic frequencies at which the model is solved should correspond to the extremes of the fundamental frequency range, and the maximum variations in the values of each component should be used, always combined in the senses which give maximum overall detuning of the filter.

In the past, it was common practice to use an "equivalent frequency deviation" in filter calculations. Using this method, all filter component parameters are modeled as constant values and the variations in these parameters are taken into account by solving the circuit at an equivalent frequency deviation, which takes into account not only the actual frequency but also the equivalent detuning due to component variations. In Annex C a formula for equivalent frequency deviation is shown.

Although the equivalent frequency deviation method is attractive due to the simplification it introduces, there are strong arguments for not using it, as follows.

- It applies the same deviation to all filters, even though the components for different branches may have different deviations from nominal e.g. different tap step sizes (or no taps) on reactors. With regard to the loss of individual capacitor elements, it is normally not the case that all the filters are simultaneously detuned to the maximum extent.
- It is not strictly accurate for anything other than sharply tuned, high Q-factor filters.
- The worst case may be when identical filters are detuned in opposite directions - this is not allowed for with the equivalent frequency deviation method.
- If other a.c. side components, e.g. shunt capacitors, reactors, transformers or lines are included in the model, then their impedance may be modeled at the wrong frequency when using the equivalent frequency deviation method.

The customer should be aware of these limitations when evaluating a bidder's design methods and calculation procedures. With modern computing tools and modeling techniques, there is no reason for the equivalent frequency deviation to be used for other than possible rough initial calculations.

Consequently, it is strongly recommended that the calculation techniques should model the frequency deviations and individual detunings of the components separately.

8.3 Network impedance for performance calculations

8.3.1 General

The network impedance is one of the most important parameters affecting a.c. filter design with conventional filters, due to the possible resonance phenomena between filter and network.

As the network impedance will change over time due to different operating configurations, connection of loads and generators, and outages of major components, it is essential that the representation used in the studies covers the whole range of possible impedance values. Normally this is done by defining some form of envelope of impedances which encompasses all possible values. An alternative approach is discussed in 8.3.2 below.

Normally, the customer defines the range of network impedance to be used for the filter design, but in some HVDC projects the customer has left the contractor to make his own estimate. As the contractor is unlikely to have access to all the necessary information about the network components, or the facilities to make site measurements, this approach will tend to result in conservative estimates being made, resulting in overdesign of the filters (see also 8.3.2).

It is therefore recommended that the customer should start the work on defining the network impedance early in the genesis of an HVDC project. The network impedance will change with system configuration and load conditions. In addition, possible future changes should be considered. In practice, it can be difficult to obtain an accurate definition. Experience from some earlier projects has shown that specified network impedance diagrams have had lower damping than actually present in the network. If the given impedance is too pessimistic, i.e. the range of impedance magnitudes is too wide and/or the damping too low, then the filter will be more expensive than necessary. Consequently, the effort expended by the customer in definition of the network impedance at different harmonic frequencies may result in significant savings in the cost of a.c. filters.

Various methods of deriving the network impedance have been used. An assessment of different methods and their merits was made by CIGRE/CIRED WG CC02 [56], and a study of network impedance modeling techniques was undertaken by CIGRÉ JTF 36.05.02/14.03.03 [54]. The reader is referred to these sources for further details.

The impedance can be calculated with the help of any computer program with which it is possible to model frequency dependent power system elements [54, 56]; however, the accuracy of these calculations is often limited due to lack of accuracy of input parameters. The result is often a pessimistic estimation of the network impedance and lower damping of the harmonics compared to the real impedance of the network. The correct modeling of the variation of component/branch resistance with frequency, in particular for transformers and loads, is important to determine accurately the damping of the network. Differences in the network harmonic impedance between phases should be considered, especially if the network impedance is dominated by long a.c. lines, bearing in mind that transpositions may not be effective at harmonic frequencies. The calculations should preferably be carried out in the frequency domain, as in the time domain the calculations will be very time-consuming due to the required detailed representation of the system.

Measurements have also been used in some cases; however, this requires special devices with high power output in order to obtain high signal to noise ratio. Further it is very difficult to cover all possible network conditions by making measurements and possible future changes will not be covered.

8.3.2 Network modeling using impedance envelopes

The impedance can be presented in forms of tables for different system configurations or of different types of diagrams. Most commonly used are envelope diagrams such as sector diagrams or circle diagrams, in which an X/R area in the complex impedance diagram is defined for a certain frequency range. The locus of the a.c. system impedance for varying system conditions and at different harmonic frequencies is defined to be within the envelope (borders) of these areas.

When no other information is available about the a.c. network, the borders are often related to the minimum and the maximum short circuit impedance of the system. A simplified approach which has been frequently used defines the maximum and minimum impedances as follows:

$$Z_{\text{max}} = Z_{\text{max}\ s.x} \times n$$

$$Z_{\text{min}} = Z_{\text{min}\ s.c} \times \sqrt{n}$$

with phase angle =

$0^\circ – 80^\circ$	$n < 5$
$\pm 75^\circ$	$5 \leq n < 11$
$\pm 70^\circ$	$11 \leq n \leq 50$

where

$Z_{\text{max s.c.}}$ is the a.c. system maximum short circuit impedance at fundamental frequency;

$Z_{\text{min s.c.}}$ is the a.c. system minimum short circuit impedance at fundamental frequency.

However, customers should be aware that such simplified estimates are unlikely to correspond to the actual system characteristics, and it is strongly recommended that greater effort is put into a more accurate representation.

Special care should be taken as to accuracy in the determination of the value of the minimum impedance, because the harmonic problems will be more critical for the system configuration corresponding to this impedance value. The value of network resistance, i.e. damping, is also highly critical.

Care should be taken in specifying impedance for low order harmonics, particularly at 2nd, 3rd and 5th harmonic. If an excessively large angle (i.e. low damping) is specified for these frequencies, calculations could indicate needs for filters tuned to these frequencies. In certain situations, it is advisable to specify separate diagrams for these frequencies.

The following advantages and disadvantages apply to all impedance envelope diagrams.

The advantages of impedance envelope diagrams are:

- relative ease of preparation by the customer and the ease with which a systematic search for a worst case impedance search technique can be applied by the contractor;
- extensions to the envelopes can be made as possible measures against future system changes and different envelopes can be given for performance and rating conditions.

The disadvantage of impedance envelope diagrams is:

- the inclusion of inapplicable ranges into impedance search area with simple envelopes, even if a restricted frequency range is considered and sectors of different amplitude are supplied for different frequency ranges. The different types of envelope suggested have different tendencies in this respect.

In the following figures, some examples of envelope diagrams are shown and their relative merits evaluated. Other variations of diagrams than those shown are also possible.

8.3.3 Sector diagram

For the sector diagram maximum and minimum angle of the impedance should be given and also the maximum impedance. Either the minimum impedance (Figure 14) or the minimum resistance could be given as the lower limit (Figure 15).

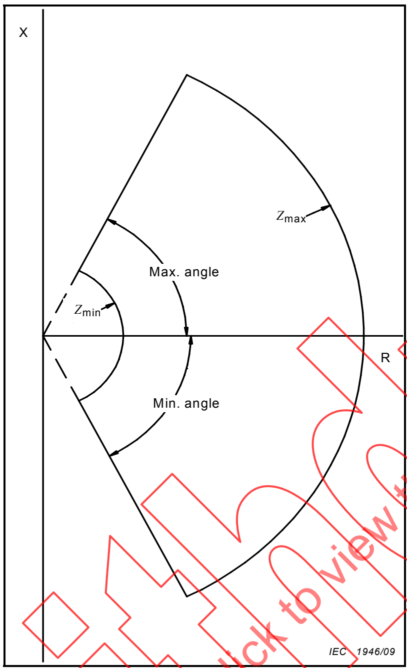


Figure 14 – AC system impedance general sector diagram, with minimum impedance

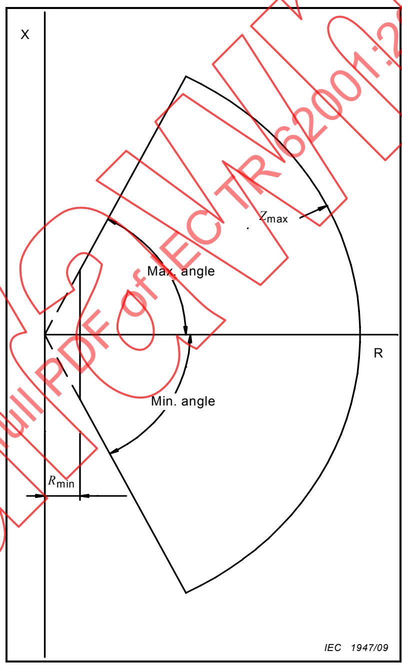


Figure 15 – AC system impedance general sector diagram, with minimum resistance

Advantages of sector diagrams

- Simple to define if little information about the network is available

Disadvantages of sector diagrams

- Where R_{max} in a harmonic range is set by a system parallel resonance, this will define Z_{max} and so result in values of X_{max}, X_{min} which often exceed the actual value
- Max and Min angle values may be relevant for low reactance values but the angles will be lower at higher reactance values

Relative disadvantages of sector diagram with minimum impedance (Figure 14)

- The relationship between Z_{min} and R_{min} is unlikely to correspond to reality; either R_{min} will be too large or Z_{min} will be too small. These values can have a critical impact on the filter design.

8.3.4 Circle diagram

For the circle diagram (Figure 16) the radius of the circle as indicated in the figure should be given. In addition to the radius, maximum and minimum angle and minimum resistance should be given.

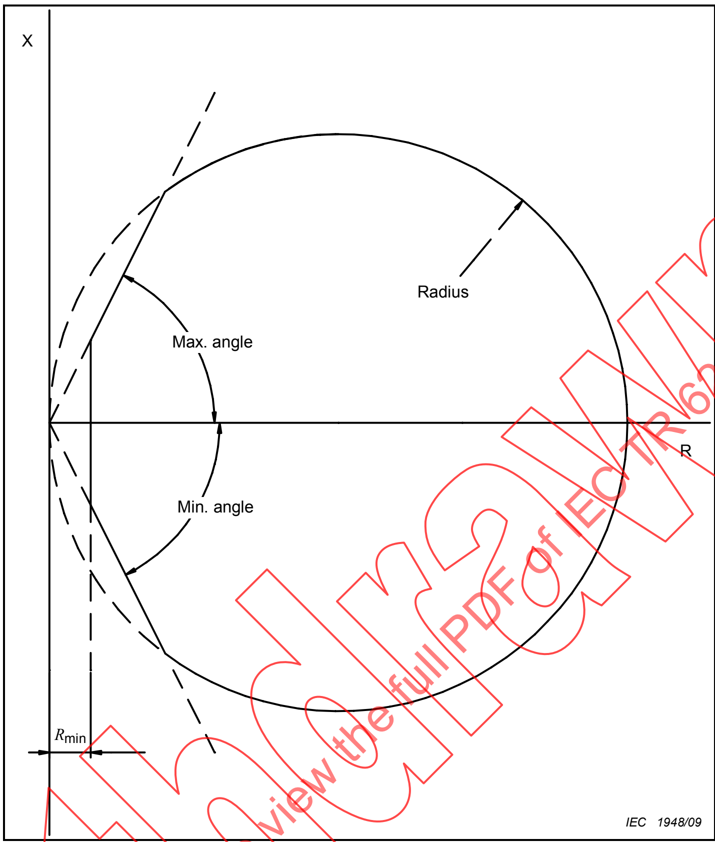


Figure 16 – AC system impedance general circle diagram, with minimum resistance

Advantages of circle diagram

- A better fitting envelope of real values than the sector diagrams
- Particularly, a more realistic approximation for characteristic harmonics 11th, 13th etc.

Disadvantages of circle diagram

- Radius is determined by the largest impedance value in the impedance range, which is generally of a parallel resonance which may apply over a more limited frequency range than that of the complete diagram (or there may be a set of resonances at different frequencies for different system conditions). Hence, this approach could result in the inclusion of an even larger non-applicable area than the sector diagram, particularly in the capacitive reactance sector for the lower harmonic range.

For most cases the circle diagram would be more accurate than the sector diagrams, and is therefore preferred. Even better, however, if sufficient information is available, is the discrete polygon approach described below.

8.3.5 Discrete polygons

For a more accurate representation of network impedance, it is necessary to have different diagrams for different frequency ranges, as the system impedance is frequency dependent. By this means, relatively limited impedance sectors can be defined for each harmonic, thus permitting a more exact matching of the a.c. filter design to the actual network conditions.

Some examples are given in Figures 17 to 20. In Figure 20, the higher order harmonics (below n=14) are defined using a conventional circle diagram, as there is little economic or technical advantage in trying to define a more exact polygon for these frequencies.

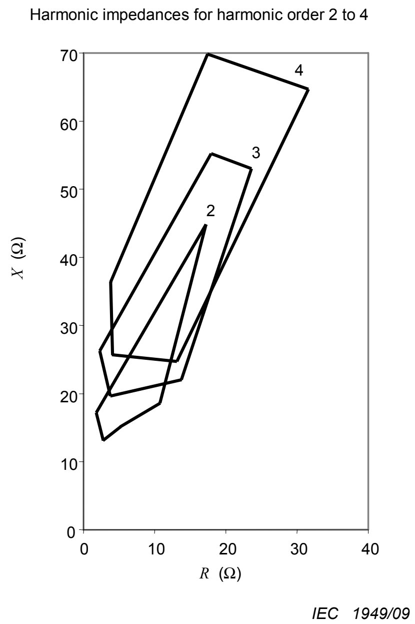


Figure 17 – Example of harmonic impedances for harmonics of order 2 to 4

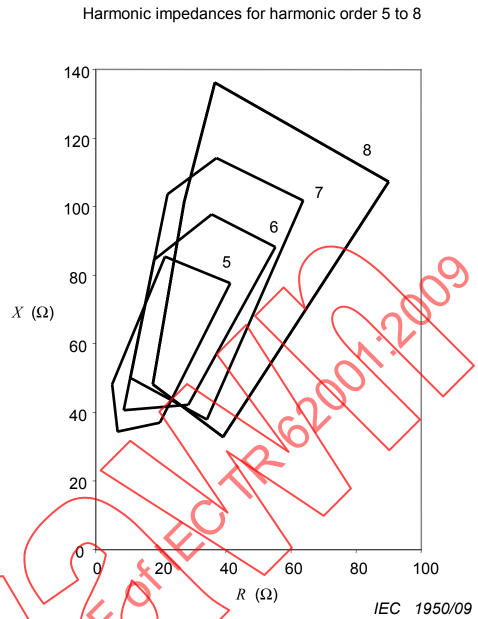


Figure 18 – Example of harmonic impedances for harmonics of order 5 to 8

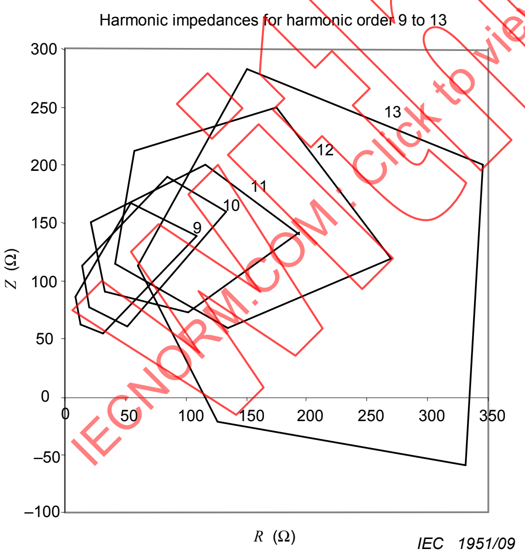


Figure 19 – Example of harmonic impedances for harmonics of order 9 to 13

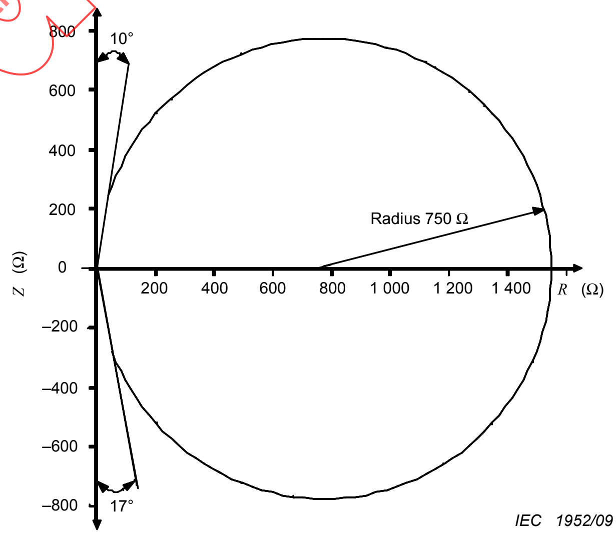


Figure 20 – Example of harmonic impedances for harmonics of order 14 to 49

If the polygons for different groups of harmonics are to be derived by computer program, then it is advisable to include in each polygon the calculated impedance points for one or two additional harmonics at both ends of the range covered. This allows for the possibility that the computer modeling may correctly predict a resonance, but at not quite the correct frequency. An additional margin in impedance magnitudes should also be included to allow for possible modeling error.

Advantages of discrete polygon diagrams

- Eliminate risk of overdesign of filters for low order and 11,13 harmonic characteristics

Disadvantages of discrete polygon diagrams

- Considerably more effort required to define the polygons for each harmonic

8.3.6 Zero-sequence impedance modeling

If the filter performance parameters include a limitation on harmonic currents, in different phases, propagating into the connected a.c. network, the modeling method will be different. The harmonic source will be applied across the point of common coupling (PCC) from where the a.c. lines emanate. For low order harmonics the impedance loci for the three phases may be different, i.e. the zero sequence impedance may be different from the positive/negative sequence impedance, and the lines may have to be modeled with positive/negative and zero sequence impedances. In order to perform exact calculations, the contractor needs the zero sequence data.

HVDC converters, however, have a negligible generation of zero sequence harmonics, and hence the modeling of the zero sequence impedance is normally not critical in this context.

The zero sequence impedance will be more damped than corresponding positive/negative sequence as the zero sequence current will be returned via the earth (and shielding wires) which has a relatively high resistance at harmonic frequencies.

8.3.7 Detailed modeling of a.c. network for performance calculation

In some specific HVDC projects, it may be feasible and desirable to construct a detailed model of the connected a.c. system to be used in the performance calculation instead of the more normal impedance envelope. This has been rarely used in the past because:

- detailed network data is not usually available to the contractor,
- the computation time for each performance calculation is greatly increased,
- large numbers of network configurations may need to be studied for each performance case.

However, if the a.c. network data is known and is relatively constant, and given the computing power now available, the use of a detailed model could be justified. Its major advantage over impedance envelopes is that it shows only the actual feasible network impedances, with full consistency among harmonics, rather than include the many non-feasible values which are encompassed in an envelope. The detailed model is particularly valuable in studying the lower harmonic orders, for which studies using an impedance envelope might erroneously indicate a need for low-order filters.

One case in which the use of a detailed model could be valuable is when the HVDC station is fed by a single long a.c. line. In this case, the a.c. side impedance is dominated by the a.c. line and changes in the network at the remote end of the line will have a relatively minor influence.

Furthermore, the unbalance between phases resulting from the transmission line asymmetry, and coupling between phases along the transmission line, will cause important effects in the harmonic domain. These effects can only be properly represented using a detailed three-phase model, as recommended by CIGRÉ WG CC02 [56].

If a detailed model is to be employed, then it is recommended that a three-phase representation is used, with accurate representation of the characteristics of the a.c. lines, transformers, generators and loads at harmonic frequencies, as discussed in 8.3 above. The network should be represented up to a sufficient electrical distance from the converter such that addition of further lines or loads makes no significant difference to the results. Sensitivity studies of the influence of assumed load models and damping should be made.

At higher frequencies, above about the 20th harmonic [56], it is unlikely that the accuracy of the detailed model will be sufficient, and for these frequencies, the normal impedance envelope should be used.

8.4 Outages of filter banks / sub-banks

Depending on the reactive power requirements on filter bank size and on the maximum voltage step allowed by the specifications for filter switching, the total filter scheme will be divided into a number of filter banks and sub banks. For some smaller projects only one or two filter banks are sufficient. For other projects, division into large number of smaller filter banks / sub banks has been necessary due the system requirements.

Redundancy requirements, meaning that the performance requirements should be fulfilled even with one filter out of service, aim to provide a more flexible and secure system for operation. However full redundancy implies additional cost and also additional space requirements. Redundancy could be obtained by a 2×100 % filter scheme or 3×50 %, 4×33,3 % and so on. The requirements on redundancy will influence the choice of the number of banks and size of each bank and also the types of filter bank used.

The technical specification should state the customer’s requirements regarding redundancy of filters. In addition, the overall reliability and availability requirements will have a strong influence. In order to fulfill the RAM (reliability, availability and maintainability) requirements, the contractor will in many cases have to consider filter redundancy. It should be noticed that an alternative/additional solution for fulfilling RAM requirements may be to rate all the components for higher stresses than indicated in the calculations i.e. an overrating of the components. Further it must not be forgotten that spare components and repair- and replacement-time are also factors in the total RAM evaluation.

In order to limit the cost and complexity of the a.c. filters, the customer should, taking into account the nature of use of the HVDC scheme, consider including the exceptions below to fulfillment of performance criteria.

- All filters should be permitted to be in service (i.e. no filter outage requirements should apply) for calculation of performance at d.c. current (or power) levels above 100 % rated load.
- No filter outage should be specified for rarely used reduced voltage operation, or, if required, performance parameter limits should be relaxed for this mode of operation.
- During emergency and/or short-term outage of filter banks /sub-banks, either no performance limits or relaxed performance criteria could apply (especially for the higher order harmonics).
- During outage of a non-characteristic harmonic filter, if provided, no limits for distortions corresponding to those harmonics may be specified. However where the low order harmonics are critical and may damage equipment in the converter sub-station or equipment in the connected a.c. system if they are not damped, redundancy of these filters may be required.

The rating of the filter components could in some cases be reduced due to requirements on filter redundancy. If, for example, two equal filters were required in order to fulfill the performance requirements, a third filter would be installed for performance redundancy. The maximum rating would therefore be based on two filters always being in service. If, however, no performance redundancy was required, there could still be requirements on rating redundancy, i.e. if one of the two installed filters were not available, the one left should be designed to continue in operation under the given conditions. Thus, the required component harmonic ratings for the case of two installed filters could be approximately double those for the case of three installed filters. This factor may partially offset the cost of performance redundancy requirements.

8.5 Considerations of probability

The usual calculation method for the determination of a.c. filter performance is based on worst case assumptions regarding operating conditions, tolerances and parameter deviations. This method has the benefit of being pessimistic and does not require special information from the customer. However the disadvantage is that the a.c. filter design will be, in most cases, based on unrealistic combinations of parameters and conditions that will probably prevail only for short periods of time. This unrealistic combination of parameters and conditions may lead to provision of filters that in reality are not required.

Many parameters which influence the a.c. voltage and current distortion are statistical in nature; some are variable due to manufacturing tolerance (transformer impedances, initial filter mistuning, firing asymmetries), while others are variable with time (a.c. voltage level, a.c. voltage distortion and unbalance, temperature effects, frequency deviation, network impedance and load level of the HVDC system).

The adverse effects of harmonics are also statistical in nature. The new approach regarding the assessment of emission limits for distorting loads, within the IEC 61000 series (IEC/TR 61000-3-6 (2008)), is to characterize the system disturbance and equipment immunity levels as probability distributions (see Figure 21). The equipment shall not disturb the operation of other equipment in the system and at the same time not be disturbed or damaged by the existing distortion in the system. It is recognized that, in the whole power system, interference can occur on some occasions and therefore there can be significant overlapping between these two distributions. The emission limit of a distorting load can thus be expressed in a statistical way.

Similarly, telephone interference limits recommended by IEEE [58] and CIGRE [41] are determined by statistics. The annoyance level depends on the sensitivity of the users and the connection signal strength. Even then a sporadic occurrence will not necessarily lead to a complaint, indeed higher noise is commonly tolerated for temporary operating modes. It thus seems reasonable to define an interference criteria related to a time probability, for example, a level not exceeded for more than say 5 % of the time. A further aspect of probability within the telephone system is the variation of characteristics such as shielding and balance, which may vary with type of cable, age, corrosion, etc. [41].

While telephone interference limits have not yet been defined in a statistical way in any standard, probability numbers could be very conveniently applied, as the noise is a question of convenience not of damage and it can be mitigated if there is a problem. Therefore an inductive co-ordination study can be performed to assess an economical interference limit for which a reasonable risk can be associated because exceeding the limit would only result in additional mitigation measures and corresponding costs. Even though the interference limits are set according to existing experience, without a detailed study, a statistical limit would have the benefit of resulting in a design which put more emphasis on harmonics likely to cause problems.

HVDC contractors already use statistical methods to determine the non-characteristic harmonic sources, when permitted by the customer's specification, based on relevant data from their manufacturing statistics, e.g. tolerance data for converter transformer leakage impedances. The implementation of a more complete probabilistic approach requires statistical knowledge of the time varying parameters (operating levels, temperature, frequency deviation, a.c. voltage unbalance, harmonics in a.c. voltage, etc.). However such statistical data is seldom available, and some parameters may be interdependent. Moreover, statistical information on the telephone system may not be readily procured. A probabilistic approach for the design of a.c. filter performances is therefore desirable but a great deal of work would be needed to achieve this goal.

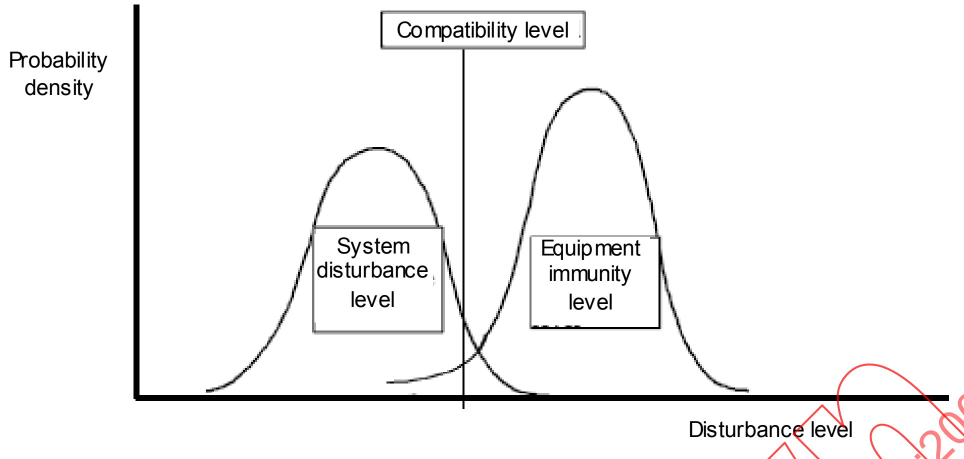
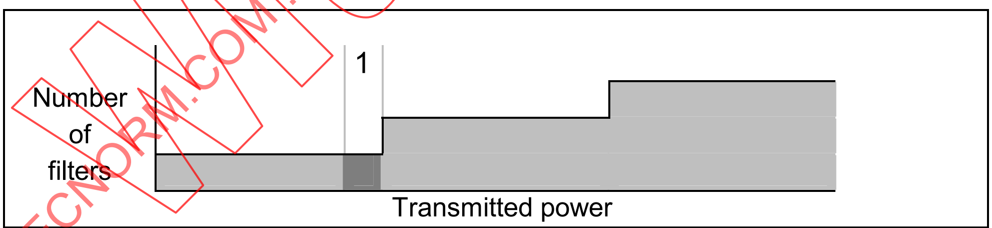


Figure 21 – Illustration of basic voltage quality concepts with time/location statistics covering the whole system (adapted from IEC/TR 61000-3-6 (2008))

It may be adequate for certain installations that the performance requirements are met e.g. for 95 % of the operating time, as earlier described. Such requirements are used for low voltage and medium voltage systems. This would give the opportunity to allow higher harmonic levels for some special operation modes, if the mode is considered to occur seldom and for short duration.

As an example, consider the very small operation range in the switching curve as illustrated in Figure 22. If a narrow band of operation where the requirements are not met, as indicated in the figure, should be decisive for the filter scheme sizing, then additional filters would be required to satisfy performance in just this narrow band of operation. In such a case a consideration of probability should be made as to how often the most critical system configuration and operating conditions will occur at the same time as operation in the narrow band. A result of such an evaluation may be that the probability is so small that the installation of additional filter is not justified.



The requirements are not met for the range indicated as '1'.

IEC 1954/09

Figure 22 – Example of range of operation where specification on harmonic levels are not met for a filter scheme solution

Any probability considerations that should be used in the calculations should be defined in the technical specification. The use of a probabilistic approach for assessing performance should however not remove the obligation to study performance under worst case assumptions, to ensure the safety of plant and other consumers.

8.6 Flexibility regarding compliance

One purpose of the technical specification is to ensure that the contractor delivers an a.c. filter which satisfies the customer's performance requirements. However, some of the criteria might be somewhat arbitrary (for example TIF =40) and some of the data derived by estimation (network impedance for example).

If, in order to meet the specified requirements exactly, a bidder has to propose a filter design which is in some respects clearly not optimal, the bidder should bring this to the attention of the customer. The customer should then be prepared to explore, jointly with the bidder, those areas in which some modification to the exact specified requirements and data could lead to a significant simplification of the a.c. filters. The financial implications of any such modifications would have to be discussed in the context of the contract.

For some projects it could be desirable to delay the installation of some filter banks until the need for such additional filters has been indicated by actual operational experience. This can especially be considered for cases where the calculations show a risk of low order harmonic resonance and the need for a low order filter. If an excessively conservative network model has been used, the installation of a low order harmonic filter may not be necessary in the real system even if the performance calculations have indicated so. In such a situation, provision for space or even foundations could be prepared for the possible later installation of a low order harmonic filter.

9 Filter switching and reactive power management

9.1 General

The design of the a.c. filters is closely linked with the reactive power management of the HVDC converter station. This clause discusses the impact of the reactive power compensation and control on the a.c. filter design, and on the strategy for switching the a.c filters. It indicates points which should be carefully considered by the customer in preparing a technical specification. Background material relating mainly to the reactive power absorption capabilities of the HVDC converters is contained in Annexes.

9.2 Reactive power interchange with a.c. network

9.2.1 General

An a.c. network has an inherent capability to supply or absorb a certain amount of reactive power at all buses for a given range of operating parameters. The maximum permitted amount of reactive power injection and withdrawal, i.e. interchange, at a given bus within the normal operating limits of the bus bar voltages is termed the reactive power absorption and supply capability, respectively, at that bus. In Figure E.3, a typical permitted reactive interchange capability of a system is shown by Curve 4 ($q_{ac(limit)}$). This feature of the a.c. network has a strong influence on the design of reactive compensation equipment and a.c. filters associated with an HVDC converter.

9.2.2 Impact on reactive compensation / filter equipment

The reactive compensation to be provided for an HVDC converter connected at a given bus is dependent on both the filtering requirements and the specified reactive power interchange at that bus. The reactive power compensation requirements comprise the converter reactive power consumption, plus the customer specified converter station interchange requirements as a function of the active power transfer.

In several existing HVDC schemes the total installed reactive power was governed by the reactive power compensation requirements rather than minimum filtering performance requirements. In such schemes the allowable deficit has been the controlling factor as the stations were either to be overcompensated or operated close to unity power factor.

Sometimes a utility may want to use the HVDC station to balance the reactive power in the system and not just obtain a minimum reactive power from the station. In such cases in particular, the overall reactive compensation design should allow flexibility and easy combinations for operators in the control centres.

Liberal interchange limits are desirable from the point of view of a.c. filter design, and result in:

- installation of less reactive power compensation equipment,
- simplified and less expensive a.c. filters,
- less a.c. filter/capacitor switchgear,
- simplified a.c. switchyard layout

and, usually of lesser importance:

- simplified controls,
- lower energy requirement for a.c. bus arresters,
- reduction in maintenance cost of switchgear.

As a rule of thumb, approximately 40 % (of rated converter station power transfer capacity) reactive power compensation can be considered to be adequate so far as the fulfilment of filtering requirements is concerned. Assuming a minimum of around 40 % compensation, then broad reactive power interchange limits generally permit the use of only a few large size simple high pass filters, which have fewer components and thus are less expensive. Narrow limits, on the other hand, will increase the number of switchable filter units required, and possibly also entail the use of more complex filter branches.

With conventional filters, designing with below 40 % compensation will mean less capacitance to devote to filters, and in order to increase per unit effectiveness it may be necessary to use complicated double or triple tuned filter design with high quality factors. Any cost saving due to the total filter size may therefore be lost due to the added complexity.

Shunt reactors may form part of an HVDC converter station to provide inductive compensation for a.c. harmonic filters especially under light load conditions where a certain minimum number of harmonic filters are required to satisfy harmonic performance requirements. In certain cases where the reactive power to be absorbed by the converters is not large, the need for shunt reactors may be obviated by operating the converters at increased control angles; refer to 9.6 below.

Specification of a low value of the a.c. filter performance parameter TIF or THFF may necessitate the installation of shunt reactors to enable connection of more filters of a high pass type, at low d.c. power levels, especially if the interchange limits are restrictive.

The a.c. switchyard layout tends to become complicated when a large number of filter equipment is to be accommodated within a specified limited space. In certain situations, e.g. hilly terrain and proximity to urban area, the saving of even a few square metres is significant and complexities such as multi-level layouts, for saving space, can be avoided if fewer number of filters are used.

The customer in his specification should allow maximum flexibility for the contractor to optimise his filter design in relation to reactive power compensation. Related issues should be discussed with the customer during the design process.

9.2.3 Evaluation of reactive power interchange

Reactive power interchange limits at a commutating bus are determined by the customer concerned by conducting steady state load flow studies under different network conditions. While conducting such studies the customer should:

- consider only plausible a.c. network operating conditions,

- include the impact of active power flow on the HVDC system. This is particularly important if the HVDC is a bulk power transmission link with parallel a.c. lines. Because the variation of active power flow on the HVDC transmission will vary the active power flow on the parallel a.c. lines as well, and this variation in active power loading of the parallel a.c. lines will influence the reactive power interchange capability of the a.c. network,
- make use of the inherent capability of generators to supply or absorb the reactive power,
- cover rare operating conditions by relaxing performance requirements and/or imposing restrictions on HVDC converter operation,
- understand that the choice of reactive power limits can have a crucial impact on the a.c. filter design and costs, and so avoid choosing unnecessarily restrictive limits or “rounded-down” values.

9.3 HVDC converter reactive power capability

After having determined the allowable reactive power interchange with a.c. network, the inherent reactive power absorption capabilities of HVDC converters can be exploited as far as possible to fulfil the specified interchange requirements.

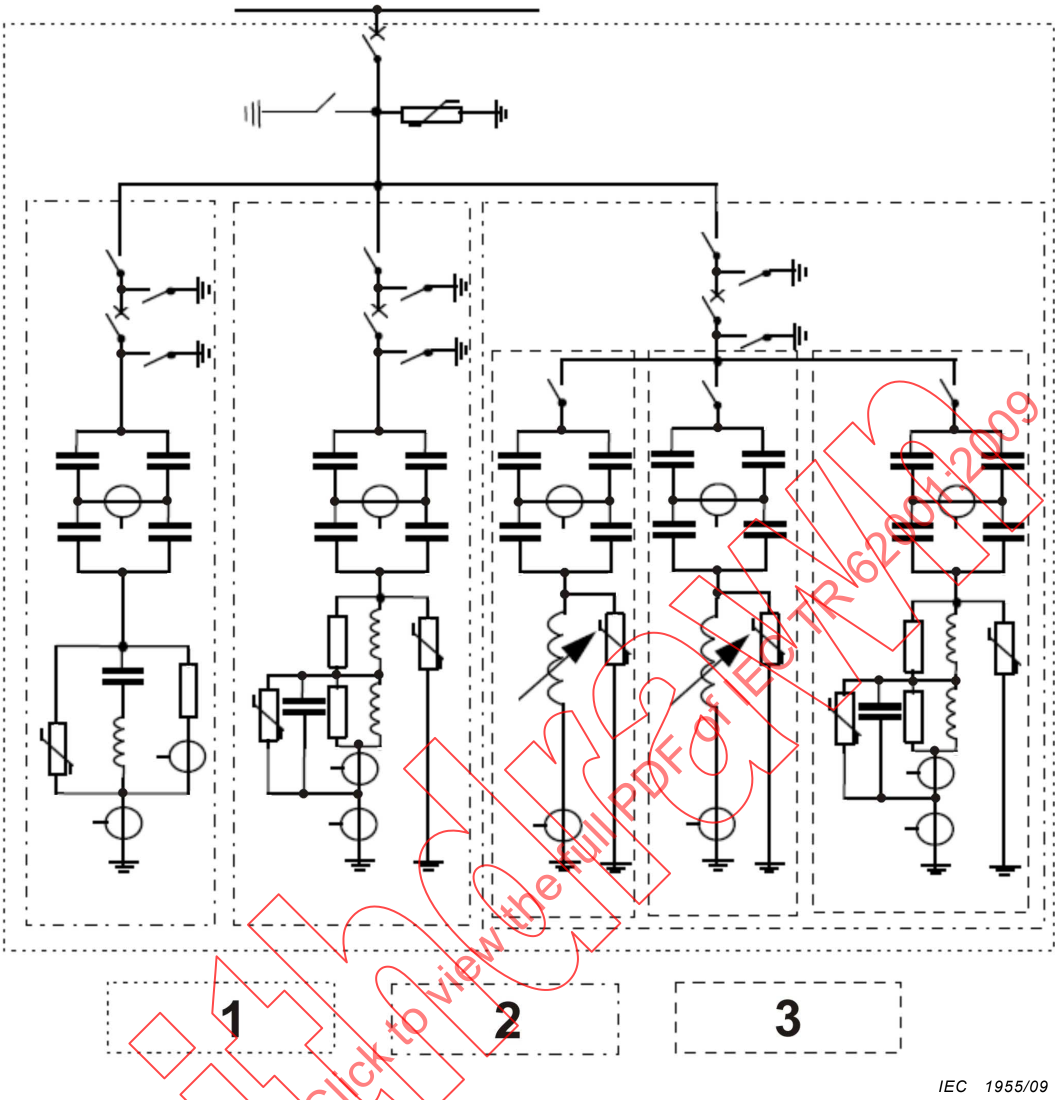
The reactive power capability of the converter under steady-state and temporary conditions is discussed in Clause E.1.

9.4 Bank / sub-bank definitions and sizing

For the purpose of filtering and reactive power control, capacitors, reactors and resistors are interconnected to form different type of filters, normally shunt type. These filters are grouped so as to fulfil the requirements in respect of filtering performance, reactive interchange and step change in the commutating bus voltage during switching. Such groups are called bank, sub-bank and branches depending on their electrical arrangement.

It is vital that the technical specification is clear in its definition of these terms, especially when related to requirements on performance under outage conditions and the maximum permitted filter outages under which operation must be able to continue.

The normally used definitions are given below and a typical arrangement illustrating the definitions is shown in Figure 23.



Key

1 bank

2 sub-bank

3 branch

NOTE Sections of filter are defined by the type of broken line enclosing them.

Figure 23 – Branch, sub-bank and bank definition

9.4.1 Terms and definitions

9.4.1.1
branch
arm

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

NOTE In interconnected arrangements, it forms a smallest tuned filter unit.

9.4.1.2
sub-bank

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

NOTE The switch does not necessarily need to have fault clearing capability.

9.4.1.3
bank

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

9.4.2 Sizing

The size of a branch, sub-bank or bank is described, normally, in terms of net reactive power injected into its point of connection (for a branch) or commutating bus (for a sub-bank or a bank) at nominal a.c. system fundamental frequency, commutating bus voltage and rated component values.

The effectiveness of a conventional passive filter in suppressing a particular or a set of harmonics is, generally, directly proportional to its size. Large limits for reactive power interchange and step change in voltage result in fewer sub-banks/banks and simple damped filters. However, the maximum size of a sub-bank/bank is also governed by the available breaker capability.

The choice of size is a function of:

- specified reactive power interchange,
- filter performance requirements,
- step change in voltage on switching,
- voltage of the connecting bus,
- redundancy requirements.

These factors are elaborated below.

The impact of reactive power interchange and filtering performance requirements on overall sizing is discussed above 9.2.1.

The step change in voltage on filter switching is a decisive factor in the sizing. The specification of a very small step will require small size filter sub-banks/banks and thus will lead to a more expensive solution due to the increased number of filter sub-banks/banks and also on account of their un-economical sizes. This will also increase the number of switchings resulting in increased maintenance requirement on the switchgear.

On the other hand, a large step change in voltage could adversely affect the a.c.-d.c. system; for instance, a 5 % steady state voltage change could mean that every switching operation at the station would be accompanied by several converter transformer tap changer operations and operations of automatic on-load tap-changers on transformers close to the station. In some cases, the ownership of these transformers may not be the same as the d.c. system, a factor which has to be considered. Consideration should also be given to other voltage controlling devices in the a.c. system, including generation, synchronous condensers, SVCs and automatically switched capacitors and reactors in the a.c. system and the impact of a large steady state voltage change on these devices.

Determination of the steady state step change in voltage under HVDC converter de-blocked and blocked conditions is discussed in Clause E.3. Limitation of the transient step change in voltage on switching is almost always dictated by the need to reduce annoyance due to light flicker, and to eliminate changes in d.c. power transfer due to commutation failure or d.c. control mode changes.

Therefore, the specified step change in voltage should be such that it optimally takes care of the above mentioned concerns of both the d.c. and the a.c. systems.

The permissible steady state voltage change caused by switching of filters should be governed by the prevailing norms of the customer. In the absence of any norms, a conservative approach would be to specify a limit in the range between 1 % and 2 %. However, in this case, the customer should be prepared to discuss with the bidders the impact of the specified voltage step on the a.c. filter design and costs, and to consider modification of the specified limit if it has a critical impact. There are some situations where a larger voltage change, say 3 % to 5 %, may be permitted, such as:

- when connecting to a weak a.c. system where it is known that the a.c. system strength will increase shortly after the d.c. is installed, or
- where the converter a.c. bus is new, electrically remote from the existing a.c. system and is not servicing any local load.

As regards the transient step change in voltage, for frequent switching operations (in the order of 5 or more times per day) a transient voltage change of 2 %, and for less frequent daily switching operations a transient voltage change of 3 % is quite normal. For very infrequent switching operations, (5 to 10 per month) larger variations could be acceptable (say up to 5 %) but this must be compared to the voltage change which could be expected for other switching operations of the same frequency, for example line energization. This can be justified in view of the prevailing use of modern state of the art HVDC controls and thyristor valves technologies which help avoid commutation failures and other transient disturbances.

The voltage of the connecting bus refers to the fact that for a given high voltage there is a minimum economic size of capacitor bank (which depends on the number of series connected capacitor units), and hence filter size.

For those instances where it is not possible to satisfy the balance of reactive interchange requirements and/or switching step requirements allied with “economic” filter sizing, it may be feasible to connect the filters to a third winding (of lower voltage) of the converter transformer (see Clause 7).

Redundancy requirements may or may not affect the total installed filter size depending on whether they are at component, branch, sub-bank or bank level. A redundancy requirement at bank level will make filter solution quite expensive, and, therefore, it should not be resorted to unless it is vital from the operational or station reliability and availability points of view.

All of these factors are specified by the customer and the contractor should carry out the sizing based on these inputs and his own design optimisation.

9.5 Hysteresis in switching points

Switching-in points of filter sub-banks/banks, at increasing converter power levels, are determined on the basis of:

- minimum filtering,
- reactive power requirements of the converters, and
- allowable reactive power import from the connected a.c. network.

Ideally, switching-out points, at decreasing converter power levels, could be the same as the switching-in points. However, it is desirable to avoid frequent switchings which could take place due to variation of converter power around an operating point. (Such variation could be due to a.c. system dynamics forcing HVDC converter to adjust its power level. This adjustment of power level could be ordered by higher level HVDC controllers such as power oscillation damping and frequency controllers.)

In order to avoid wear and tear of sub-bank/bank breakers and network operational nuisances (e.g. voltage flicker), sub-bank/bank switching-out is normally made at a lower converter power level than switching-in. In other words, the two points are separated from each other by a certain amount of converter power, normally approximately 5 % of nominal power. This is not a critical value and should be open for discussion if it significantly influences the filter design.

This difference between switching-in and switching-out points, in terms of active power, of a sub-bank/bank is known as the “hysteresis” or “dead-band ”.

The maximum hysteresis between switching-in and switching-out points which could be allowed is dependent on:

- converter reactive absorption corresponding to approximately 5 % active power variation around rated power,
- the largest sub-bank/bank size,
- change in reactive power generation, due to switching of the largest sub-bank/bank, of the prior connected sub-bank/banks, and
- change in reactive power absorption of the inverter due to switching of the largest sub-bank/bank (this is applicable for calculating maximum difference between switching-in and switching-out points for the rectifier only).

HVDC manufacturers have developed other, more sophisticated strategies for achieving the same effect as simple hysteresis, that is, avoiding unnecessary frequent switchings, and these strategies may be preferable in some applications. The general intention of such strategies is to reduce or eliminate the dead-band in the power range and so facilitate a simpler and more economic filter design. The customer should be aware that such options exist and be careful that the wording of the specification permits such solutions to be offered.

There could be special situations in a network in which there are sustained voltage oscillations following disturbances and where economics may not favour installation of an SVC to damp out voltage oscillations. The customer may decide to assign this additional task to the reactive power controller (RPC) of the HVDC station which is planned at that bus bar. In such an instance, an intentional time delay may have to be introduced, in addition to the above described hysteresis, in the RPC.

Though not related to hysteresis, it is an operational consideration that a certain minimum time should be allowed for discharge before a branch/sub-bank/bank is reconnected. The amount of time delay depends mainly on discharge resistors used in the capacitors. If for operational reasons it is necessary to re-energise the branch/sub-bank/bank in a shorter period, discharge voltage transformers (DVT) can be employed. Although this is an expensive solution, it may be feasible to use these DVTs for another purpose, for example, protection.

9.6 Converter Q-V control near switching points

The use of the HVDC converter to control the a.c. bus voltage at, and close to, the filter switching points may be required in certain situations. This feature makes use of the temporary reactive power absorption capability of the converter, and is discussed in Clause E.2.

9.7 Operation at increased converter control angles

Normally, converter operation at increased alpha/gamma is associated with operation of a long distance power transmission link at reduced d.c. voltage. However, stringent reactive power export limit also requires HVDC converters to operate continuously at high firing/extinction (alpha/gamma) angles, particularly at low converter power levels. Vindhyachal HVDC back-to-back link in India is such an example. In this scheme the customer’s specifications for reactive interchange with a.c. network were as low as ±10 MVAr. The converters are designed for continuous operation at high control angles. At low active power level the control angles are as high as 55° and at the rated power they are around 30°.

Other HVDC schemes using a similar type of control philosophy are Durnrohr, Blackwater, Etzenricht, Gezhouba-Shanghai, Welsh and Chandrapur back-to-back. Under too stringent reactive power interchange limits, in addition to increased alpha/gamma operation, the use of shunt reactors and their simultaneous switching with filter sub-banks is also required.

This mode of operation is particularly used during low power transfers when in order to meet filtering requirement more filters are required to be put into service, doing which could violate reactive power interchange limits with the a.c. network. However, operation at increased firing angles has certain disadvantages which are discussed in Clause E.1.

9.8 Filter switching sequence and harmonic performance

Filter switching-in points are determined by filtering and reactive power requirements as discussed in 9.5. The type of filters to be used is decided by the stipulated filtering requirements and harmonic impedance of the a.c. network. Base filters have to have branches tuned for dominant characteristic harmonics and are switched in first so as to meet the performance criteria and avoid overloading of damped filters such as high pass 24th harmonic branches, which are normally switched in at higher d.c. power levels.

The switching-out sequence is normally the reverse of the switching-in sequence.

Usually (except for possibly at low d.c. power levels), the switching-in points which would be required to satisfy performance requirements (the so-called "minimum filter" requirements) occur at higher d.c. power levels than the actual switching-in points, which take into account both filtering and reactive power requirements. Especially at higher converter power levels, the number of banks/sub-banks to be put in service is usually dictated by the converter reactive consumption and import limits.

A typical switching sequence is shown in Figure 24. In this figure the reactive power interchange with the a.c. network shown by curve 1 is the actual reactive power interchange ($q_{aintchng}$) for a typical a.c. filter solution whereas curve 4 gives maximum permitted reactive power interchange ($q_{ac(limit)}$) with the a.c. network.. Curve 2 gives the converter reactive power absorption. The sub-bank/bank switching points are shown by the curve 3. Figure 25 gives a diagrammatic representation of these reactive power components.

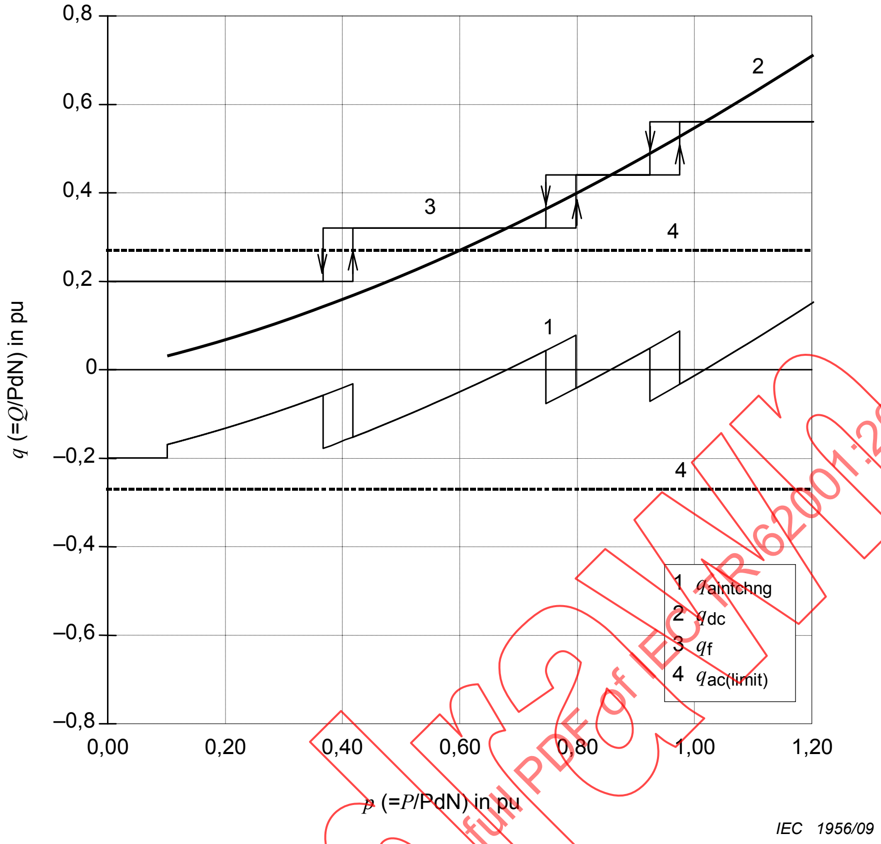


Figure 24 – Typical switching sequence

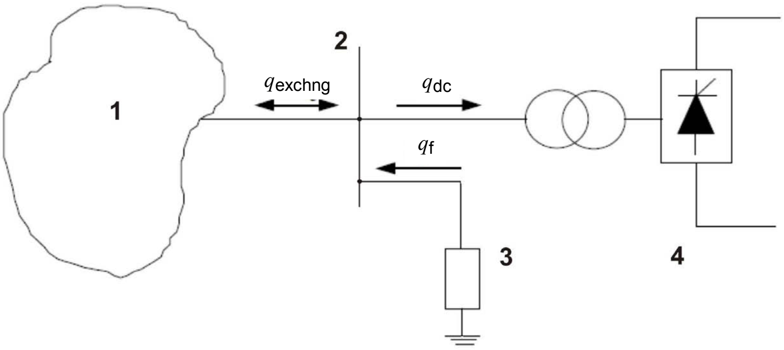
9.9 Demarcation of responsibilities

The customer and the contractor respectively should be responsible for the activities identified below.

9.9.1 Customer

The customer should define the following in his technical specification.

- Reactive power interchange limits and the applicable busbar voltage or range of voltages over which the limit is applicable. In addition, it should be stated which a.c. frequency range and HVDC system modes of operation apply, and whether the capacitor tolerance, temperature variation, commutation reactance range and control angle ranges have to be taken into consideration.
- Minimum short circuit power level at the converter a.c. bus.
- Maximum limit on step change in voltage on switching of reactive power elements or a.c. filters.
- Any requirement on filter switching hysteresis.



Key

1 a.c. network

2 converter a.c. bus

3 a.c. filter/reactive power elements

4 HVDC converter

Figure 25 – Reactive power components

9.9.2 Contractor

All other remaining activities, as discussed above, fall within the responsibility of the contractor.

10 Steady state rating

10.1 General

The calculation of the steady state ratings of the harmonic filter equipment is the responsibility of the contractor. This clause gives guidance on the calculation of equipment rating parameters and the different factors which must be considered in the studies. It is the responsibility of the customer to provide the appropriate system and environmental data and also to clarify the operational conditions, such as filter outages, network contingencies etc, which need to be taken into account.

10.2 Calculation method

10.2.1 General

Steady state rating of filter equipment is based on a solution of the following circuit which represents the HVDC convertor, the filter banks and the a.c. supply system. See Figure 26.

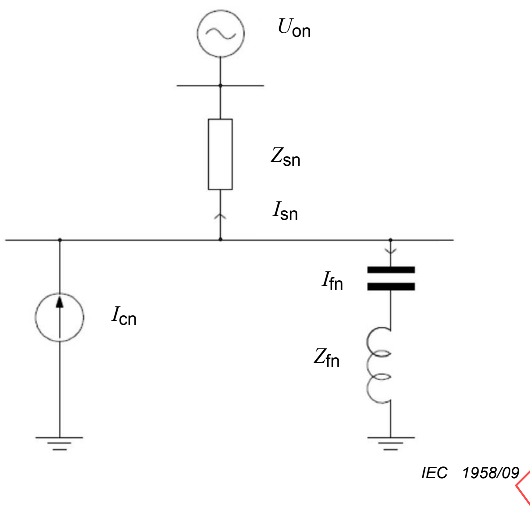


Figure 26 – Circuit for rating evaluation

The harmonic current flowing in the filter is the summation of two components, the contribution from the HVDC convertor and the contribution from the a.c. supply network.

Using the principle of superposition, the following equations can be used to evaluate the contribution to the harmonic filter current of order n from these two sources.

a) HVDC convertor

$$I^{i}_{fn} = \frac{Z_{sn}}{Z_{sn} + Z_{fn}} \times I_{cn} \tag{10}$$

where

I^{i}_{fn} is the filter harmonic current from the convertor;

I_{cn} is the converter harmonic current;

Z_{fn} is the filter harmonic impedance;

Z_{sn} is the network harmonic impedance.

b) a.c. supply network

$$I^{ii}_{fn} = \frac{U_{on}}{Z_{sn} + Z_{fn}} \tag{11}$$

where

I^{ii}_{fn} is the filter harmonic current from the system;

U_{on} is the existing system harmonic voltage.

The definition of network impedance is described in 10.5.

To solve Equations (10) and (11) the following independent variables need to be known.

- The harmonic current (I_{cn}) produced by the rectifier or inverter of the HVDC station needs to be calculated for all harmonics (see Clause 5). This evaluation must consider the worst case operating conditions which can occur in steady state conditions, i.e. for periods in excess of 1 min. The extreme tolerance range of key parameters, e.g. converter transformer impedances, operating range of the tap changer, etc, need to be taken into account. Harmonic interaction phenomena, a discussed in Clause 6, must also be taken into account.

- The pre-existing system harmonic voltage, as discussed in 10.2.2.
- The harmonic impedance of a.c. network (Z_{SN}) is discussed in 8.3. Note that different values of Z_{sn} may be defined for the calculation of $I^{i}{}_{fn}$ and $I^{ii}{}_{fn}$, depending on how the pre-existing harmonic distortion is specified (see 10.2.2).

The harmonic impedance of the filter (Z_{fn}) needs to take account of the de-tuning and tolerance factors discussed in 10.4.

The effect of interharmonics (see 4.2.4 and Clause 6), although small, should also be taken into account in the calculation of filter component rating.

10.2.2 AC system pre-existing harmonics

It is important that the effects of pre-existing harmonic distortion on the a.c. system are included in the filter rating calculations. Conventionally this has been accommodated not by direct calculation as shown above, but by creating an arbitrary margin of a 10 % to 20 % increase in converter harmonic currents (I_{cn}). However, such an approach may not adequately reflect the low order harmonic distortion (typically 3rd, 5th and 7th) which exists on many power systems. As modern converter stations produce only small amounts of such low order harmonics a simple enhancement of the magnitude may not adequately reflect their potential contribution to filter ratings.

To model a multiplicity of harmonic current sources in a detailed network model is impractical for the purposes of filter design. Therefore, it is proposed that a Thevenin equivalent voltage source is modelled behind the a.c. system impedance, as shown in Figure 26, to create an open circuit voltage distortion at the filter busbar, i.e. the level of distortion prior to connection of the filters. The magnitude of the individual harmonic voltages can be based on measurements or on the performance limits, but limited by a value of total harmonic distortion. This approach provides a more realistic assessment of the contribution to equipment rating caused by ambient distortion levels.

10.2.3 Combination of converter and pre-existing harmonics

As there is no fixed vectorial relationship between $I_{fn}{}^{i}$ and $I_{fn}{}^{ii}$, it is proposed that these individual contributions to filter rating are summated on root sum square (RSS) basis at each harmonic,

$$I_{fn} = \sqrt{I_{fn}^{i2} + I_{fn}^{ii2}} \tag{12}$$

For pre-existing harmonics, of relatively low magnitude, RSS summation is reasonable, as some harmonics may be in phase and others not, and as these relationships will vary with time and operating conditions.

Alternatively, linear addition would provide greater security against the possibility of the contributions at a significant frequency being approximately in phase, but would entail an increase in cost, particularly if used for the voltage rating of the high voltage capacitors.

Linear addition should be considered for any pre-existing individual harmonic of such magnitude that linear addition would significantly affect the current rating of the components. Otherwise, if in practice the two sources were in phase for a period of time, the filter could trip on overcurrent protection. If linear addition is to be used, care should be taken to ensure that the conditions under which the two currents are calculated are consistent, i.e. the calculated currents can occur simultaneously in practice.

10.2.4 Equipment rating calculations

The total filter current is derived as above for each harmonic order from 2nd to 50th inclusive. It is important that this range is covered to ensure that any resonance conditions between the filters and the a.c. network and between different filters are inherently considered. Harmonics above the 50th order are unlikely to have a significant impact on the total rating values and can be ignored.

The calculation of I_{fn} for each connected filter allows the spectrum of harmonic currents in each branch of the filter to be evaluated. From this current data individual element ratings can be calculated.

a) Capacitor

From the spectrum of currents in the capacitor bank (I_{fcn}) the total RSS current can be calculated as

$$I_c = \sqrt{\sum_{n-1}^{n=50} (I_{fcn})^2} \qquad (13)$$

This current is used for capacitor fuse design, and both maximum and minimum values are required.

The magnitudes of the spectrum of most significant harmonic currents should be specified.

As the voltage rating of the high-voltage capacitors is the most significant factor in determining the total cost of the a.c. filters, the question of which formula is used to derive this rating should be carefully considered. There have been many discussions among utilities, consultants and manufacturers in the past regarding this point. The most conservative assumption in deriving a total rated voltage would be to assume that a.c. system resonance occurs at all harmonics and that all harmonics are in phase. However, the use of this assumption for an HVDC filter capacitor would result in an expensive design with a large margin between rated voltage and what would be experienced in reality. In practice, amplification due to filter-a.c. system resonance may take place at some harmonic frequencies, but not at most. Similarly, some harmonics may be in phase under some operating conditions, but in general the harmonics have an unpredictable phase relationship. Other approaches have therefore been formulated by HVDC users and manufacturers in an attempt to ensure an adequate design at a reasonable cost.

The issue is therefore one of perceived risk against cost, and due to the diversity of existing opinions it is not possible to give a clear recommendation here. Various approaches are discussed below. All have been used successfully in practice on different HVDC schemes.

- In the most conservative approach, the maximum voltage (U_m) can be calculated as an arithmetic sum of the individual harmonics and the fundamental, that is

$$U_m = \sum_{n=1}^{n=50} I_{fcn} \times X_{fcn} \qquad (14)$$

where

X_{fcn} is the harmonic impedance of order n of the capacitor bank.

However, such an evaluation, especially when based on simultaneous resonance between the filters and the a.c. system at all harmonics, is overly pessimistic, as it assumes that all harmonics are in phase, and will result in an expensive capacitor design.

A more realistic method is to use Equation (14) but to assume that only a limited number of harmonics are considered to be in resonance (e.g. the two largest contributions) and all other harmonics are evaluated against an open-circuit system or fixed impedance. However, this method still assumes that all harmonics are in phase, which will not be the case in practice.

In a further approach, all harmonics are assumed to be in resonance, but Equation (14) is modified such that only the fundamental and largest harmonic component are summed arithmetically. All other harmonic components of voltage are summed on an RSS basis and added arithmetically to the sum of fundamental and largest harmonic components to evaluate U_m. This "quasi-quadratic" summation thus takes account of the natural phase angle diversity between individual harmonic components.

$$U_m = U_1 + U_{no} + \sqrt{\sum_{n=2}^{n=50} U_n^{\ 2}} \qquad (15)$$

where

U_1 is the fundamental component;

U_{no} is the largest component of all harmonic voltages;

U_n is the individual harmonic components of order n excluding the largest component.

The above may be taken a step further by adding only the fundamental component to the RSS summation of all harmonic components, again assuming resonance at all frequencies.

$$U_m = U_1 + \sqrt{\sum_{n=2}^{n=50} U_n^{\ 2}} \qquad (16)$$

This is less conservative than the method used in Equations (14) or (15), but has been substantially applied in practice and has proved adequate. The assumption of resonance at all harmonics, and the use of worst-case assumptions regarding tolerances in the calculations, provide some margin in the capacitor rating, which is assumed to cover the eventuality of phasor summation being more severe than is implied by Equation (16).

As capacitors manufactured to certain international standards have up to a 10 % prolonged overvoltage capability, it is permissible to assign a rated voltage (U_N) for the capacitor bank up to 10 % below U_m, i.e.

$$U_N = U_m /(1{,}0 \text{ to } 1{,}1) \qquad (17)$$

However, the value of U_N calculated from Equation (17) should be at least equal to the maximum fundamental frequency voltage on the capacitor bank. If this is not the case, then the assigned U_N should be the maximum fundamental frequency voltage.

NOTE In the above definitions U_n is used to denote a harmonic component (n = 1 to 50) and U_N is used to denote the capacitor bank rated voltage (as per IEC 60871-1 (2005)).

When low voltage capacitor banks are installed in filters, e.g. in double or triple frequency filters (see 7.4.2, 7.4.3, 7.5.2) the rated voltages calculated as above may not be suitable. For such banks the rated voltage may have to be increased to ensure that the banks can withstand the transient stresses, as discussed in 11.4.

From the spectrum of harmonic currents the equivalent "thermal" reactive power rating of the capacitor (single phase) can be calculated as

$$Q_c = \sum_{n=1}^{n=50} I_{fcn}^{\,2} X_{fcn} \tag{18}$$

The reactive power rating of the capacitor (single phase) is based on rated voltage (U_N) and fundamental frequency impedance (X_{fc1}) as

$$Q_c' = U_N^{\,2} / X_{fc1} \tag{19}$$

Due to the arithmetic or "quasi-quadratic" addition of harmonic voltages in Equation (14) Q_c' normally exceeds Q_c. However, in cases where the harmonic currents are large in comparison with the fundamental current Q_c can exceed Q_c'. In such cases, an increased rated voltage may need to be specified such that Q_c' = Q_c. In practice, this may be dealt with by specifying the magnitudes of the most significant individual harmonic currents.

b) Reactors

The harmonic current (I_{fln}) spectrum and the total RSS harmonic current need to be specified to the manufacturer to ensure adequate thermal design is achieved and the basis of thermal type tests is correctly evaluated. The rating of the reactor is based on

$$I_l = \sqrt{\sum_{n=1}^{n=50} I_{fln}^{\,2}} \tag{20}$$

$$Q_l = \sum_{n=1}^{n=50} I_{fln}^{\,2} X_{fln} \tag{21}$$

where

X_{fln} is the harmonic impedance of order n of the reactor.

To ensure that surface stress across the reactor does not exceed the design capability, the rated voltage across the reactor should be specified as

$$U_l = \sqrt{2} \sum_{n=1}^{n=50} I_{fln} X_{fln} \tag{22}$$

During routine switching and when the filter is subjected to fast-fronted surges, very high transient stresses can appear across the reactors. As discussed in Clause 10, these need to be allowed for in the reactor design and hence included in the equipment specification.

c) Resistors

The thermal current loading can be expressed from the harmonic current (I_{frn}) spectrum as

$$I_r = \sqrt{\sum_{n=1}^{n=50} I_{frn}^{\,2}} \tag{23}$$

The power rating of the resistor is therefore

$$P_r = \sum_{n=1}^{n=50} I_{frn}{}^2 R \tag{24}$$

To ensure that the resistor elements and bank insulation do not suffer flashovers due to the applied voltage, the rated voltage across the resistor should be specified as

$$U_r = \sqrt{2} \sum_{n=1}^{n=50} I_{frn} R \tag{25}$$

This figure, U_N, should become the basis for the determination of the creepage distance for resistor internal support insulation (see also 10.2.5). Although the choice of an arithmetic summation of fundamental and harmonic voltages appears to be unduly pessimistic and in conflict with the general approach to insulator creepage distances, the internal insulators are subjected to unusual operating conditions. The effects of atmospheric pollution can result in significant built-up of deposits on insulator surfaces which are not subject to washing by rainfall. During normal operation, the insulators experience elevated temperatures, typically 100 °C to 300 °C, increasing the risk of surface flashovers. Maintenance has typically been performed on an annual basis, but some customers are now extending maintenance intervals to 3 years. Thus a conservative approach on the above basis for internal insulation creepage may be necessary.

During routine switching of damped filters and under fast-fronted surge conditions as discussed in Clause 11 the resistors can experience very high stresses. These predicted stress levels need to be included in the equipment specification.

10.2.5 Application of voltage ratings

The voltage ratings for the equipment as defined above can be used to define the minimum level of the Maximum Continuous Operating Voltage (MCOV) for surge arresters. The full duty on the surge arresters will be determined from the studies described in clause 11.

The use of arithmetic or quasi-arithmetic summation of fundamental and harmonic voltages for individual items of equipment is intended to provide security against loading conditions which may occur only for short periods of time.

However, it would be unduly pessimistic if these voltages become the basis for the calculation of external insulation creepage distances. It is recommended that the voltage to be used for the calculation of total creepage distance should be the quadratic sum of the steady state fundamental and harmonic voltages. Thus different external creepage distances would be evaluated at various locations within a filter with graded insulation.

10.3 AC network conditions

Filter equipment should be rated for operation at the steady state voltage range of the a.c. system, typically 0,95- 1,05 pu of nominal on an EHV system. For voltage excursions in excess of this value the time duration of the overvoltage should be specified.

10.4 De-tuning effects

To ensure that filter equipment rating is sufficient to withstand lifetime operation, the following factors need to be considered:

- equipment tolerances: the extreme guaranteed range of tolerances should be used for rating studies. Unlike other effects considered here which are subject to cyclic variation, any effects due to manufacturing tolerance will persist for the equipment's lifetime;
- frequency variation: whereas normal anticipated frequency variations should be used for performance, extreme variations must be considered for rating. These extreme

conditions maybe specified as continuous or for specific time periods. The former will define continuous ratings whereas the latter will define short time overloads;

- temperature variation: whereas maximum and minimum average temperature should be considered for performance studies, absolute maximum and minimum temperatures should be considered for equipment rating. As discussed previously the temperature will affect the capacitance value and hence will de-tune the filter. In addition cold temperature conditions are of particular importance for capacitor banks, especially for energization conditions;
- tap position on reactors: adjustable taps are often provided on reactors for tuned filters to off-set capacitor tolerance effects. The effect of tap position on the tuning of the filter and its subsequent rating must be considered;
- capacitor unit failure detection schemes normally have three set levels; alarm only (first stage), alarm plus impending timed trip (second stage) and instantaneous trip (third stage). Capacitor bank rating must cater for the loading condition when operating under the second stage alarm. In some cases only a 2 stage scheme will be implemented and rating need only consider the first alarm stage;
- when multiple tuned banks of the same type are installed, it is important to consider possible circulating currents between the banks due to differences in tuning. Such currents will need to be considered for filter equipment rating. However, measures to control this effect, such as the use of paralleling buses, can be used if the filter layout is suitable.

10.5 Network impedance for rating calculations

The representation of the a.c. network harmonic impedance (Z_{sn}) for the purposes of equipment rating should be different from that used for predicting performance. As discussed in 8.3 a number of different distinct geometric shapes can be used to define the harmonic impedance for performance studies. His data should cover all normal and plausible contingency network operating conditions and load conditions anticipated throughout the lifetime of the equipment. For rating studies a wider range of network conditions may be used to ensure that equipment ratings are adequate for the anticipated lifetime. This can be achieved by specifying larger search areas and/or increased system angles. It is important to ensure that realistic levels of minimum resistance are considered to avoid undamped resonance conditions occurring.

The detailed specification of the network harmonic impedance by the customer has a direct bearing on the ratings, and hence costs, of the filter equipment.

In some cases, the zero sequence impedance of the system may be required to evaluate the voltage unbalance on the converter bus following un-symmetrical faults, such as a line to earth fault. The resultant negative sequence voltage component is used for the purpose of short time (0,1 s to 1,5 s, depending on line protection philosophy and auto-reclose features) rating of low order, mainly third, harmonic filters.

10.6 Outages

Filter equipment must be rated to withstand the increased harmonic loading which will occur when a defined number of filters are out of service. The specific outage requirement will vary from project to project and will depend upon the number of filters available and the level of power transfer required. Typically, the outage of one switched filter or filter group should not result in an overload of the remaining filters or the need to reduce power transfer. In the event of one filter or filter group being out of service for maintenance and a trip occurring on a second filter or filter group, it is strongly recommended that the customer reduces d.c. power to prevent filter overload and hence cascade filter trips. The specification should clearly define the customer's specific outage requirement criteria to be followed by the contractors in the preparation of the proposal.

In order to avoid the costs associated with installing redundant filters, or rating filter equipment for filter outages, the customer may choose to allow a reduction of transmitted d.c. power to avoid filter overload. Such a strategy can have a significant effect in reducing filter costs, especially in relatively low power schemes where the number of installed filters is small.

In cases where switched filters are used as part of the reactive power control, the filter equipment must be rated for all viable switching strategies.

11 Transient stresses and rating

11.1 General

In addition to the steady state fundamental plus harmonic loading, harmonic filters will experience transient stresses due to a wide variety of disturbances. These conditions will need to be investigated to ensure that the capability of the equipment is sufficient to accommodate the superimposed transient duty.

Such studies will require a transient analysis computer program, such as EMTP, ATP, NETOMAC or EMTDC, to model system parameters, including non-linear aspects such as transformer saturation and surge arrester characteristics. The results of these studies will indicate whether the calculated stresses exceed the equipment's capability. In such cases, the equipment rating will need to be increased to accommodate the predicted duty. Alternatively, surge arresters can be used to limit the transient duty on the equipment.

Where necessary, the results of such studies may need to form part of the equipment specification and may also become the basis for acceptance test levels.

In the case of double frequency filters the results of transient studies usually indicate that the proposed ratings of the low voltage filter components, based on steady state loading, are inadequate and enhanced equipment ratings are required to meet the transient duty.

The results of the transient studies will give important information for the specification of the individual items of filter equipment.

The transient studies discussed in this clause are the responsibility of the contractor; however, the customer must define in the specification any minimum requirements for contract stage studies. For example, the customer should define any specific network and scheme operating conditions that must be considered. Additionally any fault scenarios to be studied should be stated together with details of any auto-reclose schemes that operate on the supply network.

Although the transient studies will be performed and reported at the contract stage, the bidder will need to perform a few studies at the tender stage in order to cost the station equipment. These studies are required to establish equipment insulation levels and surge arrester ratings. The extent of any such studies should be at the bidder's discretion.

There are two main groups of studies that should be performed:

- the first, as discussed in 11.2, comprises switching impulse studies such as routine filter switching, auto-reclose events, system faults and fault application/clearance involving d.c. link load rejection,
- the second group, as discussed in 11.3, includes fast fronted waveform studies, such as lightning strikes and bus flashovers which result in rapid discharge of capacitor banks.

11.2 Switching impulse studies

11.2.1 Energization and switching

For each type of filter available in the HVDC scheme, initial energization studies need to be performed to establish maximum levels of overcurrent, overvoltage and energy. Point-on-wave studies will establish worst case conditions based on energization from the highest realistic system voltage. However, in more complex filter configurations, the same point-on-wave may not establish worst case conditions for individual items of equipment. These studies may also establish the need for switching overvoltage control devices in the breakers (pre-insertion resistors, synchronized closing, etc.) and the breaker switching capability under overvoltage conditions for overvoltage control.

Routine switching of filters, with other banks already in service, will be the most common transient duty on the filter components. The number of switching operations per annum may vary widely between schemes. For example a long distance HVDC scheme designed for bulk power transmission may require very infrequent filter switching whereas a back-to-back HVDC scheme with a reactive power control facility may switch filters frequently. An estimate of the number of switching events will be needed to accompany the transient results and should be included by the contractor in the individual equipment specifications. Frequent switching of filters is of particular importance for the capacitor banks as the high level of dielectric stress imposed during the transient event has an impact on the equipment lifetime. Standards on capacitor banks, such as IEC 60871 series and IEEE 18 [57], give guidance on the acceptable levels of transient voltage and current and the number of switching events per annum.

In a similar manner to initial energization studies, point-on-wave studies of routine switching will be needed to establish worst case conditions. The studies should consider the case of each type of filter in turn being the last to be switched, e.g. all other filters are in service at the maximum realistic system voltage. Where shunt capacitor banks are installed as part of the reactive power control strategy, the particular case of parallel switching will need to be studied. In this case, the high levels of in-rush current into one bank due to the discharge from an energized capacitor bank may result in damage to the capacitor equipment. Such studies would indicate the need for current limiting reactors to be installed as part of the bank.

The studies will need to consider the range of short circuit levels (SCL) applicable at the point of connection of the filters. There is normally no simple correlation between SCL and the magnitude of peak currents and voltages on the filter equipment.

Typical examples of the transient waveforms which occur during routine filter switching are shown in Figures 27 and 28 below.

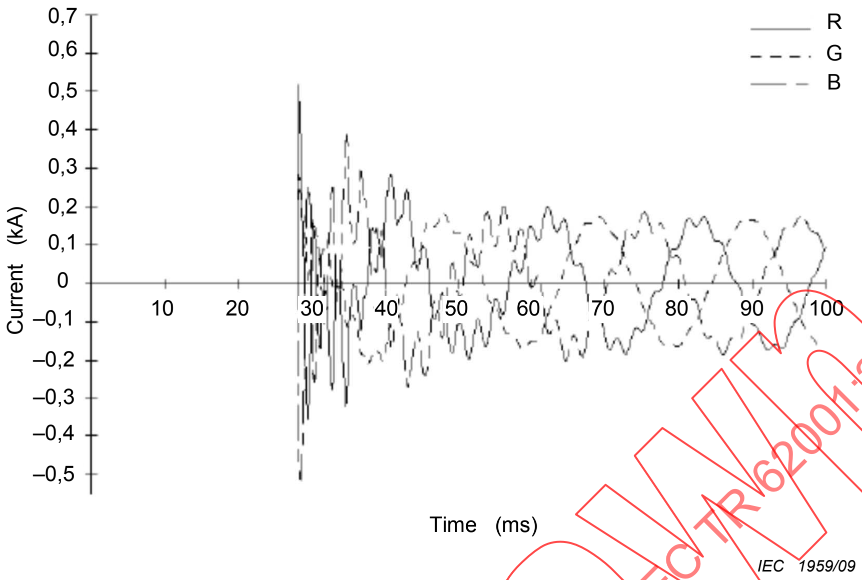


Figure 27 – In-rush current into a 12/24th double tuned filter

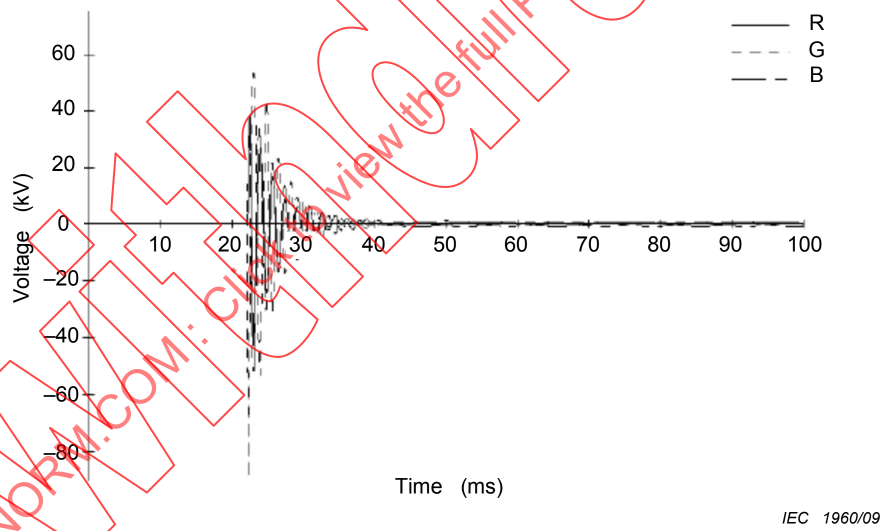


Figure 28 – Voltage across the low voltage capacitor of a 12/24th double tuned filter at switch-on

11.2.2 Faults external to the filter

Faults on the a.c. supply network can encompass both isolated faults, such as line-line and three phase faults and faults involving earth, whether single phase, two phase or three phase faults. Such faults may involve rejection of the d.c. load, e.g. blocking of the converters, leading to a large prospective recovery voltage. This voltage, exacerbated by the presence of the filters, will be limited by system line-to-earth surge arresters and is normally the basis for their energy rating. When studying such fault application and load rejection scenarios, it is important to represent accurately the operating strategy of the HVDC scheme in terms of breaker fault clearance times, filter tripping strategy and de-blocking of the converters. Normally harmonic filters are not switched during dynamic overvoltage (DOV) conditions to avoid any restriction of operation following the DOV. However, if filters do switch out this will impose a significant duty on the circuit breaker and also on any discharge voltage transformers (DVT), if installed.

Where single phase auto-reclose schemes are used on the circuit breakers of the incoming transmission lines, the strategy in the event of repeated failed re-closure attempts will need to be studied. In such cases, successive re-energization of the filters may result in significant overcurrents and overvoltages on the equipment and in particular may dictate the energy levels of the filter surge arresters. If three phase auto-reclose schemes are used, which will result in isolation of the converter station, this will also need to be studied to determine the effects on arrester ratings. Where discharge voltage transformers are installed on the filter banks they can rapidly discharge the d.c. voltage on the capacitor banks allowing re-energizing of the filters.

The duration of such transient studies would need to be chosen to cover all breaker operations and to ensure that worst case overload conditions and arrester energy absorption conditions had been reached. However, it is recognized that it is impractical to represent long breaker clearing times, e.g. several minutes, in digital studies and a reduced period can be modeled as the clearing time for stuck breaker condition.

Figure 29 illustrates a combination of fault conditions: at 25 ms, the HVDC converter is blocked resulting in a severe overvoltage on the main filter capacitor bank. At 70 ms, a 3-phase bus fault is simulated which is cleared at 100 ms, a reduced period to minimize computation time, resulting in a severe transient overvoltage on the capacitor bank.

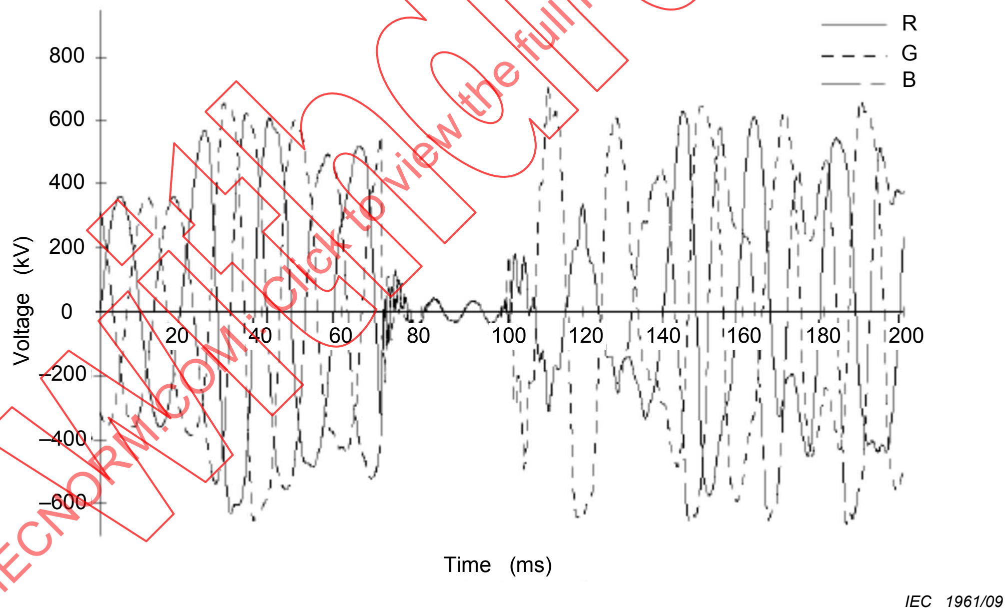


Figure 29 – Voltage across the HV capacitor bank of a 12/24th double tuned filter under fault conditions

11.2.3 Faults internal to the filter

The effects of faults within the filter will depend upon the type of filter and the electrical arrangement of the filter. Using a single tuned filter, as in Figure 6, as an example, a line-earth fault at the HV terminal of the capacitor bank will apply the instantaneous d.c. voltage on the capacitor directly across the low voltage reactor and any surge arrester, as discussed further in 11.3.2. A line-earth fault at the capacitor LV terminal would simply bypass the reactor and result in very little change in current in the capacitor bank which is the predominant filter impedance.

If the filter configuration were inverted, e.g. the reactor at the HV terminal and the capacitor connected to the neutral, a line-earth fault from the reactor HV terminal would result in a similar transient duty on the reactor as in the above case. However, a line-earth fault from the reactor LV terminal, e.g. the capacitor HV terminal, would result in a considerable fault current in the reactor, due to the low impedance of the reactor compared with the capacitor. To ensure that reactors would survive such an internal filter fault, a short circuit test of the reactor would be required.

Although the fault conditions considered above are normally worst case conditions for filter transient duty, for more complex filter configurations, such as Figures 8 and 9, other credible internal fault conditions would need to be studied.

When studying the effects of such faults on filter component and arrester ratings, it is important to consider the protective level afforded by the bus arrester and to co-ordinate the design of this arrester with the filter arresters to achieve an overall optimized design.

11.2.4 Transformer in-rush currents

Energization of the converter transformer, or adjacent conventional transformers, will result in significant levels of in-rush current that can be sustained for considerable periods of time. As the in-rush currents are asymmetric and with a high harmonic content, particularly of low order harmonics, they can result in harmonic current flow in adjacent filters. In applications where low order harmonic filters are installed such effects will need to be studied. Although in normal practice the converter transformers would be energized prior to filter switching, during fault recovery conditions, transformer switching on adjacent converter poles, or switching of adjacent grid transformers, energization can occur with filters connected. Studies will indicate the need for overvoltage control devices in the breakers for the definition of economic insulation levels of the equipment and/or to decrease the occurrence of commutation failures.

Studies involving transformer in-rush currents need to model the transformer in some detail including both linear and non-linear, e.g. saturation, inductances. The losses within the transformer, which will dictate the decay of in-rush currents, must be modeled.

11.3 Fast fronted waveform studies

11.3.1 General

Because of the large rates of change of voltage and current involved in these studies, it is important that stray inductances and capacitances within the filter circuits and equipment are modeled. Thus the physical location of the equipment, and particularly of surge arresters, must be considered when modeling the filter.

11.3.2 Lightning strikes

Although direct lightning strikes on filter equipment are unlikely, especially if overhead earth-wire protection is provided, the effect of strikes on the remote a.c. system transferred to the filters must be considered. The maximum voltage on the filter terminal will be limited by the main HV surge arrester. These surges will be transferred to the low voltage components of double frequency filters and may have a significant bearing on their insulation levels. Where appropriate, applied lightning strikes should be simulated at various points within the HV substation and at various distances along the a.c. lines from the station.

11.3.3 Busbar flashover studies

A flashover to earth on the filter HV busbar will cause a rapid discharge of the filter capacitor bank through the filter components. Such an event may occur during a high system voltage, however, the capacitor fuses should not operate for this condition as they are tested to withstand short circuit currents. Due to the short time of these discharges (a few microseconds), they fall into the same category as lightning impulses and this is not normally a decisive rating case.

11.4 Insulation co-ordination

From the results of the studies described in 11.2 and 11.3 the overall insulation co-ordination of the filter can be derived. The need for surge arresters distributed within the filters will be determined. In most cases, the choice between the arrester's protective voltage level and energy absorption capability and the voltage withstand capability of the protected equipment will be based on relative costs. Although low voltage station class arresters are relatively inexpensive, if significant energy absorption capability is required, then parallel housings are needed and costs may be high. In such cases increasing equipment insulation levels may be the optimum solution.

When modeling surge arresters, it is important to consider the maximum tolerance on the arrester characteristic when evaluating protective levels and the minimum tolerance when evaluating energy absorption capability.

There are a number of possible connection arrangements for filters with embedded surge arresters. Typical examples for double tuned filters are shown in Figure 30.

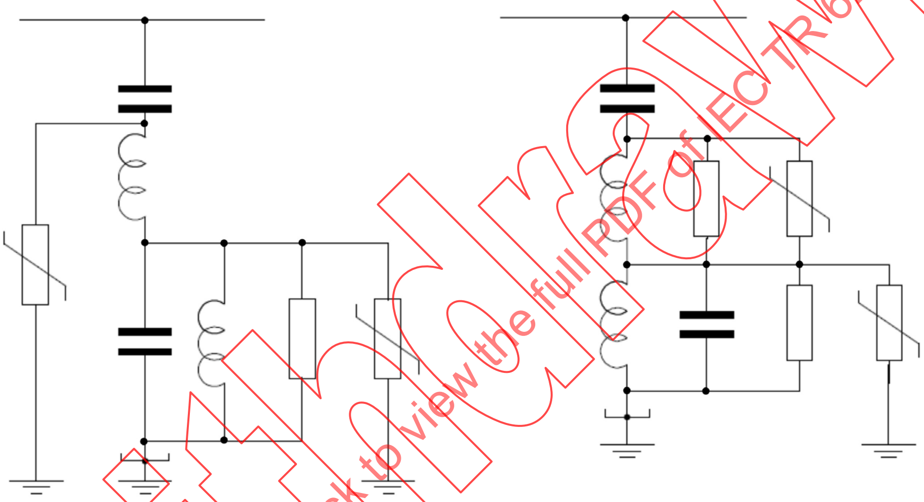


Figure 30 – Typical arrangements of surge arresters

The results of the lightning and switching impulse studies will confirm that the required margins between the equipment withstand levels and the corresponding surge arrester protective levels, according to IEC 60099-4 (2004) or the customer's specification, are achieved. Note that margins in excess of those normally specified by IEC 60099-4 (2004) will result in increased filter costs. The energy absorption duty imposed on surge arresters by lightning surges will normally be less than the energy arising from the fault conditions discussed in 11.2.

In the case of the multiple frequency filters described in 7.4.2, 7.4.3 and 7.5.2, the results of the fault studies or switching studies usually indicate that the maximum transient voltages on the low voltage capacitors greatly exceed the steady state ratings as derived in 10.2.3. As the cost of such banks is usually low, increasing the rated voltage such that overload capability complies with predicted maximum transient voltage can give an acceptable design without incurring the need for special designs of surge arresters.

By establishing a coherent insulation co-ordination scheme throughout the filter, it is possible to define the following parameters for the filter equipment.

- lightning impulse withstand level (LIWL);
- switching impulse withstand level (SIWL), if appropriate;

- power frequency voltage;
- clearance (line-line);
- clearance (line-earth);
- creepage distance;
- transient current through arresters and filter components;
- protective levels of filter arresters;
- filter arrester locations and requirements.

These parameters can be defined at each terminal of the equipment or in the case of large HV capacitor banks at a number of points where support insulators, current transformers or voltage transformers may be connected. The neutral points of each phase of the star-connected filter are normally individually isolated by a low, but consistent insulation level, and then brought together to form a single star point which is then connected to earth.

It is important that an insulation level is defined for the neutral of the filter to avoid spurious earth faults during transient disturbances.

12 Losses

12.1 Background

The cost of losses can be a significant factor of difference between the designs of different bidders for an HVDC scheme. The customer needs to ensure that loss evaluation is made according to clearly defined procedures, and under comparable conditions, for each offered design.

An introduction to HVDC converter station losses is given in Annex F.

Harmonic filters associated with the a.c. side of HVDC converter stations are typically responsible for up to around 10 % of the total converter station losses. Unlike many plant items the losses for harmonic filters can only be determined by calculation, especially those relating to losses at harmonic frequencies (although the loss figures for the individual components of the filters may be available as the result of works tests).

The widely accepted standard procedure for calculating losses in HVDC stations is defined in IEC 61803 (1999). This proposes calculation of losses under essentially nominal conditions, which is a fair basis for most HVDC plant.

However, for a.c. filters, the calculated losses can vary over a wide range depending on factors such as detuning, a.c. network resonance, and level of negative sequence component in the a.c. supply voltage. Consequently, a calculation made under nominal conditions can greatly underestimate the likely level of losses under realistic operating conditions.

The customer should therefore be aware that by following the guidance of IEEE 1158, he may not obtain a realistic estimate of probable a.c. filter losses. Furthermore, as the losses pertaining to different a.c. filter designs vary substantially, he will also not be able to make a fair comparison of the designs offered by different bidders.

The following items therefore offer guidance to the customer, where appropriate, on how to define alternative conditions for calculating a.c. filter losses. It is suggested that the filter losses should be calculated both under the nominal conditions of IEC 61803, and under the suggested alternative conditions described in 12.4 below, in order to provide all the information needed by the customer.

12.2 AC filter component losses

12.2.1 General

The a.c. filters comprise capacitive, inductive and often resistive elements, all of which contribute to the total losses of the converter station. As part of the filter design process, account will have been taken of the loss capitalization in choosing the number and type of filters required. Subclause 7.4 highlights the various advantages and disadvantages of tuned filters, which typically produce low losses, against damped filters (see 7.5) which generally produce higher losses on a per MVAr basis.

Further discussion with respect to overall filter component costs, taking into account their losses, is provided in [42].

12.2.2 Filter / shunt capacitor losses

For large high voltage capacitor banks having ratings of many MVArs, the loss angle becomes important; the lower the loss angle, the lower the losses are for the bank.

Table 2 below details the subdivision of losses within a typical all-film type capacitor unit.

Table 2 – Typical losses in an all-film capacitor unit

Source of loss	Loss W/kVAr	
	Internally fused unit	**Externally fused unit**
Dielectric	0,05	0,05
Discharge resistors	0,05	0,05
Other (fuses and connections)	0,05	0,01
TOTAL	0,15	0,11

The above losses are typical; guaranteed values would be in the order of 20 % higher. Fuseless capacitors have similar dielectric, discharge resistor and connection losses to those stated above. In respect of externally fused units, the losses due to the external fuse are additional to those quoted. With improvements in the choice and design of dielectric, it is notable that the losses in the capacitor unit discharge resistor now tend to dominate. The requirements and duty for such resistors are not within the direct control of the capacitor manufacturer, but are dictated by discharge time requirements imposed by international standards or the customer's own requirements. If an enhanced discharge requirement is specified then the losses as shown in Table 2 will be higher.

The losses discussed above refer to new capacitor units. Dielectric losses tend to reduce with time, reaching their minimum figure within a few hundred hours of operation for all film type capacitor units. However, the reduction is minimal, and because the dielectric loss is no longer the major contributor to losses, the effect of the reduction on the total filter losses is minimal. Tests conducted by capacitor manufacturers also confirm that the losses at low order harmonics (in terms of W/kVAr) are similar to the values given above at fundamental frequency.

The power losses of each individual capacitor bank, assuming that the loss angle is the same at harmonic frequencies as at fundamental frequency can be determined by:

$$P_{\mathrm{c}} = \tan(\delta) \times \sum_{n=1}^{n=N} I_{\mathrm{cn}}^{2} \times X_{\mathrm{cn}} \qquad (26)$$

where

P_c is the filter capacitor loss;

n is the harmonic number;

N is the maximum harmonic order (typically 50);

I_{cn} is the calculated current in the capacitor at harmonic order n;

X_{cn} is the capacitor reactance at harmonic order n;

$\tan(\delta)$ is the tangent of the capacitor loss angle.

Shunt capacitor banks are often provided in addition to harmonic filters to provide part of the total converter station reactive power requirements. Their losses, at both fundamental and harmonic frequency can be assessed in a similar manner to filter capacitors as discussed above. However, because the losses of the capacitor units themselves are low, the effects of losses in other components which may then become significant should not be overlooked. In this respect, losses due to the following plant items can typically increase the losses due to the capacitor units alone by some 50 %:

- the interconnecting cables and busbars;
- the capacitor bank switchgear;
- the capacitor bank (discharge) PT;
- the inrush reactor (when provided);
- the capacitor fuses;
- the capacitor bank internal connections.

12.3 Filter reactor losses

12.3.1 General

In general, filter reactors (and where provided, resistors) are the dominant source of total filter losses; this is particularly so for a filter bank that provides attenuation for low order harmonics, either in the form of single frequency tuned filters or damped types.

For single frequency tuned filters, the filter designer is often required to make a compromise between the Q (quality) factor for the reactor at fundamental frequency and at the tuned harmonic frequency. At fundamental frequency, to minimize losses the requirement is to specify a Q factor as high as possible, whereas at harmonic frequencies, in particular the tuned frequency, it is desirable to specify a Q factor compatible with the filter performance requirement. The required Q factor at the harmonic frequency may be low when the filter is likely to be subjected to wide detuning effects because of large system frequency variations and/or ambient temperature range. The final balance can often be a compromise between these conflicting requirements, especially when a filter reactor manufacturer's lowest initial cost design is not optimal in respect of losses.

Means are however available to the reactor designer (at least for naturally air cooled reactors of open construction) to control or optimize this balance of Q factor requirements at the various frequencies by means of additional de-Q'ing coils installed on the reactor, or even by the use of self-tuning filters.

For damped filters, the choice of reactor Q factor at harmonic frequencies is generally unimportant in terms of achieving the required performance and optimal rating, leaving the filter designer a relatively free choice in specifying Q factor at fundamental frequency to satisfy the balance between reactor cost and losses. However, for double tuned damped filters, the choice of reactor Q factor at harmonic frequencies requires careful optimization to minimize the effects of circulating harmonic currents within the filter itself. Increasing the Q factor may in certain circumstances increase the harmonic losses in the reactors.

The reactor Q factor at harmonic frequencies is generally defined with a certain range of tolerance around a nominal value. For the calculation of losses the minimum Q (i.e. the highest resistance) rather than the nominal value should be used.

The power losses in the reactor can be determined by:

$$P_l = \sum_{n=1}^{n=N} \frac{I_{ln}^2 \times X_{ln}}{Q_n} \tag{27}$$

where

P_l is the filter reactor loss;

n is the harmonic number;

N is the maximum harmonic order (typically 50);

I_{ln} is the calculated current in the reactor at harmonic order n;

X_{ln} is the reactor reactance at harmonic order n;

Q_n is the reactor Q factor at harmonic order n.

12.3.2 Filter resistor losses

In determining the overall filter configuration, the designer will have evaluated the choice between tuned and damped type filters and also between the various types of damped filter in terms of minimizing filter resistor losses. In this context, consideration should have been given to the reduction in resistor loss that can be gained by the use of third order and C type filters rather than second order type, against a generally poorer performance. Consideration will also have been given to whether it is necessary for single frequency tuned filters to be provided with an external resistor to achieve the required filter Q factor at the tuned harmonic frequency.

In determining the choice between the various types of damped filter, it should be remembered that especially for a.c. filters connected to a high system voltage the cost of the resistor bank itself is not directly proportional to the required loss dissipation since the cost of the insulation required can be a significant proportion of the total cost.

The power losses in the resistor can be determined by:

$$P_r = \sum_{n=1}^{n=N} I_{rn}^2 \times R_n \tag{28}$$

where

P_r is the filter resistor loss;

n is the harmonic number;

N is the maximum harmonic order (typically 50);

R_n is the resistance in ohms at harmonic order n;

I_{rn} is the calculated current in the resistor at harmonic order n.

12.3.3 Shunt reactor losses

Shunt reactors may form part of an HVDC converter station to provide inductive compensation for a.c. harmonic filters especially under light load conditions where a certain minimum number of harmonic filters is required to satisfy harmonic performance requirements. The derivation of their losses is similar to that in conventional transmission system applications. It should be noted that in general their losses at harmonic frequencies are almost negligible in comparison to those at fundamental frequency.

12.4 Criteria for loss evaluation

Loss evaluation is often given a high profile by customers purchasing HVDC converter stations in their tender analysis. The criteria for their assessment therefore needs to be consistent and unambiguous and be clearly defined in the technical specification, which should not benefit or disadvantage one bidder against another.

IEC 61803 provides a set of criteria for assessing a.c. filter losses and is often specified by purchasers of HVDC converter stations/schemes. As such, it usefully provides a means of assessing designs from a variety of potential bidders on an equal basis. However, there are instances where the criteria specified in this standard do not always fully reflect operating conditions occurring in practice, which may give rise to losses of a different magnitude. These particular instances are discussed later.

The various aspects that need to be considered when assessing losses are:

a) fundamental frequency a.c. filter busbar voltage,
b) fundamental frequency and ambient temperature,
c) a.c. system harmonic impedance,
d) harmonic currents generated by the converter,
e) pre-existing harmonic distortion,
f) anticipated load profile of the converter station.

Each of the above items is discussed in turn below.

a) fundamental frequency a.c. filter busbar voltage

Since the choice of a.c. filter busbar voltage is not a sensitive issue, i.e. it should not in general favor one design of a.c. filter configuration against another, losses should be determined for nominal a.c. filter busbar voltage.

b) fundamental frequency and ambient temperature

Initially it might appear that in common with the choice of fundamental frequency a.c. system voltage, loss assessment should also be based on the nominal value of fundamental frequency.

Whilst this approach is generally satisfactory for the majority of other components comprising the converter station, it may be inappropriate for a.c. harmonic filters, and the choice of fundamental frequency and ambient temperature variation may be a sensitive issue. Depending on the type of filter arrangement, the filter harmonic losses under the extremes of frequency variations (and of ambient temperature where appropriate) can vary significantly from those calculated using nominal frequency and a 'nominal' temperature. This is especially significant for arrangements which comprise single or double frequency tuned filter branches. For damped filters the effects of such variations is however negligible.

Therefore, in order to provide the customer with a fuller knowledge of the losses possible from each filter design, it is suggested that loss assessment for a.c. harmonic filters should be determined at the extremes of fundamental frequency and ambient temperatures as specified for harmonic performance calculations.

This should be in addition to the calculation method using nominal frequency and an ambient temperature of 20 °C (IEC 61803), which is of use in comparison of losses for the overall converter station.

c) a.c. system harmonic impedance

The choice of an appropriate system harmonic impedance for the calculation of losses is also a sensitive issue. HVDC project specifications have tended to indicate (and IEC 61803 recommends) that for loss assessment the a.c. system should be assumed to be open circuited "so that all the converter harmonic currents are considered to flow into the a.c. filters".

However, this criterion neglects the fact that resonance between the a.c. filters and the supply system harmonic impedance can occur leading to magnification of the harmonic currents generated by the converters (and any other sources).

A choice of system harmonic impedance more representative of conditions actually occurring in practice, is to use the impedance employed for the determination of filter performance. (The alternative use of the system harmonic impedance employed for filter rating conditions may be too pessimistic for loss assessment.)

As with item b) above, this calculation could be done instead of, or in addition to the calculation with open circuited a.c. system.

d) harmonic currents generated by the converter

IEEE 1158, subclause 4.3.1 and several HVDC project specifications recommend that the determination of a.c. filter losses should be based only on the characteristic harmonic currents generated by the converter and imply that non-characteristic harmonics should be neglected.

However, for several HVDC schemes, it has been necessary to include low order harmonic filtering specifically to attenuate residual non-characteristic harmonic currents to satisfy the performance criteria. In such cases, in order to obtain a realistic assessment of expected losses, the filter loss calculation should take these non-characteristic harmonics into account, as they may have a significant impact on the magnitude of filter losses. Depending on the approach adopted by the customer, this may be requested instead of, or in addition to, an assessment which excludes non-characteristic harmonics.

In respect of converter characteristic harmonic currents for loss assessment, values calculated for 'performance' conditions are appropriate, i.e. those based typically on nominal values of delay angle and commutation reactance.

If non-characteristic harmonics are to be considered, then values for reactance imbalances between converter transformers comprising a 12 pulse group, imbalances between individual converter transformer phases, and imbalances in delay angle between valve groups in a 12 pulse pair and within a 6 pulse valve group, should be based on 'expected' levels rather than 'guaranteed' levels, subject to the agreement of the customer.

The effects of negative phase sequence voltages on losses in converter plant is often overlooked in the assessment of losses. Such voltages present at the converter station a.c. supply system result in positive sequence third harmonic currents being produced by each converter and therefore influence the losses in any associated low-order harmonic filters. These losses can be substantial, and the customer is advised to obtain a realistic knowledge of their likely level. For such a loss calculation, the level of negative phase sequence voltage used should be that defined for the assessment of harmonic performance.

e) pre-existing harmonic distortion

Whether the effects of pre-existing harmonic distortion should be included in the loss assessment or not largely depends on the requirements of the performance specification. If in the assessment of performance the effects of pre-existing harmonic distortion are to be neglected (see also 8.1.6) then it is also appropriate to neglect them in loss assessment. On the other hand, where the performance requirements state that pre-existing harmonic distortion should be included, losses should also be based on their consideration.

Where the converter station includes power electronic reactive compensation, e.g. an SVC, as part of the total package, such plant may itself be a source of harmonic current generation and to comply with the performance criteria may require associated harmonic filters. Nonetheless a certain level of its harmonic current will flow into the harmonic filters associated directly with the converters and such levels should also be taken into account in their total loss assessment.

f) anticipated load profile of the converter station

The evaluation of the economic cost of losses from the a.c. filters will be heavily dependent on the expected load profile for the converter station, which also takes into account the amount of time that each converter operates in rectifier and inverter mode (for bi-directional schemes) and operation under 'ready' (or 'standby') mode conditions.

('Ready mode' is defined as the condition when all the equipment necessary for operation of the link is live and transmission may be established by deblocking the valves. It is also often termed 'standby mode'. Load losses are those corresponding to the operation of the link at any particular operating condition above ready mode, up to and including full load).

For certain applications, it may be a requirement that in 'ready mode' a minimum number of filters should be connected even though the thyristor valves are blocked. The number of filters connected for such conditions would be that which satisfies the harmonic performance requirements for the minimum feasible d.c. load condition and also satisfies the reactive power balance requirement.

For each load condition assessed, the number of a.c. filters in service should be consistent with the performance and reactive power balance requirements and the total losses should be determined for consistent operating parameters (delay angle etc.).

The losses for each of the individual loading conditions may then be weighted with suitable factors representative of the anticipated operating profile to determine the total equivalent losses. It should however be noted that depending on the approach adopted by the customer for evaluating the cost of losses, losses at fundamental and harmonic frequencies may be weighted differently, as may be those for ready mode and load losses.

13 Design issues and special applications

13.1 General

This clause provides some guidance regarding a selection of more advanced design issues and some special filter applications, always with reference to conventional passive a.c. filters. Newer technologies, for example active filtering, are described in Clause 20.

Experience from numerous HVDC schemes is condensed in the following. The subjects discussed include topics which have arisen in a number of projects, as well as some more unusual applications.

Some of these topics may have an impact on the wording of the customer's technical specification, but most are included in order to assist the customer during the bid evaluation stage and subsequent discussions with the bidders and later the contractor.

13.2 Performance aspects

13.2.1 Low order harmonic filtering and resonance conditions with a.c. system

The mechanism of generating non-characteristic low-order harmonics is well known and described in Clauses 5 and 6 of this document. The particular influence of negative sequence voltage on the generation of 3rd harmonic is treated in 5.4.6.

Harmonic a.c. filters tuned for the characteristic 12-pulse harmonics behave as a capacitive impedance at lower frequencies. By nature the a.c. system harmonic impedance, which is in parallel with the filter impedance, creates parallel resonance phenomena at converter busbars. In some HVDC schemes therefore low-order harmonic filters have been installed to damp such resonance [42, 43] and to limit the distortion generated by some non-characteristic harmonics from the converters.

From experience, such types of filters are extremely expensive and due to the normally low MVAr rating of the filter capacitors (which themselves are expensive) and the low tuning frequency of the circuits, the filter reactors need to be designed with unusually high inductance values and fundamental frequency ratings. Additionally, the losses, if damping resistors are provided, are relatively high.

This type of filter may need to be in service over the whole range of converter load. Considering the reactive power requirements, this would have an impact on the number of minimum filters possible at light load conditions and increase the reactive power exchange with the a.c. system. In some schemes this surplus has been compensated with additional shunt reactors, while some other schemes operate the converters with increased firing angles and higher reactive power consumption.

The accurate modeling of the harmonic a.c. system impedances at the second and third harmonic is important in order not to overdesign such low order filters. For harmonics below the 11th order, a detailed and accurate representation is recommended to ensure that magnification of harmonics is damped out to the optimum. If this is not possible during the planning stage, some flexibility and allowance for risk should be given to the contractor to study this phenomenon during project execution and to mitigate any problem under his own responsibility at a later stage of the project. In some cases, converter control with special features could be used as a solution for low order harmonics problems instead of expensive harmonic filters [44].

It is also vital to model accurately the harmonic interaction between a.c. and d.c. sides of the converter, and the influence of the converter control system, when determining the need for, or the design of, such low-order filters (see Clause 6). Ignoring these factors can result in completely misleading conclusions, and possibly the unnecessary specification for a low-order filter to be installed.

A major disadvantage of low order filters (3rd harmonic, or 3/5th for example), is that they are loaded not only by currents from the converter, but also from other harmonic sources in the a.c. system. Often such sources are not the responsibility of or under the control of the customer, may not be filtered locally, and their magnitude is not known. They may also have come on line due to industrial development taking place after the design of the HVDC station. The currents from such sources may, furthermore, be magnified by resonances within the a.c. network. It is therefore difficult to predict how much network harmonic current may flow in the low-order filters, and in the past low-order filters have been tripped or damaged due to such overloads. Over-rating of the filters is the only solution, but it is difficult to predict how much over-rating is needed to ensure security, and the filters can become very expensive.

It is therefore advisable to expend considerable efforts, if necessary, in studying low-order harmonic problems using accurate modeling, in order to try to avoid the necessity of installing low-order filters. The customer should be aware of the issues and be prepared to discuss with bidders any aspects of the technical specification, for example the prescribed a.c. system impedance envelope, level of specified negative sequence voltage or individual harmonics voltage limits, which may force the contractor to include low-order filter branches in the design.

13.2.2 Definition of IT, THFF and TIF factors to include harmonics up to 5 kHz

In most technical specifications, the maximum harmonic order to be considered for a.c. filter performance is the 50th. However, a few specifications have extended the range to be considered up to the 83rd harmonic at 60 Hz, i.e. 5 kHz. The impact on the filter design and costs when considering harmonics higher than the order of 50 can be significant, and careful consideration should be given by the customer before making such a requirement.

Standard communication on analogue telephone lines should not be significantly affected in this upper frequency band between the 50th harmonic and 5 kHz by the level of harmonics actually generated by the HVDC converters. However, if the a.c. filter design does not include high-pass damped filters, then potential resonance conditions between tuned a.c. filters and the a.c. system could be created. These would need to be studied in order to avoid excessive interference in the nearby communication systems. To obtain realistic results of such studies, proper modeling of frequency dependence for the major components such as lines, transformers and loads is of great importance. However, the frequency dependence is largely unknown in this upper frequency range and so such detailed studies are generally not feasible.

If high-pass damped filters are used in the converter stations, the higher order harmonics injected into the a.c. system will be negligible. However, the use of high-pass filters large enough and with sufficient damping to satisfy stringent performance criteria over this extended frequency range may increase the filter costs and losses significantly.

The customer is therefore faced with a dilemma - if the technical specification limits the performance requirements to the 50th harmonic, then the bidders may find that the most competitive filter design is one using double-tuned filters at the characteristic harmonics, with an inductive impedance at frequencies above the 50th harmonic. Such a design would fulfill the specified requirements, but could create a resonance with the a.c. system at higher frequencies, amplifying harmonics which would otherwise be negligible.

If however the customer extends the frequency range to say the 83rd order at 60 Hz (or 100th order at 50 Hz), and if the levels of specified TIF etc. are those typically used for schemes with a maximum harmonic order of 50, then rather large and highly damped filters may be needed, at a considerable extra cost.

The customer should therefore consider the options carefully before extending the specified frequency range for a.c. filter performance above the 50th order. Two possible alternative approaches could be considered:

- specify performance requirements only up to the 50th harmonic, but specify in addition that the a.c. filters must have a damped characteristic above the 50th (possibly also defining the maximum permitted filter impedance phase angle at harmonics above the 50th), or
- specify performance requirements up to the 83rd order, but increase the maximum limits for TIF, THFF or IT accordingly, in order to avoid an unnecessarily expensive filter design.

13.2.3 Triple-tuned filter circuits

Double-tuned filter circuits have been established in the past as a standard design for passive a.c. filters, as the savings in the high voltage capacitor banks and a.c. switchgear justify a filter design with more than one tuning frequency. In certain circumstances, further optimization may be possible if more than two tuning frequencies can be achieved. In tenders for recent projects, manufacturers have identified a cost saving advantage if triple-tuned filters could be provided (see also 7.4.3).

In the past, the introduction of triple-tuned a.c. filters has been resisted, mainly on the grounds that on site-tuning would be difficult. However, the use of modern instruments eliminates any serious difficulties. Tuning is still more complicated than for single- or double-tuned filters, but is quite feasible. Moreover, if the filter is designed so that sharp tuning is only required at one of the frequencies, with broad-band damped characteristics at the other two frequencies, then sufficiently accurate tuning can be readily achieved.

A triple-tuned filter will generally be attractive if the alternative design requires small filter bank sizes at an extremely high a.c. system voltage. In order to achieve an economical design of HV capacitor, it is then desirable to filter several major converter harmonics within one filter bank. If necessary, high pass characteristics can be implemented with additional damping resistors.

The following requirements can also lead to a triple-tuned filter being considered as a solution:

- operational requirements for reactive power control within narrow limits,
- combination of stringent THFF or TIF voltage distortion combined simultaneously with low IT product limits,
- minimizing filter reactive power installation close to generators,
- low order filtering combined with a 12th/24th filter,
- saving in a.c. switchgear and space,
- lower reactive power of a 3/12/24th filter at light load conditions compared to a 3rd + 12/24th circuit, thus reducing need for shunt reactors,
- higher redundancy for all type of filters used.

Possible disadvantages to be considered (see also 7.4.3), apart from the more complicated on-site tuning, are:

- sensitivity of the tuning to blown capacitor fuses,
- number of current transformers (CTs) required to ensure protection of all components, or possible overrating of unprotected low voltage components.

The customer and contractor should therefore take all these factors into account and give serious consideration to the use of triple-tuned filters if this would provide the most economic solution.

13.2.4 Harmonic a.c. filters on tertiary winding of converter transformers

Some HVDC schemes up to a rated power of approximately 200 MW to 300 MW have been arranged with harmonic a.c. filters connected to a tertiary winding of the converter transformers, for example Blackwater, McNeill and Vybourg HVDC converter stations.

Savings can be expected in the space and investment costs of the filter circuits, including the a.c. filter breakers, because the limitations on economic minimum capacitor bank rating are reduced by employing a lower connection voltage. In addition, identical voltage and MVAr design of the components for both rectifier and inverter side can save costs in providing a minimized number of spare items for the converter station. Further, with this solution the filter reactors can be connected in the line side of the tertiary filter. Then, the filter main capacitor can be made in a simple three-phase arrangement, simplifying the a.c. filter protection compared to a conventional HV filter design.

Consideration should be given to filter outages. Any spare or redundant filtering has to be provided on a per-transformer rather than a per-station basis, and this can significantly reduce any cost advantage.

With this solution, the series connected transformer impedance between the filter and the HV system side reduces the contribution of the higher order harmonics and this can simplify the filter arrangement (high pass filters only being needed for higher frequencies). If shunt reactors are required, the tertiary busbar connection (typical voltage range between 30 kV and 60 kV), allows air core type reactors to be provided, which are probably more economical compared to oil immersed type HV shunt reactors.

The transformer costs compared to a conventional scheme will slightly increase and the savings in the filter areas have to be compared against this, to determine the optimum solution. The following aspects relating to the converter transformer should also be taken into account:

- the additional tertiary winding has to be designed for the short circuit duty and has a relatively low leakage impedance from tertiary to the HV bus winding;
- the transformer reliability will be lower;
- the four winding converter transformer is not a standardized item of equipment and for system studies a detailed transformer model needs to be developed by the contractor to prove all the assumptions and ratings;
- the converter transformer impedance selection has to reflect the requirement to limit the short circuit currents to acceptable limits; but on the other hand, the choice of the transformer impedances has an impact on the overall harmonic performance of the a.c. filters and needs to be chosen in such a way that resonances between the filter circuits and the a.c. system are damped out to a minimum;
- the voltage profile at the tertiary filter busbars has to be considered when calculating the reactive power compensation, and in general a larger reactive compensation will be required than if filters were installed on the high voltage bus.

13.3 Rating aspects

13.3.1 Limiting high harmonic currents in parallel-resonant filter circuits

Double-tuned or triple-tuned filters include parallel resonant circuits, which create the anti-resonance points between the tuned frequencies. For the component current and voltage ratings of these circuits, the damping at harmonic frequencies is an important factor. Unless a separate damping resistor is included in the circuit, the circulating harmonic current is limited mainly by the resistance of the reactor. Optimization between the feasibility of providing L-C components with high harmonic current ratings and the alternative of loss intensive resistive damping is one of the major tasks for the filter designer.

An iterative design procedure is required, since if the reactor quality factor changes, the current and voltage ratings in the parallel resonance circuit can vary significantly. Close co-operation between the system designer and the component manufacturer is needed to obtain an economic component design.

If in special cases, the quality factor of the reactors has to be reduced beyond what is possible within the reactor itself, an additional series damping resistor can be connected to the filter reactor coil or to the filter capacitor.

13.3.2 Transient ratings of parallel circuits in multiple tuned filters

For double-tuned and triple-tuned filters, experience has shown that the transient ratings of the components of the low voltage tuning circuits are of major importance in the filter design. Therefore, it is recommended to include representative oscillograms for the worst case transient voltage stresses in the relevant component specifications.

In some cases with extreme low damping in the circuit, voltage oscillations have to be considered for the decisive voltage - time curve for the capacitor voltage ratings e.g. NEMA characteristics. The transient voltages across capacitors is used to design for the dielectric stresses inside the capacitor units.

For low order harmonic filters, extreme magnitudes of transient low order harmonic currents and voltages can occur due to the harmonic current injection caused by transformer saturation effects. For such filter components, the transient ratings in terms of currents, voltages and energy dissipations may be the decisive cases. It is the responsibility of the contractor to define these ratings and to prove that the filter design is adequate. The worst case for the different components has to be selected out of various study cases varying fault initiation, fault duration and fault clearing scenarios for different loading and a.c. system conditions.

13.3.3 Overload protection of high-pass harmonic filter resistors

If resistors are provided in high-pass filters, different cases of overload conditions can stress the resistors during emergency situations. Such cases need to be checked against the protective scheme and the short-time overload ratings of the resistors. Typical examples are:

- mismatch of filter configuration versus load,
- internal faults or interruptions in the filter circuit,
- converter maloperation,
- frequency deviation during emergency system conditions,
- future modification of the a.c. system impedance, leading to filter-a.c. system resonance.

In some HVDC schemes, the resistors are not directly protected by their own current transformer. Some manufacturers' protective schemes include the ability to calculate the resistor stresses from other values measured within the filter circuit, as input to the protective relaying scheme. However, if required, it is also possible to provide an additional resistor current transformer and the related protection functions. It is recommended to include in the specification the requirement for specific resistor protection but request the bidder to propose, as an alternative, another solution in accordance with his practical experience and design philosophy, to be discussed during the bid evaluation process.

13.3.4 Back-to-back switching of filters or shunt capacitors

Back-to-back switching refers to switching one filter or shunt capacitor bank on a bus to which one or more other bank(s) are connected. Such switching tends to cause high inrush current in the filter or capacitor bank being switched in.

If tuned filters are used, the tuning reactors are sufficient to limit these inrush currents. If one or more shunt capacitors in parallel are included in the design, it is recommended to provide additional current limiting reactors in the shunt capacitor banks to damp the discharge between the individual branches. For circuit breaker design aspects refer to 18.7.

Another additional advantage could be achieved, if the current limiting reactors are chosen so that the shunt capacitor banks are tuned to some higher order characteristic harmonics or alternatively - in case only 12th/24th filters are installed - to a frequency slightly lower than the 35th. By this means, parallel resonances between the filters and the shunt capacitor will avoid all characteristic 12-pulse harmonics higher than the 25th and will be able to be shifted to non-critical frequencies.

13.3.5 Short time overload – reasonable specification of requirements

This subclause discusses how far inherent short time overloading of the filters due to system emergencies should be reasonably specified. Short time overload for filter components can be caused by one or more of the following system emergency conditions:

- short time overvoltages in the a.c. system,
- short time a.c. system frequency deviations,
- short time overload of the HVDC converters.

All combinations of frequency excursions, detuning of filter components and a.c. bus voltage levels need to be studied to determine the worst case loading conditions.

As an example, typical short time durations to be considered can be classified as:

Normal system conditions: 10 min - 2 h duration

Disturbed system conditions: 1 min - 10 min duration

Emergency system conditions: 1 s - 60 s duration

Also, when designing filter components for all these requirements with respect to lifetime and risk, a reasonable duty cycle should be clearly defined. These definitions should also reflect the initial and follow-up system conditions for the system duty cycles.

Evidently, it would be desirable that the decisive rating of filter components should not be determined by abnormal situations of short-time duration. Often, filter components properly rated for steady-state conditions will also withstand short-time conditions. However, these conditions must be calculated and the short-time capability of the filter components checked.

In the event that the short-time condition proves to be decisive, the customer and contractor together should consider whether it is economically reasonable to specify the filter for the short-time condition in question, or whether in such a possibly unlikely event the filter should be allowed to trip. The probability of the combination of short-time conditions with maximum detuning conditions should also be questioned.

The effect of short time loading on the various filter components is discussed below:

a) Filter capacitors

Short time fundamental frequency overvoltages may be decisive for the voltage rating of the capacitors. Due to their worst case harmonic voltage loading, capacitors include some inherent overvoltage capabilities as long as both maximum harmonic voltage ratings and short time overvoltage do not occur at the same moment. If both the steady state harmonic ratings and the short time system overvoltages are superimposed, the sum of both should be reflected within the voltage-time characteristic of the capacitor.

The short time system frequency range should be considered when calculating the maximum fundamental frequency voltages and currents across and within the filter capacitors with the filter detuned to the minimum/maximum extent. This may include outages of capacitor units and the worst case tolerances assumed for the rating calculations leading to the highest voltage and current stresses for the capacitors.

The voltage and current rating of the filter capacitors has to be checked against the short time overload operation of the HVDC converters. However, normally, for converter overload conditions all filters/shunt capacitors are energized, and so the loading per filter is usually less onerous than during the emergency cases assuming outages of filter branches, occurring at partial loading conditions, which tend to determine the filter ratings.

b) Filter reactors

The current stresses are of greatest interest for the filter reactors. The specified steady state ratings need to be checked against the short time overload stresses.

c) Filter resistors

Filter resistors are the components most sensitive to overload, due to the loss dissipation. The overload stresses depend on all the impacts discussed above. In some recent projects studies showed that the rating of the resistors is the critical point when considering short time overloads.

Detailed calculations are necessary to determine the worst case short time overload of the filter resistors.

13.3.6 Low voltage filter capacitors without fuses

For double- and triple-tuned filter arrangements, the low voltage capacitors are generally not stressed by fundamental frequency current and voltage. Therefore, the fuses of these capacitors need to be designed for the harmonic current stresses, which vary depending on the loading conditions of the converters and on the actual number and type of the a.c. filters in service. From these varying loading conditions the fuse operating currents have to be co-ordinated with the maximum worst case current loading conditions of the capacitor units.

For operating currents lower than the rated values, the fuses will not be able to clear failed capacitor units due to the missing dominating fundamental frequency component in the current. Therefore in some HVDC projects, low-voltage filter capacitors without fuses have been used for parallel tuning circuits. In some cases, these have been designed for extremely high harmonic current ratings (due to detuning and outages of filter banks). For example, in some filters, 11th and 13th harmonic current ratings up to approximately 1 000 A rms for low voltage components of double tuned filters have been required.

13.4 Filters for special purposes

13.4.1 Harmonic filters for damping transient overvoltages

In some HVDC projects harmonic filters of a low-order type are used for both steady state and transient filtering. Transient filter to limit temporary overvoltage (TOV) at the converter station busbar can be used for limiting the saturation overvoltages of the converter transformers after a.c. bus faults or load rejection. If the short circuit level at the a.c. busbars is very low, the overvoltages may be quite high.

During transformer saturation the second and third harmonic transient overvoltages caused by the injected harmonic transformer currents can be high, if the a.c. system impedance resonates with the a.c. filters close to the second or third harmonic. In this case, the filters need to be designed to absorb a high energy level and to damp the saturation overvoltages for the first time peaks before other counter-measures can be initiated e.g. filter tripping, SVC operation, etc. It is desirable to hold the steady state load rejection voltage to between 1,1 p.u. and 1,2 p.u. compared to the bus voltage prior to the fault.

As an example, for the 1 000 MW Chateauguay HVDC converter station, two filter banks (2×135 MVAr 2^{nd} harmonic highpass filters) have been installed. Special design studies were executed for determination of the amount of energy to be dissipated in filter resistors and filter arresters.

13.4.2 Non-linear filters for low order harmonics / transient overvoltages

Non-linear filters can be required to be designed for two different filtering performance requirements. These two requirements are filtering of harmonics in the steady state range, and transient filtering of non-characteristic harmonics during fault recovery conditions in order to damp/limit transient and/or temporary overvoltages. The non-linear characteristics of this filter are created by connecting non-linear metal-oxide arresters in series with other filter tuning devices.

As an alternative approach to that discussed in 13.4.1, a special filter was designed and successfully commissioned in Austria for the Dürnrohr and Vienna South-East HVDC converter station. For one particular a.c. system configuration, various studies were carried out to detect the worst case scenario for temporary and transient overvoltages. The damping in the a.c. system was relatively low, and therefore low order harmonic overvoltages, superimposed on the fundamental frequency overvoltages, were caused by transformer saturation phenomena and amplified by the low damping of the a.c. system during low short-circuit ratio (SCR) operating conditions of the a.c. system. These overvoltages occurred almost undamped and the a.c. breakers seemed to be insufficient to clear against these fault overvoltages. Studies recommended the installation of a SVC combined with low order harmonic filters, to limit the transient and temporary overvoltages including transformer saturation phenomena.

The decision for the Vienna South-East and Dürnrohr stations was to install a non-linear filter for the 2nd and 3rd harmonic with the filter arrangement as shown in Figure 31. This filter arrangement has practically no losses at fundamental frequency and inserts its filtering capability from a certain trigger level (determined by the arrester arrangement). A group of parallel connected arresters inside the filter configuration controls the steady state and transient impedance of the filter. The arresters have been designed for the worst case energy dissipation during fault conditions.

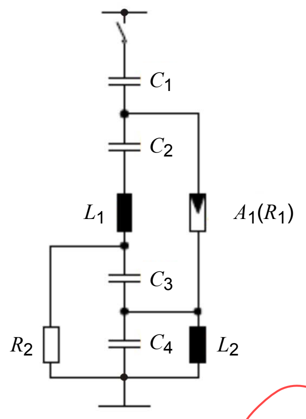


Figure 31 – Non-linear low order filter for Vienna South-East HVDC station

13.4.3 Series filters for HVDC converter stations

Existing experience in a.c. harmonic filtering is based almost entirely on the use of shunt type filters. Some detailed investigations have been carried out in the use of a mixed configuration of series and shunt filters for Itaipu and one actual application, in the Uruguaiana back-to-back station in Brazil, has given good operational experience.

A series filter is functionally similar to the wave trap used in power line carrier applications and is built with an inductor (in the range of 1 mH to 2 mH) in parallel with a series-connected capacitor plus resistor (Figure 32), tuned to a single resonance frequency. If several resonance frequencies are required, a number of such filter circuits can be cascaded in series, each of them tuned to a particular harmonic frequency. Multiple-tuned series filters (Figure 33) can also be used, presenting two or more impedance peaks (impedance peaks for carrier and/or for radio frequency may also be included if necessary). A damped band-stop characteristic can also be achieved to filter a range of higher order harmonics.

The above-mentioned investigations have indicated that, considering the converter as a source of harmonic current, the use of a series filter is efficient only if it is associated with a shunt impedance of relatively low impedance, such as can be obtained with a capacitor bank and/or shunt filter. Therefore, the application of a series filter should be done in a mixed configuration of series and shunt filters (Figure 34).

Depending on the specific requirements of the project and on an economic evaluation, one single series filter for the whole converter station, installed between the shunt filter bus and the a.c. line bus, or one filter for each line connected to the a.c. converter station can be used. For the solution with a single filter for the whole station, the series filter should be formed by several identical branches in parallel, due to reliability considerations.

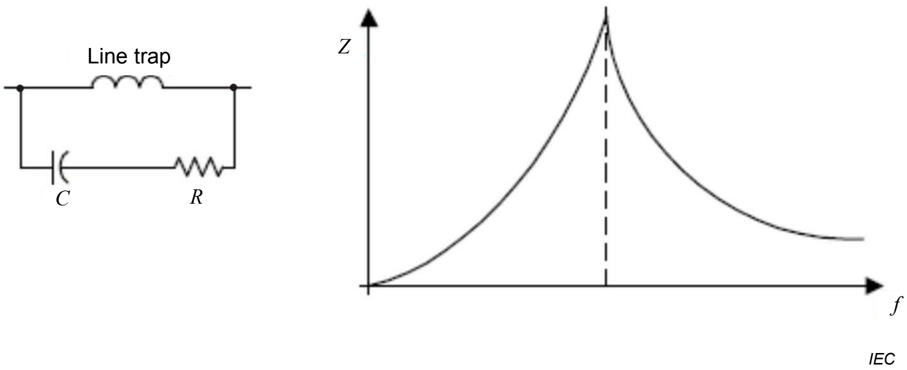


Figure 32 – Single-tuned series filter and impedance plot

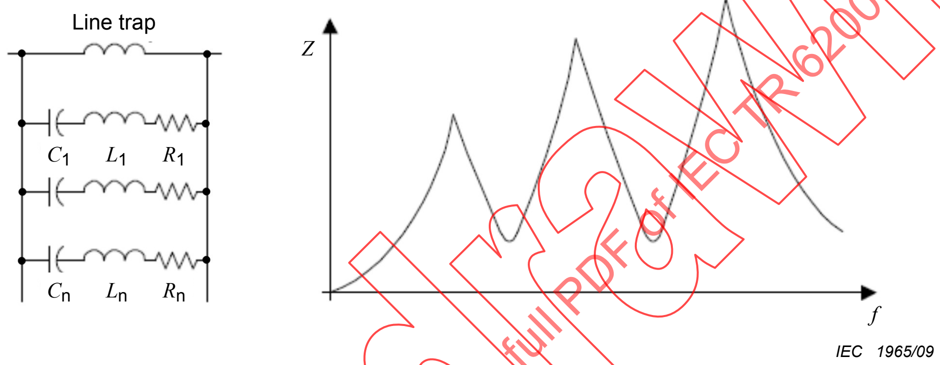


Figure 33 – Triple-tuned series filter and impedance plot

Advantages of series filter circuits are:

- fewer capacitor units and smaller filter reactor size than for shunt filters,
- less space requirements,
- no need for circuit breakers and associated switchgear, but only parallel disconnect switches (assuming that these can remove a faulted parallel branch on-load or if a no-redundancy approach is acceptable),
- minimum of protection equipment.

Disadvantages of series filter circuits are:

- the main reactor has to carry the fundamental frequency line current,
- capacitor/overvoltage protection against short-circuit faults is expensive,
- no reactive power support comparable with conventional shunt filters,
- if high pass resistors are provided, the resistor losses are relatively high,
- components need to be designed with a high short circuit capability,
- protective devices must be rated for full a.c. bus voltage,
- may introduce fundamental frequency or sub-harmonic resonance and stability problems,
- relatively complicated protection schemes.

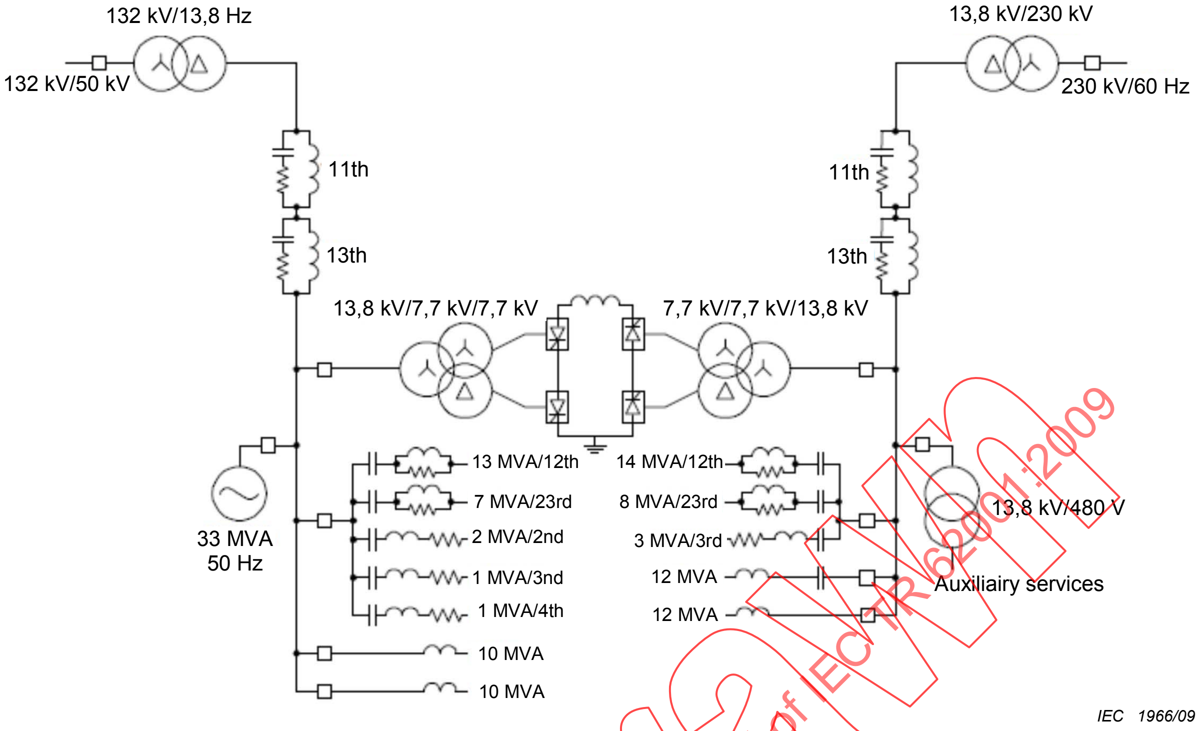


Figure 34 – Mixed series and shunt a.c. filters at Uruguaiana HVDC station

There are several applications with particular harmonic performance requirements and/or converter station design requirements that could justify consideration of a mixed filter configuration. Some of the application characteristics for which the mixed solution should be examined are discussed below.

- Where low minimum a.c. system impedance is combined with requirements for limited emission of harmonic currents into the a.c. system, giving conditions which are hard to satisfy with the shunt filter solution.
- For areas of higher soil resistivity (greater than 1 000 W-m) the coupling between power and telecommunication lines is high and potential interference problems may dictate very low limits on harmonic currents in the a.c. system, thus favoring the use of mixed series and shunt filters.
- In applications in which the connected a.c. system includes important shunt capacitor bank and/or underground cables, these capacitors produce low impedance nodes for high order harmonics, draining the major part of the harmonic currents into the a.c. lines. Series filters could be the most economic means to limit these currents and the resulting interference level.
- The ability of series filters to limit the harmonic current entering the a.c. system to desired values, independently of the equivalent harmonic impedance of the a.c. system viewed from the converter station, may represent an important consideration. This is particularly so in view of the usual difficulty in obtaining realistic equivalents, particularly for the future expansion of the a.c. system.
- In those applications in which the steady state voltage control during light load and/or the control of the overvoltage during converter blocking impose limitation on the shunt filter size and/or require the use of shunt reactor, the mixed filter configuration represents an attractive and economical solution, because for the same filtering performance this configuration reduces considerably the size of the shunt bank to be installed.
- In cases requiring essentially only the control of the harmonic currents fed into the a.c. system, the mixed solution should be examined because the shunt part of the scheme could be limited to a simple capacitor, determined by the station reactive requirements, and the series part would be a single reactor.

In the investigations made for the Itaipu scheme, studies of the use of a mixed filter were done as one possible solution to improve the interference performance in the a.c. system connected to the inverter station of the Itaipu HVDC system, with very good results as compared with other solutions investigated. In this case, the major problem to be mitigated was the effect of the very high soil resistivity (3 600 W-m) and the very high capacitance in the a.c. system (cables and large 345 kV shunt capacitor banks).

The mixed filter in the Uruguaiana back-to-back was installed in view of the requirement for voltage and overvoltage control and the harmonic performance specified. With a shunt filter scheme, the reactive power to be installed would be 72 % (Base P_{dN} = 50 MW) to comply with the harmonic performance requirements, but would make the steady state voltage and overvoltage control impossible. With the mixed filter, the shunt filter in the 50 Hz side could have been only 24 % in order to have the same harmonic performance, but had to be increased to 48 % due to the station reactive requirements.

In studies to be carried out to decide on the use of the mixed filter configuration, the following effects of this filtering on the converter station design and performance should be examined:

- there will be a reduction in the short-circuit ratio (SCR), that could be compensated by a decrease in the converter transformer reactance, although this solution produces a certain increase in the harmonic current generated by the converters;
- in case of error in the adjustment of the impedance angles of the series and shunt parts of the mixed scheme, there is the possibility of an increase in the harmonic voltage at the point of connection to the a.c. system;
- the mixed scheme may affect the operational flexibility of the converter station, requiring some additional on-load switching equipment.

The procedure to define the mixed filter scheme, including its ratings, is not much different from the conventional methodology used for a shunt scheme.

13.4.4 Re-tunable a.c. filters

In special circumstances, the temporary re-tuning of a.c. filters to act at different frequencies may be an option, as illustrated by the following example.

For the Quebec/New England Multiterminal HVDC system, re-tunable a.c. filters have been used at Radisson and Nicolet substations. For both stations, this has been done as a retrofit action to solve problems that arose after the installation of the original filters had been completed.

At Radisson, this solution has been used to avoid interaction between a.c. side fifth harmonic and d.c. side sixth harmonic for certain system conditions and in the presence of geomagnetically-induced currents (GIC). When the a.c. side fifth harmonic becomes greater than a predetermined value, the 36th/48th harmonic a.c. filter is re-tuned to the 5th harmonic (Figure 35) by opening the switch S1. The switch is closed by the operator when the conditions have returned to normal.

At Nicolet, the problem was due to a system resonance around the 3rd and the 5th harmonic. The 24th and 36th single-tuned filters were modified to permit retuning to the 5th and the 3rd harmonic respectively.

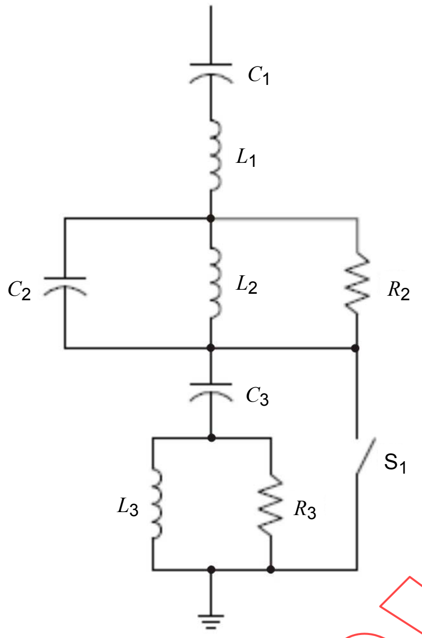


Figure 35 – Re-tunable a.c. filter branch

13.5 Impact of new HVDC station in the vicinity of an existing station

An increasing number of new HVDC links are being planned with their terminal stations located in the electrical vicinity of existing HVDC converter stations. This entails due consideration of the impact on performance and rating of the existing converter station a.c. filters as well as additional design requirements on the new converter stations. The objective should be, as far as possible, to design the filters of the new converter stations without modifying the filters of the existing stations.

The performance aspects to be considered in the design of filters for the new converter stations are as follows:

- the performance parameter limits should be specified with due consideration to the effect of the existing converter stations. In doing so, [41] and [44] can be used;
- generator harmonic current limits, if applicable, should be such that the total effective injection does not exceed the permitted limits;
- the effect of resonance between the filters of the existing and the new stations must be taken into account;
- the a.c. system harmonic impedance to be used in the design calculations should be defined with due consideration of the existing station and its filters.

The rating aspects to be considered are as follows:

- additional harmonics coming from the existing stations should be taken into account. Normally, these together with a.c. system harmonics are considered in terms of certain percentage increase of the harmonics of the station under design;
- increase in rating due to outage of similar frequency filters at the existing stations;
- increase in rating due to possible resonance between the filters of the existing and the new stations.

The technical specification should include, or otherwise make available, full details of the design of the a.c. filters in the existing converter station, including sufficient information for all the above-listed aspects to be considered in the design of the new filters. In contractual terms, the technical specification must be very clear on the boundaries of responsibility of the customer and the contractor in relation to the a.c. filters at the two stations.

13.6 Redundancy issues and spares

13.6.1 Redundancy of filters – Savings in ratings and losses

Field experience with a.c. filters in HVDC stations has in general shown a very high level of reliability, and constant improvements in filter component design are tending to increase this reliability still further. There is therefore a tendency to reduce costs by eliminating the requirement for redundant filters, particularly in relatively low-power HVDC schemes.

However, redundancies in filter circuits can provide a number of advantages, even when the investment costs for such a redundant system are a little higher compared to an otherwise optimized filter arrangement. Apart from improving the reliability / availability of the converter station, the use of redundancy can reduce the filter losses and component ratings in the individual filter branches.

If a shunt capacitor is in any case needed for reactive power purposes, it may be worthwhile to convert this into an additional filter branch, to provide added redundancy.

These concepts can be illustrated by an example based on recent experience. Supposing that unity power factor is required at rated load, two very economical solutions a) and b) which use double tuned high pass filters, are possible. Below, the relative merits of these two solutions are compared.

a) Solution with two double tuned filters and an additional shunt capacitor

In this case, two almost identical redundant filters are assumed to provide adequate characteristics for harmonic performance and reactive power control. A common practice is to start at light load conditions of the converters with one filter, then the second circuit will be energized in the range between 40 % and 50 % of rated load. Typical harmonic performance requirements can be fulfilled up to rated load. To fulfill unity, power factor requirements up to rated load only a simple shunt capacitor bank is required additionally.

The advantages of this solution compared to solution b) are:

- simple filter arrangement and redundancy (1 out of 2);
- saving LV filter components and space requirements.

The disadvantages are as follows:

- higher ratings of filter components if the filter has to be designed for all loadings during outage of any filter branch (one out of two in the whole operating range). This has a great impact on the harmonic current ratings and rated power of high pass damping resistors;
- the filter performance in the upper loading range of the converters is worse compared to solution b). Also the operational losses can be expected to be higher.

b) Solution with three identical double tuned filters

This solution uses three identical double tuned filters with no shunt capacitor.

The advantages of this solution are as follows:

- higher availability and better harmonic performance (2 out of 3) in case of forced outage of a filter branch. In this case, both harmonic performance and component stresses in the remaining circuits are lower compared to solution a);

- component ratings of filter reactors, capacitors and resistors are significantly lower compared to the components for solution a). Therefore, most of the filter components are less expensive. This applies especially for filter damping resistors.

Operational losses are significantly lower, since mostly the harmonic losses are the determining factor of the filter losses.

The disadvantage is:

- the increased number of LV filter components in the circuit leads to a more complex circuit arrangement and to enlarged space requirements.

It is always recommended to check, whether solution a) or b) is the more reliable and cheaper solution. This evaluation has to consider the component costs, the loss evaluation of the operational filter losses and the overall reliability and availability of the a.c. filter arrangement.

13.6.2 Internal filter redundancy

Component redundancy within a filter is not normally used, except within capacitors. Depending on the kind of capacitor fusing - whether internal or external - some additional capacitor elements and/or capacitor units can be built in as voltage redundancy. However, true redundancy inside the filter is not possible, because every failure in a capacitor unit increases the voltage stress on all other capacitor elements and will detune the filter circuit.

The voltage stress during normal operation conditions and after fuse blowing can be reduced and optimized with two measures:

- small subdivision of internal fused capacitor elements, and
- higher rated voltage for the complete capacitor bank, which will reduce the probability of capacitor element/unit break down.

In addition, the smaller the capacitor subdivision, the less is the detuning of the filter in case of a blown fuse. On the other hand, the smaller the capacitor subdivision, the more fuses there are to blow. Thus, the total de-tuning allowance for blown fuses may be no smaller.

The layout of a capacitor bank in the form of a bridge does not increase the voltage withstand or redundancy. The bridge connection is only for capacitor unbalance protection based on a sensitive detection of blown fuses.

An important design issue is how many fuses can blow (it makes no difference whether they are in series or in parallel connection) before maintenance and capacitor unit change is required, considering:

- capacitor voltage stress, or
- filter detuning beyond specified tolerance.

Normally, the number of failed capacitor elements for permitted filter detuning is much less than the allowed number for voltage stress.

13.6.3 Spare parts

The optimum number of filter component spare parts is mainly dependent on redundancy requirements. In the case of no filter redundancy being provided, as for example in some Scandinavian schemes, it is desirable that all types of filter components should be on stock in the converter station, or adjacent to it. To reduce down time following failures, it is recommended to have some filter components stored mounted in complete sets, e.g. filter resistors.

In cases where filter redundancy is required (1 out of 2 or 2 out of 3), the spare part solution may differ depending on the type of redundancy required with respect to filter performance or rating. If redundancy is related only to rating purposes, it is recommended to follow the recommendation for the non-redundant cases as described above. However, if the redundancy requirement also covers filter performance, complete sets of spares may not be required. For instance only one spare of each type, e.g. one insulator, one resistor element per type, etc. needs to be stored instead of a complete resistor, including structures and insulators.

One spare of each type of filter reactor needs to be stored. For filter capacitors, a minimum number of capacitor cans of each type must be provided. For this reason, it is desirable where possible that the filter design uses identical capacitor units for each individual type of a.c. filter.

14 Protection

14.1 Overview

The type of filter protection to be installed depends to a significant extent on the configuration of the different a.c. filter branches and on the contractor's normal practice and preferred protection techniques. It may also be affected by requirements on guarantees and on filter performance. The detailed definition of a.c. filter protection equipment is normally left for the contractor to determine.

The technical specification therefore is usually restricted to general requirements regarding protection, redundancy requirements, interface definitions and any customer specific requests. In this way, the interests of the customer are safeguarded while still leaving maximum scope for the contractor's preferred solutions.

The customer must however, be well aware of the different techniques of a.c. filter protection, and in the bid evaluation stage be prepared to ensure that the bidder's proposed solutions meet the customer's overall technical requirements. The information given in this clause is mainly concerned with giving the customer the background information needed for this stage of technical discussions with the bidder.

The IEC standards with relevance to the protection of a.c. filters are the following: IEC 60044-1 (1996) [2], IEC 60044-2 (1997) [3], IEC 60044-5 (2004) [4], IEC 60549 (1976), IEC 60871-1 (2005), IEC/TR 60871-3(1996), IEC 60931-3(1996), IEC 60871-4(1996).

14.2 General

In general, the extent and type of protection equipment depends on technical requirements, the size of the filter or shunt capacitor bank and on the cost of the protected components. Specific decisions must be made between:

- protection functions which prevent damage to components (overload protection, unbalance protection); and
- protection functions which limit damage to components (short circuit, earth fault protection).

In each case the cost of protection must be carefully weighed against the cost of the high voltage or power components that are being protected. On average, the value of the protection equipment should not be higher than approximately 10 % of the value of the protected components.

It is therefore not possible to specify the different types of protection units every filter or shunt capacitor bank must have. The selection must be made in each case depending on voltage, power, security standard and fault probability.

Particularly in the case of small and relatively low cost components, it must be considered whether using a component with higher voltage (or power) design margin is less expensive than a special protection unit with current or potential transformers. A good example of this would be the low voltage filter capacitors in C-type filter arrangements.

In certain specific cases of resonances in the power grid, it may be possible to generate an early warning signal, so that a pre-defined change can be made either automatically or by operator action in the filter and/or the a.c. system configuration.

The question of redundancy must also be decided in each case between the customer and the contractor. A higher reliability normally has a higher cost. On the other hand, with no redundancy, the consequences of failure of the complete system must be taken into consideration. Factors to consider are:

- what is the normal standard elsewhere in the a.c. system?
- is redundant protection equipment justified for the rated power of the filter or capacitor bank?

A good compromise can be partial redundancy for only a few main functions. If the decision is for full redundancy, the main and redundant systems should not use identical sources of actuating signals.

As an alternative to redundant protection functions, some functions can be covered with back-up protection functions. For example, differential protection is a partial back-up for short circuit protection while earth fault protection is a less sensitive back-up for capacitor unbalance protection.

The work of the contractor should be to deliver a scheme with an overview of main and back-up protection for every filter component, including what protection is overlapping. It is desirable that main and back-up protection are not sourced from the same CT.

In each case, the customer should specify the minimum standard to which the contractor must provide in terms of:

- protection philosophy,
- standard of potential transformers (PTs) and CTs,
- standard of protection,
- protection functions,
- types of interfaces, including type and number of auxiliary switches for HVDC control, switchyard control, alarm system, event recording system, etc.,
- customer specific requests (e.g. design of trip signal circuits),
- mechanical standards,
- type and number of auxiliary voltages.

The number of PTs and CTs in the banks and sub-banks should be optimized together with the PTs in the busbar, according to the protection philosophy. Important aspects for the planning and arrangement of inductive PTs are:

- maximum time for filter discharge,
- requirements for auto-reclosing,
- circuit breaker layout.

Filters are normally arranged in a star connection with the star-point solidly earthed. In networks with reactive earth fault compensation or isolated star-point, the protection must be reconsidered.

In principle, the protections should be designed so that external transient disturbances do not result in filter protection trip signals. Such disturbances include:

- a.c. system faults,

- transformer switching,
- switching of parallel capacitor banks,
- commutation failures in the HVDC converters,
- d.c. line faults.

The a.c. filter protection should be co-ordinated with the a.c. switchyard protection.

14.3 Bank and sub-bank overall protection

14.3.1 General

Such protections cover more than one filter component and can also protect components outside the filter, such as the conductors between the current transformer and the filter and the earth connection. They are also useful to detect earth faults and breakages in the filter connections.

14.3.2 Short circuit protection

Short circuit protection is only effective between the incoming line current transformer and the line side of the first components, depending on the total fault impedance of the circuit. The short circuit relay is normally a standard requirement for the protection of the conductors between the current transformer and filter. Depending on the capacitor inrush current, it is sometimes necessary to delay the trip signal by 5 ms to 10 ms. The ratio of CTs in filter branches can be low in comparison with the ratio of line CTs. For short-circuit current protection, it is important that CTs are accurate enough to reproduce the short-circuit current with full d.c. shift in the secondary circuit.

14.3.3 Overcurrent protection

This is also generally a standard protection requirement, sometimes in combination with the short circuit relay function. This protection is not very effective for filter and shunt capacitor banks, since only the reactor is really protected. For capacitors the applied voltage, not the current, is the critical factor and only heavy faults in the capacitor bank can be detected with overcurrent. This function can be implemented either with an inverse time characteristic or in the form of current-definite-time steps. Normally no separate evaluation of fundamental and harmonics is required, but a technically good solution would be to check the important harmonics separately for overcurrent. This method results in a very comprehensive protection.

14.3.4 Thermal overload protection

This kind of protection is one of the most important functions, although an overall overload protection can only protect the weakest filter component with the shortest heating time constant that is carrying the main filter current. Therefore, it must be determined in each case, whether an overall overload protection will be installed and/or if individual protection for reactors and resistors will be installed separately. Normally the overall overload protection cannot protect a damping resistor because the current through the damping resistor is not proportional to the main filter current. A damping resistor can only be protected by measuring individual harmonics. In single tuned filters, the overall overload protection can be used for both reactor and capacitor. The following remarks should be borne in mind:

- the construction and function of an overload relay can vary from the simple up to the highest complexity;
- a fundamental prerequisite when deciding on the level of complexity, is the level of knowledge of the reactor thermal time constants over the frequency range of interest;
- the ambient temperature assumed by the overload protection can be a design input with a fixed setting of the maximum calculated ambient temperature or an actual temperature measurement. A temperature measurement must be checked continuously for correct functioning and plausibility;

- if sufficient knowledge of the reactor's thermal characteristic is not available, a simpler version of overload protection can be selected. This could be a true effective current measurement or with an additional filter function to increase the sensitivity;
- for the ideal function, a true current rms measurement is not enough. The overload protection must also take into account the frequency dependent thermal loss characteristic of the reactor. The ohmic resistance of a reactor depends on the frequency and so the evaluation of each harmonic current is different. In order to implement an exact overload function, the more expensive digital type of equipment is required.

14.3.5 Differential protection

This kind of protection is normally used only as an overall protection. A differential protection is only efficient when it operates separately in each phase and is stabilized against outside failures to avoid influences from higher frequencies. It is recommended that the input currents be filtered with a fundamental frequency bandpass to eliminate or avoid these influences. The differential protection could otherwise operate in case of transformer switching, due to the inrush resonance between filter and transformer zero sequence impedance. The differential current setting should be very low (20 % to 30 % of the main current).

The differential protection detects phase to earth and phase to phase faults but cannot detect isolated failures, such as an arc-over of components in the filter branch.

Another kind of differential protection is a single phase protection relay between high voltage and low voltage zero sequence systems. But here again, the currents must be filtered against higher harmonic influence. With this kind of differential protection, it is not possible to provide a phase segregated protection scheme.

14.3.6 Earth fault protection

This function can be applied only in a star-point earthed network in the earthed filter star-point. Earth fault protection works with an overcurrent or inverse time characteristic and uses the current from the star connection of the three phases to earth. It is a reliable but slow back-up function for differential protection (and also a rough back-up for unbalance protection). It detects every asymmetry between the phases much like a differential protection between phases. It also detects every asymmetry coming from outside the filter.

For the high trip threshold that is required to avoid spurious tripping on external events, either the time delay for the trip signal must be very high, or the sum of the phase currents must be filtered by a fundamental bandpass characteristic, generally by a second order filter. With both types, the trip signal must be delayed a few seconds (depending on the current setting).

14.3.7 Overvoltage and undervoltage protection

Equivalent to the overcurrent protection for reactors, the overvoltage protection is one of the most important types of capacitor protection. Usually the bus bar voltage is the source for overvoltage protection, but the voltage from PTs in the feeder can also be used.

In the case of HVDC system operation, the valve control can usually reduce steady state fundamental a.c. system overvoltages (not the harmonics). An immediate overvoltage trip of the HVDC converters and filters during transient overvoltages, like load rejection or switch-off due to overhead d.c. line failures, can increase the amplitude of the overvoltage. Any fast overvoltage protection should generally have a time delay of 5 ms to 20 ms and then initiate a sequential filter tripping sequence.

The need for overvoltage protection should be decided separately from case to case.

Surge arrester protection is covered in 18.5.

The undervoltage protection is mostly a system control function and not a protection function. This function can be also used as an interlock to avoid energizing a filter or shunt capacitor that has not been completely discharged. With potential transformer-aided capacitor discharge, re-energization is possible within 0,3 s up to 1 s, fast enough for auto-reclosing in the power grid. In all other cases, where fast discharge cannot be guaranteed, the filter or shunt capacitor switch-on-signal to the breaker must be interlocked to ensure complete capacitor discharge.

14.3.8 Special protection functions and harmonic measurements

Depending on different parameters, like the type of filter design, a.c. system conditions and other special requirements, additional protection functions can be required. These can include protection against excessive harmonic currents or voltages.

The installation of a Fast Fourier Transform (FFT) analyzer (refer to Clause 18) can be added to enhance such protection.

14.3.9 Busbar- and breaker failure protection

Busbar- and breaker failure protection are not specific filter and shunt capacitor protections but general substation protection requirements.

Filter protection (adjustable rated values, interfaces, signals etc.) should, however, be co-ordinated with any substation protection.

14.4 Protection of individual filter components

14.4.1 Unbalance protection for filter- and shunt capacitors

The capacitor units represent in financial terms the main cost in a filter and so the protection of capacitor units is one of the most important functions.

Usually the capacitor bank arrangement is in the form of a bridge with two pairs of identical branches, each with series and parallel connected capacitor units. This construction allows the installation of a very sensitive unbalance protection, using the current (or voltage) in the transverse connection. In most cases, capacitor units with internal fuses are used, but the unbalance protection system can also be used with minor modifications (higher current steps in case of fuse operations) for capacitor units with external fuses. Unbalance protection is not a substitute for short circuit protection, but it can help protect an unfused capacitor arrangement.

The design of a current transformer to be used in an unbalance protection must be done very carefully. On the one hand, the CT must be suitable for the short circuit current, but on the other hand, it needs a very low transformation ratio. The CT saturation and secondary burden must also be taken into consideration. The rating of a current transformer for unbalance protection must be specified very carefully because in the case of a partial short-circuit in a capacitor branch, high frequency transients resulting in high current stresses on the current transformer can appear. The point of CT saturation should be selected such that in case of a high short circuit current in the primary, the secondary connected equipment of the unbalance protection will not be overstressed by excessive current or voltage. The primary winding of the current transformer may be protected by means of surge arresters.

Normally the unbalance current protection is in principle an overcurrent relay with different settings for alarm and trip. The function detects not only the operation of capacitor element or capacitor unit fuses but also all other asymmetries in the bridge, including earth faults and open circuits. Criteria for alarm and trip signals should be decided by the contractor after discussion with the customer.

Instead of an overcurrent relay in the transverse capacitor connection, other methods can be used such as:

- detection of neutral voltage,

- different voltages over capacitor phases,
- different currents through capacitor phases.

The disadvantages of the above methods compared with the bridge current measurement are not only a lower sensitivity, but most importantly a long-time delay for the trip signal due to a high dependency on a symmetrical grid voltage such that disturbances in the power grid will influence these measurements and so a compromise is unavoidable.

In unearthed shunt capacitor arrangements an unbalance current measurement in the neutral is sometimes used. Refer to Figure 36.

Normally the inherent unbalance current of a bridge can be calculated in the factory in accordance with the measured tolerance in capacitance. This inherent unbalance current can increase or decrease during the lifetime of a filter due to voltage variation and primarily due to the different heating of bridge arms caused by solar radiation. Every change in symmetry of the bridge arms such as the opening of an element fuse results in a change (increase or decrease) in the unbalance current.

In recent years, especially with the introduction of digital protection systems, a high standard of resolution can be achieved so that the balancing of the capacitor bridge to a very low unbalance current is no longer needed.

Depending on the cost and importance of the protected component, the unbalance protection should be provided with the following:

- fundamental frequency band pass for filtering the unbalance current. Transient inrush oscillations within the transverse bridge arm can thus be eliminated in the protection circuit;
- compensation of unbalance current in proportion with the main filter current to eliminate the voltage variation influence on unbalance current;
- compensation of very slow changes in unbalance current, caused by solar radiation;
- potential to re-adjust the effect of residual unbalance current to zero after changing bridge components;
- storage of the last fully compensated unbalance current value after filter switch off and its comparison with the current after switch on. With this approach, fuse failures at the moment of filter switch-on can be detected [The unbalance protection needs some milliseconds after filter switch-on, however, for full operation];
- comparison of compensated unbalance current against limits for alarm and trip signals;
- calculation of the value of unbalance current deviation caused by the operation of one capacitor element fuse, as well as the maximum permissible number of fuse operations. Thus it will be possible to detect and count the number of failed capacitor elements;
- storage of the total number of blown fuses (also over filter switch-off periods). If the number of counted blown fuses is higher than a pre-set value, an alarm and/or a trip signal should be given;
- the possibility to detect the branch of the capacitor bridge where faulty capacitor units are located. For this purpose, an additional voltage input is required for a power direction measurement in the transverse connection of the bridge;
- the possibility to select different settings for the numbers of failed capacitor units for alarm and trip signaling;
- check of the uncompensated unbalance current with respect to limits;
- recording of the value of unbalance currents at regular time intervals on a line printer or in a digital monitoring system.

In filters with isolated or impedance earthed star-points, there is a possibility to construct shunt capacitor banks in an arrangement with parallel capacitors in star connection. Between the two star points a current transformer can be used to compare the unbalance between the two capacitor banks. For this arrangement, a current direction measurement is also possible to detect the faulty phase and bridge arm.

14.4.2 Protection of low voltage tuning capacitors

In some filter configurations, small additional low voltage capacitor arrangements are required. For these capacitors, an independent bridge construction with a current transformer is generally too expensive because the cost of the capacitor bank is less than the cost of the CT and associated protection. In such cases, it is recommended to design the bank for a higher voltage-level - as a minimum, with one more capacitor unit in series than required - for the designed voltage withstand. In certain types of filter, it is often possible to protect the low voltage capacitor by means of monitoring current in some other “leg” of the filter (e.g. through a resistor).

14.4.3 Overload protection and detection of filter detuning

A current dependent overload protection is only necessary for reactor coils or resistors, but not for capacitors.

Depending on the filter design, the reactors and resistors are generally situated on the earth side of the filter, while capacitors are situated on the high voltage side. This can also be reversed. In the first case, relatively inexpensive current transformers can be used for measuring the reactor and resistor current for overload protection.

For the calculation of an overload condition of a reactor, harmonic currents should be evaluated in addition to the fundamental frequency.

In comparison to reactors, the overload protection for resistors is much easier because the ohmic resistance is less dependent on frequency, and also the time constants for the different harmonic frequencies do not vary greatly. A true rms measurement of current is sufficient as the basis for a digital or analogue thermal model of the resistor. Although it is dependent on the design of the filter, in general, higher order harmonic currents tend to overload the resistor while lower order harmonic currents tend to overload the reactor.

In the event that there is a CT in a resistor branch, the level of fundamental frequency current can be used to determine the extent of filter detuning. A filter with a fundamental frequency tuned bypass circuit should have negligible fundamental current in the resistor branch provided the fundamental frequency is near nominal.

14.4.4 Temperature measurement for protection

The method of direct temperature measurement at hot spots in components, such as is used in transformers, has, up to now, not been applied to conventional filter components since the costs are too high.

14.4.5 Measurement of fundamental frequency components

Low voltage capacitors with series connected reactor (such as in a C-type filter), are often used to minimize the fundamental frequency losses in parallel resistors. By filtering to obtain the fundamental current in the resistor, a sensitive additional protection for the capacitor and reactor can be achieved (refer to the attached highpass filter protection scheme, Figure 37). The fundamental current in the damping resistor branch should disappear to zero at rated conditions (rated fundamental frequency). If the tuning capacitor in series with the filter reactor changes reactance, caused by a disturbance in a capacitor element, the fundamental current through the resistor can increase, in most cases by a higher amount than by normal frequency deviations.

In addition, a breakage in the capacitor/reactor wiring can also be detected with this method.

14.4.6 Capacitor fuses

A capacitor unit consists of a number of parallel and series connected capacitor elements. Capacitor element fuses are a type of protection which limits the damage to the unit, but they cannot prevent damage to other units from incorrect voltage distribution, unlike overload or unbalance protection equipment. The capacitor fuses are only intended to disconnect faulty elements.

The number of external parallel connected capacitors and the available short circuit current of the supply system should not affect the current limiting capability of element fuses.

External capacitor fuses can clear faults inside the capacitor unit and external capacitor bushing flashovers. The advantage of external fusing is that blown fuses can be visually detected very easily and quickly. The disadvantage is that in the case of a fault in one capacitor element, the complete capacitor unit will be switched off. Further, the fuse is exposed to the ambient conditions. The main application of external fuses is in low and medium voltage capacitor banks with many parallel capacitor units and relatively few units in series.

Internal capacitor fuses can clear capacitor element failures and therefore are much more sensitive, given that every capacitor element in a capacitor unit has its own fuse.

Element fuses are, in general, not designed for overload protection of capacitor elements. They have to resist very high inrush and discharge currents, which are limited only by the circuit impedances. Therefore the sensitivity of element fuses must be much higher than the maximum permissible element current.

The effect of one blown internal fuse is less in comparison than with external fuses, the voltage stress on the remaining capacitor elements being relatively small for the loss of a single element. Moreover, internal fuses are protected from ambient influences. The main application of internal fuses is in high voltage capacitor banks with several series connected capacitor units. It should be noted that internal fuses do not provide protection against a short circuit between internal connections or a short circuit between active parts and casing, both of which may lead to case rupture.

Fuseless capacitors are discussed in 20.2.4.

14.4.7 Protection and rating of instrument transformers

In radial power systems with auto-reclosing operations, the discharge of capacitors can be ensured using inductive PTs before re-energization. The arrangement of PTs can be either directly on the filter feeder or on another feeder of the substation provided that the connection between the capacitor and PT is secure. The rating of such discharge PTs must be done carefully. On the one hand, the high discharge d.c. current through the primary windings of the PT (approximately 10 A -15 A) must be considered in relation to its dynamic consequences, but on the other hand, the thermal load of the discharge must be calculated. Normally every inductive PT, however, has to discharge overhead lines and cables and so the thermal and dynamic stress during discharge of a capacitor, whose capacitance is comparable with that of an overhead line, is generally not a problem. The main condition for PT rating is the total thermal load from the permissible number of discharges per time unit (1 h). It is necessary to specify and limit the number of discharges (capacitor switch on/off cycles) permitted per hour. Common values for the number of discharges allowed are approximately 5 in the first hour and one in every subsequent hour.

Discharge PTs can be connected from line to earth, but they can also be connected isolated from earth across the capacitor line-side terminals. In such a case, the secondary winding cannot be used for measurement or protection purposes.

In all cases where no discharge PTs are used, the possibility of reclosure with capacitor trapped charge is an important condition to consider in determining circuit breaker ratings.

The possibility of ferro-resonances with inductive PTs exists when no burden is connected with the PT in parallel. Normally, the filter impedance is in parallel with the PT and suppresses any oscillation. Ferro-resonance effects can be reduced or avoided with a reduced magnetic induction (less than approximately 0,6 T) in the PT.

A higher overvoltage factor of the PT (the factor in p.u. up to which voltage the transformation ratio of PT is linear, normally approximatively 1,9) increases the linearity of the transformation to the secondary voltage during disturbances such as load rejection. The internal resonance frequencies of the PT can be shifted up or down by changing the overvoltage factor, which can be an advantage if one internal resonance frequency of the PT would otherwise coincide with a harmonic frequency.

CTs in filter branches mostly have a low current ratio. It must be confirmed that the secondary windings give a true reproduction of primary fault currents for all protection purposes, especially short circuit current protection.

The secondary windings of unbalance CTs, when shorted, should withstand the effect of the primary short circuit current.

14.4.8 Examples of protection arrangements

An examples of a typical protection scheme for a simple shunt capacitor bank is shown in Figure 36 and for a C-type filter in Figure 37. It should be noted that protection schemes may vary considerably depending on the particular features of a given filter design and on the protection philosophy adopted.

14.5 Personnel protection

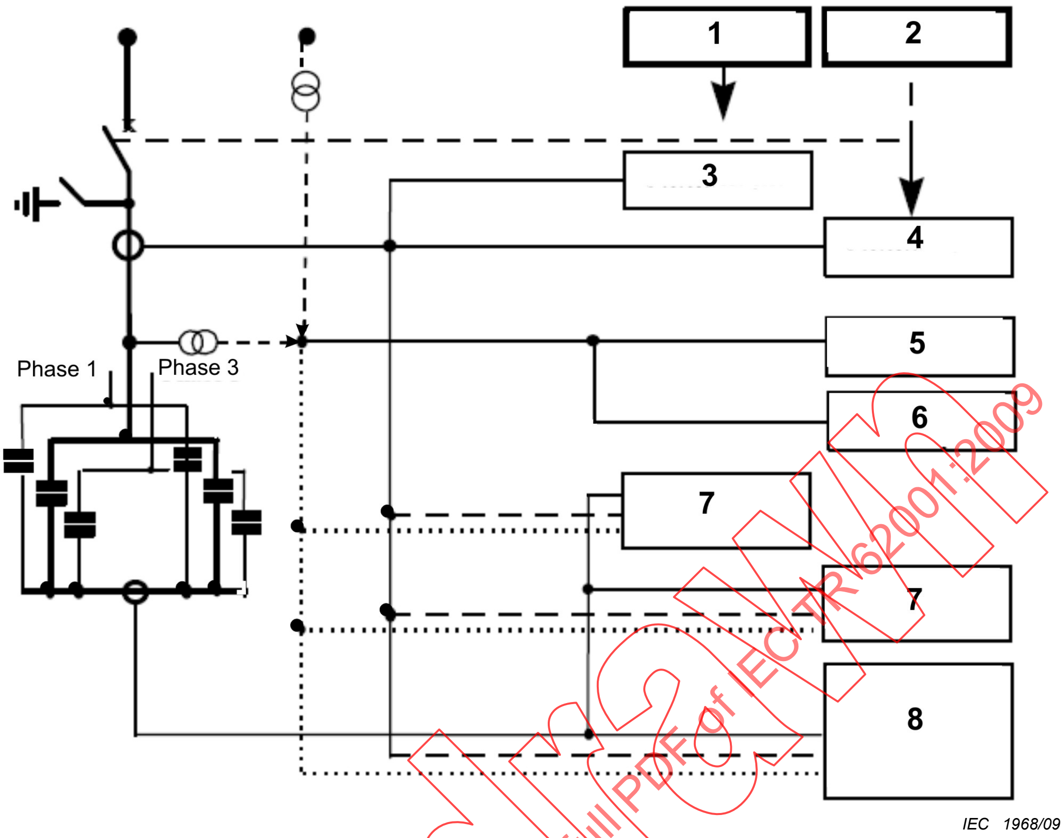
Each capacitor unit must be discharged before energization. Complete discharge and earthing is an unconditional requirement before any work or maintenance is performed on filter and shunt capacitor circuits.

All capacitor units are now usually equipped with internal (or external) discharge resistors in parallel with the capacitor. To reduce the losses (to minimize tan d), the value of discharge resistors is very high. Depending on the resulting time constant, the discharge time can vary between a few minutes and a quarter of a hour.

Normally the operation and possible failure of internal (or external) discharge resistors cannot be checked during operation and maintenance. There is no guarantee, therefore, of a complete capacitor discharge after de-energizing. External discharge resistors can be checked more easily during maintenance but they are exposed to the ambient conditions with the possibility of corrosion.

An alternative with minimal or negligible losses is one using inductive PTs (capacitive PTs are not suitable for this purpose). In the case of de-energizing, the complete capacitor is discharged within approximately 0,3 s to 1 s. These PTs need not be directly in the filter feeder but it must be guaranteed that the connection between filter capacitors and PTs is maintained long enough that the capacitors can be discharged completely. In floating filter circuits with an unearthed PT arrangement, the discharge to earth must be done separately as an additional item.

Before any work is performed on high voltage components, the relevant safe work standards of the country and utility must be followed. Special sets for earthing the capacitor units before touching are recommended.



Key

1 alarm signal
2 trip signal
3 overcurrent protection
4 overcurrent protection
5 under/overvoltage, 1 step
6 overvoltage, 2 step
7 unbalance current
8 unbalance current, maximum number of capacities failures

Figure 36 – Example of a protection scheme for an unearthed shunt capacitor

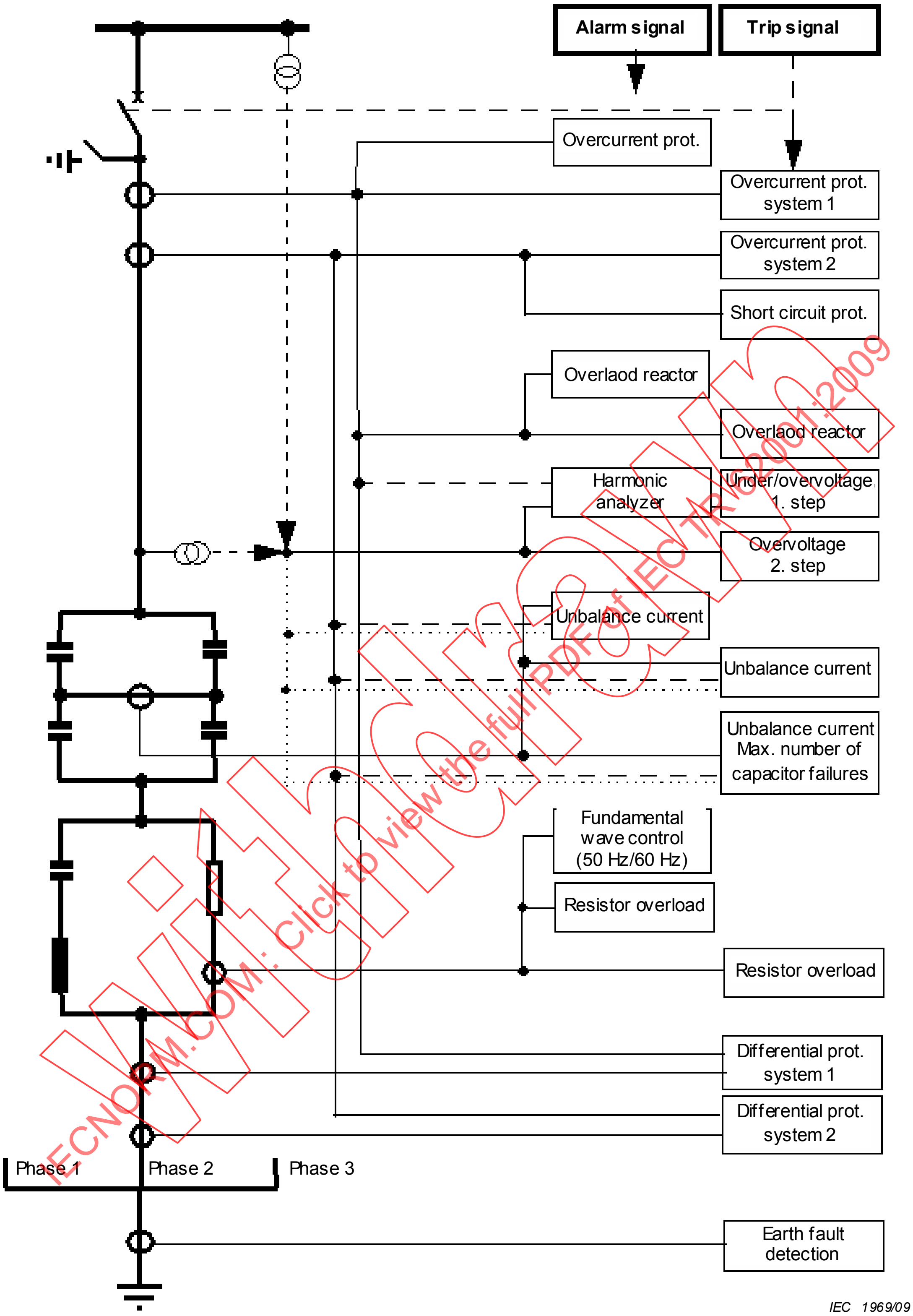


Figure 37 – Example of a protection scheme for a *C*-type filter

15 Seismic requirements

15.1 General

The intention of this clause is to give the customer's engineers dealing with a.c. filters sufficient background information in order to understand the implications of seismic requirements for a.c. filter design, and to have a basis on which to discuss aspects of seismic design with bidders. Any seismic requirements for the filters will be defined in the technical tpecification in the same way as the requirements for the rest of the converter station.

AC filters consisting of capacitors, reactors, resistors, etc. constitute structures which might be subjected to mechanical loading imposed by the shaking of the ground during earthquakes. Compared to other mechanical loading, such as wind loading or electromagnetic forces, seismic requirements usually represent the most severe mechanical loading to these structures.

The time variable ground motion during an earthquake results in a vibration response of the filter structure inducing mechanical stresses in the foundation system and in the individual components of the filter structure. Further it causes displacements of the structure relative to other equipment in the switchyard.

The aim of the seismic design of the equipment is to achieve adequate performance of the structure during earthquakes at acceptable expense. In the case of severe seismic loads, the whole filter design may be affected, e.g. the choice of mechanically robust configurations may be preferred.

Adequate seismic performance means that at least the functionality of the equipment is maintained during and after the seismic event. This requires that

- the structure is safely anchored to ground, considering the quality of soil at site,
- the structure withstands the mechanical stresses induced in its individual components, in particular in the support insulators,
- adequate electrical connections and spacing to neighboring structures with respect to relative displacements provided.

With respect to the special nature of electrical equipment which contains a large amount of brittle material (porcelain), it is important that realistic loads and reasonable evaluation criteria are defined by the customer. However, the seismic design qualification discussed in this clause is the responsibility of the contractor. Information on the specification of seismic requirements may be found in IEEE 693-1997 [59].

15.2 Load specification

15.2.1 Seismic loads

Proper seismic engineering for a specific project requires specification of the seismic activity of the region of installation by quantitative engineering parameters. Usually this is done by defining a "design earthquake", that is a specification of the seismic ground motion at site in terms of the maximum ground acceleration and the so-called "response spectrum".

The maximum ground acceleration is expressed in fractions of gravity (g). The selection of the design value of ground acceleration is a balance of site specific geophysics, desired reliability of the equipment and costs. In earthquake-prone areas, the horizontal component of the maximum ground acceleration typically ranges between 0,1 g to 0,5 g, while the vertical component is typically 50 % to 80 % of these values. Certain sites can have even more extreme values. Levels of ground acceleration up to around 0,15 g and moderate safety factors against failing of the members of the filter structure usually do not require extra efforts for seismic engineering and thus no extra costs to achieve seismic performance are involved.

A response spectrum in general is used to predict the maximum effect to be expected from a given type of impulsive loading acting on a simple structure. In the context of seismic engineering, the response spectrum is a family of curves of the estimated maximum acceleration evaluated for a structure consisting of a single spring and mass (single-degree-of-freedom structure) of varying natural frequency, plotted over frequency, for different amount of damping in fractions of critical damping.

The response spectra describe the dynamic properties of a seismic event in that the curves show the anticipated amplification of the movement of the structures as a function of frequency. Usually the earthquake motions do not contain frequencies over about 33 Hz so that the vibrations induced in structures with natural frequencies above 33 Hz will not be amplified.

If no response spectrum for a specific site is available to the customer then the "required response spectrum" (RRS) of IEEE 693 [59] may be used. As an example the RRS for moderate seismic requirements is shown in Figure G.1. The maximum ground acceleration in this spectrum is 0,25 g.

If the filter structure is mounted on a primary structure (building, platform, etc.) which affects the structural response, then it might be necessary to derive a secondary response spectrum (floor response spectrum) based on the ground response spectrum and the modal properties of the primary structure.

15.2.2 Additional loads

Additional loads which have to be considered acting simultaneously with the seismic loads are:

- dead weight,
- normal operating loads (electromagnetic forces at normal service).

In some rare cases, further additional loads such as wind load and short circuit load may be specified to act simultaneously with seismic loads. If such load combinations are requested, then the relevant data for the additional loads (e.g. wind speed or short-circuit currents) must be given.

15.2.3 Soil quality

In addition to the loads described above, the quality of the soil has to be considered. The impact on the ground anchoring is depending on the type of soil, e.g. rock, clay, sand, etc. In areas with porous material, the whole filter area, or parts of it, may be anchored to one common foundation. The soil properties should therefore be specified by the customer.

15.3 Method of qualification

15.3.1 General

The qualification may be done by analytical methods or by testing. The customer should specify which kind of qualification the contractor shall apply. If testing is preferred, then the customer may accept a verification of the seismic performance based on results of tests previously performed on structures of similar design and similar seismic requirements. For details on seismic qualification by testing, reference is made to IEEE 693 [59].

The usual practice for qualification however is by analytical methods.

15.3.2 Qualification by analytical methods

Seismic qualification by analytical methods requires the representation of the filter structure by an equivalent model which must be sufficiently detailed to establish accurately the static and dynamic behavior of the equipment. For this purpose, it is assumed that the mass of the structure is concentrated into a number of discrete parts of lumped masses which are connected by elements representing the mechanical properties of the structure.

The kind of the analytical method, static or dynamic, mainly depends on the type of equipment. Complex structures with natural mechanical frequencies within the seismic frequency range (0,1 Hz - 33 Hz) usually require a dynamic analysis which is mostly done by the response spectrum method as described further below. For simple structures with fewer components a static analysis may be sufficient. In any case, the numeric calculation is carried out using a generally accepted computer program.

One of the following analytical methods is usually applied:

a) Response spectrum analysis

A structure consisting of several spring/masses will have a number of different natural vibrations, denoted vibration modes. Each mode vibrates in a specific form (mode shape) at a distinct natural (modal) frequency. The determination of the mode shapes and the modal frequencies is called modal analysis. The response of the structure may be found by the superposition of the maximum responses of each individual mode which are obtained from the response spectrum, scaled to the prescribed maximum ground acceleration value. In practical cases, only a few modes need to be considered in the analysis to obtain adequate accuracy.

The resultant maximum response determined from the individual modal responses is usually done by the square root of the sum of squares (SRSS) method. If not otherwise stated, 2 % modal damping is assumed for each mode shape. If increased structural damping is employed, measurements are usually required to verify modal frequencies and modal damping ratios.

The response spectrum assumes fully linear behavior of the structure. When the structural system is considered to be non-linear then a so-called time history analysis may be applied. By this method, a record of ground motion, usually in terms of acceleration versus time, is used to calculate the stresses, accelerations and displacements of the structure at discrete time steps during an earthquake. This method however is rather calculation extensive and time consuming and therefore only used in rare cases.

b) Static coefficient method

This method may be applied on structures having one significant mode out of several other modes. Then the seismic load on the structure may be supposed to be an equivalent static load and the seismic forces on each component of the equipment are obtained by multiplying the value of the mass of each component times the maximum acceleration (at a damping value of 2 %) given in the response spectrum. Usually a safety factor (static coefficient) of 1,5 is further applied to account for the effects of the other modes.

An example of this type of structure may be a head type current transformer consisting of a concentrated mass mounted on an insulator. The significant mode will be a rocking mode excited by the shaking of the ground in horizontal direction.

c) Static analysis

This method is applicable when the equipment may be assumed to be rigid, i.e. the natural mechanical frequencies exceed 33 Hz. Then, the seismic forces on each component of the equipment are obtained by multiplying the value of the mass of each component times the maximum ground acceleration.

15.3.3 Design criteria

The design criteria define the required minimum safety factors, as well as the buckling requirements.

15.3.3.1 Minimum safety factors

For each member of the structure, the stresses caused by the combined loads from seismic and additional loads must be calculated and depending on the type of material, minimum safety factors with respect to breaking and yielding must be maintained.

- Brittle materials

For components containing brittle materials, such as ceramic insulators, a required safety factor with respect to the breaking strength should be specified by the customer. The breaking strength of the brittle component (insulator) is defined as the minimum strength value guaranteed by the manufacturer of the concerned component. If no value is specified for the required safety factor, then a minimum safety factor of 2 should be used for insulators and other components made of brittle materials.

- Ductile materials

For components made of ductile materials such as steel and aluminum members, the required safety factor is defined with respect to the yield point or with respect to the ultimate strength. The applicable safety factors should be in line with usual engineering practice as given for example in national building codes.

If no information on safety factors is available, then the following minimum safety factors should be applied to the material under consideration:

a) 1,2 on the yielding strength,

b) 2,0 on the ultimate strength.

15.3.3.2 Buckling requirements

The seismic qualification should ascertain that the structure safely resists buckling due to the member loads induced by the seismic event. Buckling requirements are usually stated in the applicable building codes.

15.3.4 Documentation for qualification by analytical methods

The specification may require one of the following levels of documentation:

a) Seismic statement

This comprises a short summary of the seismic verification, describing equipment, methods, loading and most important results.

b) Seismic qualification report

The extent of this report shall be sufficient to understand the analysis procedures and models and to allow the verification of the major results. It should contain:

- a short summary,
- a drawing of the equipment and its support showing the major components,
- a description of structure and the corresponding analytical model,
- loads and load combinations,
- a description of the analytical method and of the adequacy for application,
- results from dynamic or static analysis (displacements, forces and moments, stresses on elements, foundation loads).

15.4 Examples of improvements in the mechanical design

In case where the seismic load requirements are decisive for the mechanical design of the different filter structures some typical measures can be taken:

- use of mechanically stronger material in structures (e.g. steel and porcelain) and in the filter component itself,
- use of other geometrical design of support structure and insulators than common practice (e. g. support insulators mounted in an angled position instead of vertical),
- use of common foundation for several filter components,
- use of stays, either inside the support structure to ground or outside to ground or a combination of both,
- vibration isolation of the structure from ground by the use of springs,
- increase of structural damping by the use of dampers.

Sometimes two or more of the measures listed above are combined.

16 Audible noise

16.1 General

An important consideration of converter station design is to prevent potential annoyance of people living nearby due to intrusive audible noise. The intention of this clause is to inform customers of the background to audible noise limitations and the relevance to a.c. filter design. The treatment of audible noise limitation in the technical specification can be significant, and the issue may also be prominent during bid evaluation discussions and the subsequent project design.

It is recommended to relate the specification requirements to regulations on environmental noise for homes, residences and communities near to the converter station.

Requirements for attaining an acceptable noise environment may become a key parameter for the layout of the converter switchyard, affecting both technical and economical aspects, and may have an impact on the a.c. filter system design (e.g. circulating current in a double tuned filter may give rise to unacceptable noise), as well as the design of individual components. The inclusion of special sound-limiting measures in equipment design will add to the cost of that equipment.

Since corrective measures for noise reduction during and after commissioning are usually expensive and time consuming, it is recommended that the customer should pay due attention to audible noise requirements already during the preliminary planning stage when selecting the site of the converter station. Audible noise limitation is often an important consideration in licensing of the converter station site.

Audible noise may be defined as an assembly of acoustic waves in air at frequencies perceived by the human ear. Noise may consist of a monofrequency acoustic signal (tone) or of sounds containing a distribution of frequencies. For definitions of acoustic parameters, see Annex H.

Sound active components such as a.c. filter reactors and capacitors should be designed and arranged within the yard so as to minimize sound radiation to noise-sensitive areas around the converter station.

16.2 Sound active components of a.c. filters

The most prominent electrical components which are sources for audible noise emanating from an HVDC station are the converter transformers, the d.c. smoothing reactors, shunt reactors if used, PLC reactors and the capacitors and reactors of a.c. filters. Thus the a.c. filters are only one of several sources for the acoustic noise of an HVDC station. In addition, the acoustic noise caused by electrical discharges (corona noise) will contribute to the overall acoustic noise.

The generation of sound by capacitors depends on the voltage applied across the capacitor. The electric forces within the capacitor elements (rolls) causes them to vibrate resulting in case vibrations of the capacitor units.

The sound generated by air core reactors results mainly from vibrational winding forces caused by the interaction of the current flowing through the winding and its magnetic field. In case of iron core reactors further vibrations of the apparatus are induced by forces acting in the magnetic circuit.

In both cases, capacitors and reactors, the vibrations of the surface of the apparatus generate acoustic noise which is radiated as airborne sound into the vicinity of the equipment.

Since these noise-generating forces are proportional to the square of the electrical load, voltage or current, the frequency spectrum of force and thus of sound differs from the electrical frequency spectrum.

As an example, Figure 38 shows the current spectrum of a filter reactor. It is assumed that the current consists of a component with fundamental frequency f and one harmonic component with harmonic number n.

Figure 39 depicts the vibration force components acting on the winding of the reactor. The force consists of components with frequencies $2f$, $f(n-1)$, $f(n+1)$ and $2fn$.

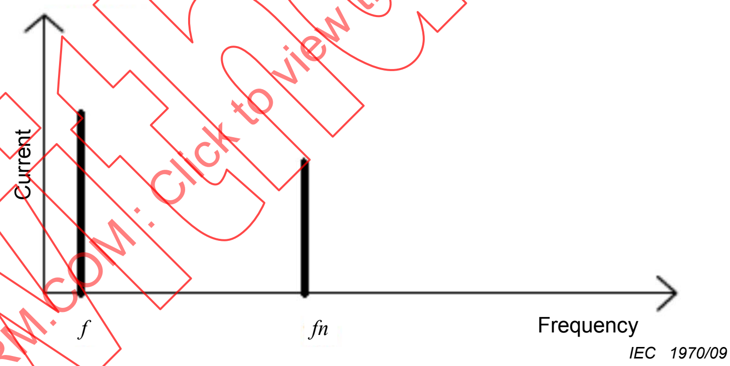


Figure 38 – Electrical spectrum

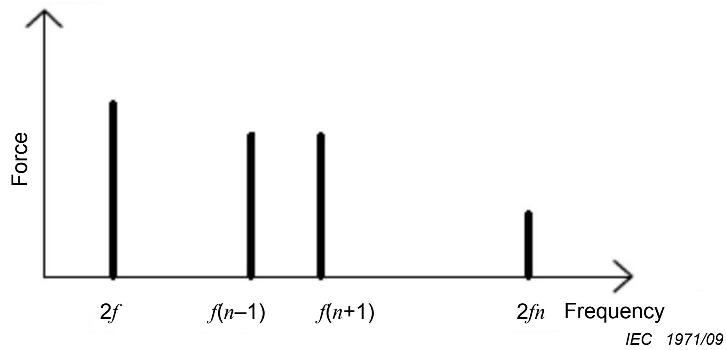


Figure 39 – Force spectrum

In common with any mechanical structure, a capacitor or reactor with distributed mass and structural properties has several major structural resonances. Amplification of the equipment vibrations and thus increased sound generation may occur if one or several frequencies of the force spectrum coincide with these structural frequencies.

For proper consideration of the acoustic behavior of the filter components, it is therefore inevitable to include both the fundamental and the harmonic content of voltage and current.

Depending on the physical size and on the power rating of the filter capacitors and reactors the sound power of these components ranges between 60 dB(A) to 80 dB(A).

16.3 Sound requirements

The objective of sound requirements is to limit the level of noise around the converter station in general and in particular to obey regulations on environmental noise for homes, residences and communities near the station. This goal is accomplished by the noise management provided by the contractor for the complete converter station. Since the a.c. filters represent only one of several noise-active components, it should be up to the contractor to apply adequate sound criteria on the individual switchyard components (usually in terms of maximum allowable sound power level) so as to meet the overall sound requirements.

When specifying sound requirements, it is necessary that the customer clearly specifies valid operating conditions for the station. For economical reasons, it is advisable to consider only normal operating conditions and to exclude short-time, or any extreme, conditions from sound requirements. Here normal operating conditions means steady-state conditions that last longer than a specific time, normally more than one day, but possibly as short as a few hours, depending on any applicable regulation or code of practice.

The sound requirements for a converter station at stated operating conditions are usually specified by the customer in terms of a maximum allowed sound pressure level at particular points in the vicinity of the station, or at a specific contour surrounding the station.

Sometimes this contour is chosen to be the fence line around the converter station. Typical values for achievable sound limits at the fence range between 50 dB(A) and 60 dB(A). However, such a requirement may result in a sound reduction strategy which is not necessarily adequate. The sound requirement at the fence might be met by avoiding the installation of sound-intensive components close to the fence. However, this may not lower the sound level of noise-sensitive areas more distant away from the station, which was the purpose of the requirement.

Therefore, it is advisable to specify particular sound-critical points or a contour containing these critical points more distant relative to the station, where the impact of noise may be crucial and statutory sound requirements have to be met.

In virtually all countries there exist public regulations for environmental sound. Such requirements are established by national, federal or provincial agencies specifying maximum allowable noise levels for various land-use categories. Usually, the maximum allowable noise level for living areas ranges from 40 dBA to 50 dBA which is reduced by another 5 dB if the noise is made up by one or several distinct tones. Details on requirements, measuring procedures and evaluation of results are described in ordinances of these regulations. It is advisable that the customer refers to the relevant environmental sound regulation rather than establishing his own rule.

16.4 Noise reduction

The procedure for meeting the sound criteria for converter stations can be categorized in two steps. Firstly, the station should be planned for an acoustically optimized station layout and secondly the sound-active components should be designed and constructed for low-noise generation.

The first measure against noise is the maximum possible separation between the area designated for the erection of the sound-active components and the sound-sensitive area by grouping sound-active components so as to hinder the propagation of sound waves into sound-critical directions by making use of the natural topography of the area, or using the sound screening effects of the converter house or other buildings. Care should be taken in designing and locating these buildings adequately for acoustic requirements. For example, it may be necessary to avoid the use of thin panels which could be excited by the sound waves of nearby active sound components and could thus redirect and even amplify the noise.

Components or groups thereof sometimes have a strongly non-uniform pattern of sound radiation. Capacitor stacks for example may show a distinct directivity of sound radiated from the stacked capacitor units. A potential incident by station sound at a critical nearby location may be avoided by orienting the components so to have no predominant sound radiation in this critical direction.

Low-noise design of the switchyard equipment requires minimizing the vibrational amplitudes of the sound radiating surface of the components. For this purpose it is essential to properly design the equipment so that the natural frequencies of the component do not coincide with the frequencies of the major excitation forces. If the noise level however can still not be met, then further sound reduction by providing sound reducing screens might be applied. However, it should be borne in mind that such measures may be costly, depending on the necessary extent for sound reduction.

Consideration should also be given to the mounting structure and to the electrical connections of the sound-active components so as to avoid transmission of component vibrations to other equipment.

Another measure to reduce the noise, not commonly used today, is to apply an active sound-cancellation technique comprising, for example:

- microphones installed at the sound radiating surface,
- an amplifier and control circuitry,
- loudspeakers installed close to the sound radiating component.

17 Customer specified parameters and requirements

17.1 General

This clause is intended to serve as a check-list for a customer preparing a technical specification, and gives a review of which essential parameters and requirements must be specified.

Whenever appropriate, cross-references to those sections where more detailed information is available, are given at the right hand side of the page.

The following parameter information, for the bus where the filters will be installed, should be given by the customer:

- at both ends of the HVDC transmission scheme,
- for each stage of development,
- for any expected future changes.

17.2 AC system parameters

17.2.1 Voltage

The following voltages should be specified:

- the nominal system voltage, that is, the voltage by which the system is designated;
- rated a.c. voltage, that is, the rms phase-to-phase fundamental frequency voltage, which is often used to define rated reactive power (MVAr) of the filters;
- steady-state voltage ranges, that is, the ranges over which the a.c. filters shall be able to work and over which all performance and continuous rating requirements are to be met. Different ranges may possibly be defined for the calculation of performance and for rating.

Any special voltage capabilities outside the steady-state range should be specified as these may influence the design (e.g. rating) of the filters, e.g. temporary overvoltages.

17.2.2 Voltage unbalance

The negative sequence component of a.c. voltage calculated according to the method of symmetrical components is that balanced set of three-phase voltages whose maxima occur in the opposite order to that of the positive sequence voltages. It is generally expressed as a percentage of the rated voltage and it is mainly responsible for the generation of third order harmonic current by the converter.

As the negative sequence component normally varies with time and system conditions, the value to be specified should be the maximum value which is to be used in the determination of non-characteristic harmonics. It may be advisable to specify a lower value for use in filter performance calculations than for rating purposes, in recognition of the time-varying nature of this parameter. The customer should be aware that specifying too high a value of negative sequence voltage to be used in the performance calculations, may force the contractor to include a 3rd harmonic branch in the filter solution.

Typically the negative sequence voltage is in the range of 0,5 % to 2,0 % [43]. If a converter is located in the close vicinity of a generating station even lower values could apply.

17.2.3 Frequency

The following frequencies should be specified:

- the nominal frequency of the a.c. system;
- steady-state frequency variations, that is, the ranges, in conjunction with the a.c. voltage steady-state ranges, over which the a.c. filters shall work and all performance and continuous rating requirements shall be met;
- short-term frequency variations, that is, the limits and duration of short-term frequency excursions for which the filtering performance is required to be satisfied or for which the filters must be adequately rated. Specific filtering performance during such variations may be specified (e.g. in some Scandinavian projects a variation of ± 1 % with a duration of maximum 30 s has been specified);
- frequency variations during emergency. During an emergency, the a.c. system frequency may reach extreme values for limited periods. These excursions and their expected durations should be specified. Under such conditions, the a.c. filters should remain in service without damage but should not be required to meet the performance specified (e.g. in Sweden a variation of at most +2 Hz to –3 Hz with a duration of 30 min has been reported. Such variation is expected once every second year. Due to variations within the +2 Hz to –3 Hz limits, an equivalent duration of only 10 min has been used for rating purposes).

17.2.4 Short circuit level

Maximum short circuit level and minimum short circuit level at the a.c. bus where the a.c. filters are to be connected should be specified. These levels should be specified either in power (MVA) or in current (kA) and the applicable a.c. voltage stated.

Different values of maximum short circuit level may be specified for different use, e.g. for filter performance or rating, mechanical strength of busbars and power circuit breaker interrupting capability.

The X/R ratio for the fundamental frequency may also be specified in case of special breaker requirements.

17.2.5 Filter switching

Maximum permissible voltage change at filter switching and the applicable minimum short circuit level should be specified. Normally this parameter is specified in percent of nominal voltage. Alternatively, the maximum size of switchable filter bank or sub-bank (in MVAr) can be given.

Filter switching will also create transients which may have to be controlled. Measures to control switching transients are the use of pre-insertion resistors and/or opening resistors or synchronized switching. If the customer has preferences regarding any of these measures, this should be specified.

17.2.6 Reactive power interchange

The allowed limits of interchange of reactive power between the a.c. system and the converter station, have to be specified for all operating conditions of the HVDC transmission.

17.2.7 System harmonic impedance

The a.c. system impedance at harmonic frequencies, to be used in filter performance and rating calculations, must be specified.

17.2.8 Zero sequence data

Data concerning zero sequence impedance should be given for the purpose of, for example, short time rating calculations and possible telephone interference studies along connecting a.c. overhead lines.

17.2.9 System earthing

The earth fault factor or reactance ratio X0/X1 should be indicated at the point of connection. Alternatively, the type of earthing system can be given, e.g. effectively earthed or earthed via a coil.

17.2.10 Insulation level

The lightning impulse level and switching impulse level for the HV and neutral connections, and the respective protective margins, should be specified. The protective margins for items of filter equipment should also be specified, noting that these may be different for different types of equipment.

17.2.11 Creepage distances

The creepage distance based on a specific creepage, expressed in mm/kV, should be specified (IEC 60815).

An increased requirement is usually specified for bushings or insulators attached in a horizontal position.

If the creepage distance is specified, it is important to co-ordinate this parameter with given parameters for insulation and pollution levels.

17.2.12 Pre-existing voltage distortion

Pre-existing voltage distortion existing on the connecting a.c. bus should be specified, as it must be taken into account in the a.c. filter rating, and may also be needed for performance calculations. If possible the distortion should be given as maximum levels for each harmonic frequency (measured before the station is built). Otherwise, the total voltage distortion may be specified.

It is also desirable to specify the source impedance for the pre-existing harmonics. In general, this is taken to be the same as the harmonic impedance of the system but in some cases, where there are other nearby specific identifiable sources of distortion, it would be more accurate to state the actual harmonic impedance between that source and the filter bus.

In cases where the performance criteria is based on a total acceptance level, i.e. existing plus new harmonics, the method for adding these two harmonic sources should be specified. Possible methods can be linear or root-sum-square.

When specifying the pre-existing voltage distortion, frequencies other than multiples of the fundamental may be relevant, depending on which sources of harmonics can be identified, e.g. railway systems.

Determination of pre-existing voltage distortion is not easily done but in IEC 60071-1(2006) [7], IEC 60071-2(1996) [8], IEC/TR 60071-4(2004) [9], IEC/TS 60071-5(2002) [10] some information is given.

In the absence of detailed knowledge about pre-existing harmonic distortion levels, some allowance may be made by specifying that a certain percentage increase on the converter generated harmonics be taken into account for equipment rating.

17.3 Harmonic distortion requirements

The harmonic distortion limits at the HVDC station bus and possibly in the surrounding a.c. system should be defined following applicable regulations or standards.

Redundancy requirements, if any, should be specified. This requirement shall if possible follow the customer's normal philosophy, e.g. a MTBF value for either the d.c. link as a whole or the filters can be indicated. It should be clearly stated if the redundancy refers to filtering performance and/or rating or/and reactive power requirements.

17.4 Environmental conditions

17.4.1 Temperature

When specifying ambient temperatures, it is always the dry-bulb air temperatures at the site of the installation which should be used.

The minimum, maximum and average ambient temperature should be specified. As per applicable standards for the individual filter components (capacitors, reactors, etc.), certain ranges or categories of the ambient temperature are considered to be normal. Ambient temperatures outside these limits are considered as unusual service conditions and should be brought to the bidder's attention.

17.4.2 Pollution

Fog and contamination conditions should be specified. The type and levels of these requirements can for example follow practice used in nearby substations with the same nominal voltage and environmental pollution characteristics, or follow applicable standards IEC 60507 (1991), IEC 60815 series, IEC 62271-1 (2007).

17.4.3 Wind

Maximum continuous and maximum gust, needed for equipment and equipment support mechanical strength design, should be specified.

17.4.4 Ice and snow loading (if applicable)

Maximum ice thickness with and without wind is needed for structure design and should be specified.

Maximum depth of snow should be specified, to define the equipment height above snow, i.e. effective ground level.

17.4.5 Solar radiation

Maximum incident solar radiation may be specified. This is needed for rating of reactors, resistors and rating of capacitor banks in case of large banks equipped with unbalance protection.

17.4.6 Isokeraunic levels

Lightning stroke density at the station should be specified. Normally, this parameter is used for the overall station lightning protection design.

17.4.7 Seismic requirements

Seismic performance requirements should be specified for sites in seismic active zones.

The maximum ground acceleration in horizontal and vertical direction and, if available, a floor response spectrum of the zone where the equipment will be installed should be specified. Further, information on the type and the quality of the soil should be provided.

17.4.8 Audible noise

Noise from a.c. filters has to be co-ordinated with the total noise from the converter station or substation. The total permitted noise from the station should take into account requirements of any applicable regulations or codes of practice. The effects of noise are generally treated as those concerning nuisance to the public outside the boundary of the station or noise effects in the working environment.

17.5 Electrical environment

The following information and parameters may be specified if applicable.

- The presence of another nearby HVDC converter station should be stated, if applicable. The source impedance, filter configuration and harmonic generation data should be given.
- Adjacent transformers, shunt capacitors or reactors should be identified, if applicable. The size in MVA or MVAr should be given as well as the short circuit impedance for a transformer. The reason behind the need for these parameters is a possible requirement that inrush currents have to be limited. (Adjacent here means that another substation is located within the same station area as the converter station.)
- Adjacent surge arresters data should be specified if applicable, due to the possible influence on the insulation co-ordination study.
- Geomagnetic currents flowing in connecting a.c. lines may have an impact on the rating of the different filter components, on filter protection performance and on transformer saturation, with an impact on filters connected to the transformer tertiary. In areas where high geomagnetic currents are to be expected parameters such as amplitude, frequency of occurrence and duration should be specified.

- If any practice related to boundary, limits are used by a customer these should be supplied where applicable. Example of such boundary limit is the magnetic field associated with reactors or personal safety.

17.6 Requirements for filter arrangements and components

17.6.1 Filter arrangements

If any restriction or preferences exist related to the filter arrangement itself, this should be specified.

If seasonal re-tuning is not allowed, this should be specified.

If any restrictions related to number of filter discharges per hour exists, this should be specified.

If binary switching of filters is allowed, this should be specified.

If preference for any specific earthing system of the filters exists, this should be specified.

17.6.2 Filter capacitors

Preferences on type of fuses to be used for capacitors may be specified, i.e. internal or external fuses or non-fused capacitors for special applications.

Maximum discharge time of a capacitor may be specified as well as minimum allowable re-insertion time for a capacitor bank.

Acceptable levels of capacitor unit or element failures corresponding to alarm, delayed trip (stating required delay) and trip levels should be stated.

17.6.3 Test requirements

Test requirements for filter components, i.e. capacitors, reactors, resistors, arresters etc. may be specified, normally by references to applicable standards.

If test requirements are not specified, then a list of tests is required to be included by the bidder in his bid.

17.7 Protection of filters

Any protection requirement for a specific filter, or filter component, may be specified.

17.8 Loss evaluation

For optimization of filter design, a capitalized loss factor should be specified. The conditions under which filter losses are to be calculated should be clearly stated.

17.9 Field measurements and verifications

Field tests can be divided into sub-system and system tests. Such tests may be specified to verify component behavior and filter performance. Normally the sub-system tests are performed by the contractor while the system tests can be performed jointly by the customer and the contractor. The contractual implications of any filter performance test results should be clearly stated.

17.10 General requirements

The following general requirements should be specified where applicable:

- safety measures such as surrounding the filter yard by a fence or mounting filter components on steel structures with a specific height,
- anti-corrosion measures such as painting and galvanizing,
- maintenance intervals,
- maintenance accessibility, especially if a hydraulic platform is required to remove capacitors etc.,
- quality assurance program to be followed,
- mounting aspects / physical limitations,
- limitations on available site area,
- any specific risks due to birds, snakes, or vermin.

18 Equipment design and test parameters

18.1 General

18.1.1 Technical information and requirements

Depending on the chosen filter arrangement (see Clause 7), the filter will be made up of a combination of capacitors, reactors and resistors, connected to the a.c. bus by suitable switching equipment. Additional equipment must be included such as surge arresters for overvoltage protection and instrument transformers as part of the filter protection system.

There are a number of factors which all have significant influence on the design and the ratings of the filter components. Basic information which the customer has to provide in his bid request is described in some detail in the foregoing Clauses 15, 16 and 17.

This clause aims to give the customer some guidance for:

- particular technical information on the filter components the customer should provide in his specification,
- requirements on design, production, testing, installation and maintenance of filter components, which should be specified by the customer,
- specific technical information on the equipment, which the customer should require to be presented in the bidder's tender.

18.1.2 Technical information to be provided by the customer

The a.c. filters are commonly installed outdoors, although indoor installation is possible. Unusual environmental site conditions should be brought to the contractor's attention, such as severe pollution (industrial or marine), severe seismic requirements, unusually high wind velocity, stringent acoustic noise requirements, etc. Such requirements may be decisive for the equipment design.

The customer should indicate particular information on operational aspects of the a.c. filters. If applicable, the customer should indicate that the devices used for filter switching should be designed for frequent switching operations, as this may be required for reactive power control, and the customer should specify the expected number of operations per year. Any temporary overvoltage conditions under which the filter should be disconnected, should also be specified.

18.1.3 Customer requirements

18.1.3.1 Design, production, installation and maintenance requirements

Since the filter components are "live" parts, fencing of the filter equipment for achieving personnel clearance may be used. Alternatively, instead of fencing, the equipment may be mounted on special support structures which elevates live parts to a height commensurate with personnel safety standards. The customer may specify what method should be adopted and he should specify the minimum safety clearance.

It is recommended that the customer requires the contractor to specify the type of support insulators used for the mounting of the filter components and the capacitor bushings. Usually the insulators and bushings are of porcelain type. Sufficient creepage and clearance must be provided for reliable operation of the equipment. Based on information available to the customer regarding the pollution conditions encountered at the site, the customer should prescribe the minimum creepage distance of the insulators. Typical values for specific creepage are between 25 mm/kV to 45 mm/kV depending on the site pollution level. (See IEC 60815 series, as well as 17.4.2 of this document). Creepage requirements should be based on the maximum voltage (including harmonics) appearing across the insulators or bushings, evaluated in accordance with 10.2.4 and 10.2.5 of this document.

The customer may require the filter to be made up as far as possible by identical interchangeable components so as to simplify maintenance and stocking of spares.

For ease of transportation and installation, the customer may require that each equipment component should be equipped with lifting eyes or similar provision for lifting the unit.

The customer may impose a maximum height requirement for any equipment. He may further require a maximum limit on weight of components (capacitor units for example) depending on their location relative to other filter equipment. If the contractor exceeds those limits, he should provide appropriate tools for handling during installation and maintenance.

The outline of the filter components should be designed so as to eliminate as far as possible any visible corona at voltage levels typically up to 20 % above rated voltage.

The customer may advise the bidder that the filter components shall be designed to withstand the operational mechanical forces without damage or reduction of life. These are vibrational forces during normal operation, electromagnetic forces during external faults, wind forces, ice loading and seismic forces, if applicable. In case of breakage of one support insulator, the construction must remain stable. The customer may require a static calculation of the filter structures.

The customer may require the contractor to guarantee a maximum annual failure rate for certain filter components such as capacitors, current transformers, etc. on condition that the specified maintenance is provided.

18.1.3.2 Quality system and documentation requirements

It is recommended that the customer specifies his minimum requirements on the contractor's quality system to be applied by the contractor to the design, production, testing, installation and maintenance of the a.c. filter equipment.

Usually, the quality program is documented by the contractor's quality manual. The customer should review the contractor's manual and he should reserve the right for auditing the quality system as described by the manual.

As a general guideline the application of ISO 9200 [36] or other internationally recognized quality program standards of comparable level should be adequate for the supply of the a.c. filters equipment.

Further to the standard quality program, the customer may state specific requirements on the kind and quality of materials and workmanship. These should include for example requirements on materials used for terminals and electrical wiring, surface protection by galvanizing or painting, specific requirements on welding, etc.

The customer may specify requirements on the contractor's documentation. Usually the activities for design and production inspection, testing, installation and commissioning are based on inspection and test plans. The inspection and test plan should define hold points for witnessing inspection or testing by the customer or by an organization representing the customer.

It is recommended that customer requests the contractor to submit this documentation for approval during the detailed design stage of the equipment.

18.1.3.3 Test requirements

For general requirements, it is recommended that the customer should refer as far as possible to the applicable standards and recommendations from IEC, ANSI or IEEE. It should be made clear on which standard body, IEC or ANSI/IEEE, the design, rating and testing of the filter equipment shall be based on.

The test program for component specific tests will depend on a number of parameters such as the general technical concept of the filter, overvoltage protection, service experience with specific components gained from other HVDC projects, etc. The test program should ascertain that the specific component will provide the required performance and will withstand all defined electrical and environmental conditions encountered in the field. However, it should be borne in mind that requirements for tests covering unrealistic conditions may considerably increase the cost for the equipment.

The test program should be established in co-operation between the customer, the contractor and his sub-supplier. Usually it is split into routine tests, type tests and if necessary special or "other" tests. It may be advisable that the customer or his representative plans to witness type and special tests. This is of particular importance in case of difficulties in performing a test, or if there are any doubts about the test result. In this case, the customer's representative may assist in making an immediate decision on how to proceed with testing.

Certified test reports on previously performed type tests on similar units may be accepted in lieu of performing a type test. Relevant test reports should be submitted to the customer for approval, including a report on deviations in design or technical data. If accepted in lieu of performing a type test, these reports should be included in the inspection and test report as part of the documentation.

If applicable, the contractor should perform a seismic qualification for each equipment component mounted on its support structure. Seismic qualification may be performed either by analytical methods or by testing (see Clause 15).

18.1.4 Technical information to be presented by the bidder

The customer should require the bidder to provide a general description of the filter layout including a schematic diagram clearly identifying the individual filter components. The number of units of filter components including spare units should be indicated by the bidder.

The lists of electrical data presented in the following sub-sections are intended to be a guideline for the customer on how to specify a particular filter component. Further parameters and further information may be requested by the customer if deemed to be useful. Such required information for example may refer to the thermal time constant of reactors, resistors and of arresters.

The numerical values of the individual parameters for each component are chosen by the bidder depending on his filter design. Since some of the values, in particular for tolerance may be critical and sometimes difficult to achieve, such values are usually defined in consultation with the component sub-suppliers.

The customer may require the bidder to indicate the amount of manpower for maintenance (in days per annum) necessary for reliable operation of the equipment under defined operating conditions.

18.1.5 Ratings

The following ratings are required to be specified for the various filter components:

- Rated harmonic frequency

The rated harmonic frequency is that frequency to which the relevant parameters for harmonic filter performance are referred. For single tuned filters, this frequency is equal to the tuning frequency, for double tuned filters this may be the geometric mean frequency of the two tuning frequencies or may refer to both tuned frequencies.

- Voltage rating

The rated voltage U_N (rms) assigned to an a.c. filter capacitor bank is discussed in 10.2.4. The rated voltage of the capacitor units U_r (rms) must be higher than or equal to the rated voltage U_N of the capacitor bank divided by the number of series connected units.

It should be noted that there are considerable differences between IEC 60871-1(2005) and IEEE 18-1992 [57] in terms of permissible long duration overvoltage capabilities of capacitors. (See IEC 60871-1 Clause 19 and IEEE 18-1992 Subclause 5.2.3).

It is recommended that the contractor presents oscillograms of the transient oscillatory voltage appearing across the capacitor banks, together with the anticipated number of events per year, in his specification to the capacitor sub-supplier.

The rated voltage of a reactor or resistor is the arithmetic sum of the voltages at fundamental and harmonic frequencies. The rated voltage across a reactor or resistor is discussed in 10.2.4. The voltage rating to ground depends on the position of the reactor or resistor relative to other filter components and may differ from the voltage rating between the terminals.

- Current rating

The rated current is the square root of the sum of the squares of the current at fundamental and harmonic frequencies (see 10.2.4).

18.2 Capacitors

18.2.1 Capacitors: general

There are two internationally accepted standards applicable for the capacitors for a.c. filters, that is firstly IEC 60871-1(2005) and secondly IEEE 18-1992 [57]. It is recommended to refer for general requirements on capacitors to one of these two standards.

For clarification of terminology, the following definitions are used.

- Capacitor element: In practice, normally an individual package (coil, roll) consisting of aluminium foil and insulating paper and/or plastic film.
- Capacitor can or unit: The metallic case including bushing(s), internal discharge and grading resistors, capacitor elements connected in series and parallel, and, if used, element fuses.
- Series group: A set of capacitor units connected in parallel. Several groups are connected in series to meet the voltage requirements.

- Capacitor rack: A metallic framework containing one or several series groups including interconnection buswork and insulators as required.
- Capacitor stack: One or several capacitor racks mounted on a set of base insulators for rack-to-rack insulation, including inter-rack and rack-to-rack connections.
- Capacitor bank: One or several capacitor stacks including inter-stack connections and including the associated monitoring and protective equipment. Often, a capacitor bank consists of sets of two identical stacks connected in parallel so as to provide a bridge arm for measuring unbalance between the two stacks.

In single line diagrams, the capacitor bank is represented by a lumped single phase capacitor.

18.2.2 Capacitors: design aspects

The contractor should illustrate the circuitry of the individual capacitor banks and capacitor units to show how the specified capacitance values are arrived at.

- Capacitor units:

Depending on the environmental site conditions, it may be advisable to make the cases of the capacitor units from stainless steel. The cases should be designed as to allow for expansion and contraction due to all ambient and loading conditions expected during the life of the unit including short term and transient conditions. The capacitor manufacturer should provide the criteria for determining when expansion of the case is normal and when it is due to capacitor failure.

Usually the capacitor units are bolted to the rack. Each capacitor unit should be mounted so that it can be easily removed from the rack and replaced without removing other units or disassembling any portion of the rack. Depending on the weight, if necessary each capacitor unit should be furnished with lifting eyes.

The dielectric fluid used within the capacitor unit shall be environmentally safe and biodegradable. The capacitor unit must not contain PCB type fluid. The capacitor elements should be vacuum dried inside the case prior to impregnation with the dielectric fluid. After impregnation, the capacitor unit should be sealed immediately upon removal of the impregnant reservoir.

The current, voltage and kVar rating of the capacitor units as well as the measured capacitance or the tolerance class should be given on the capacitor unit nameplate, as per IEC/IEEE standards.

- Discharge resistors

Each capacitor unit should be provided with internal discharge resistors in accordance with IEC 60871-1 or IEEE 18. Longer discharge times (which will reduce losses) may be possible if agreed by the customer.

- Fuses

Fuses are intended to protect the case of the capacitor unit from rupture due to capacitor element failures. Internal fuses are intended to safely isolate failed elements during any operational condition.

The customer should indicate which type of fusing – internal, external or non-fusing – is considered acceptable and he should define the criteria for alarm and trip level settings of the unbalance protection. The contractor should show how his proposed fusing / unit arrangement will meet the customer's requirement.

- Racks

Usually the capacitor racks are supplied fully equipped with all capacitor units, insulators, and connections. Lifting eyes should be provided to facilitate assembly of the racks into the stacks. Depending on the environmental site conditions, it may be advisable to make the racks of hot dip galvanized structural steel or corrosion resistant structural aluminium. No drilling should be permitted after galvanizing.

The structural members of the racks should not be used as electrical buses. There should be only one single electrical bond between a group of capacitor units and the capacitor rack. All structural members of the rack should be electrically connected together in order to ensure adequate earthing of the rack during maintenance. The rack should be provided with adequate connections for earthing.

Each rack should be clearly labelled with the weight of the fully equipped unit, the phase and bank of which it forms a part, and the maximum and minimum capacitor unit capacitances which may be substituted into the rack as spares. Suitable warning labels should be affixed.

- Capacitor bank

Special attention should be drawn to the capacitor bank design so as to meet acoustic sound power levels as specified in the technical specification (see Clause 16). A sound power calculation should be provided for each bank.

18.2.3 Capacitors: electrical data

The following Table 3 is a checklist of data which could be used by the contractor for purchasing the equipment or to inform the customer of the design parameters.

Table 3 – Electrical data for capacitors

Capacitor design parameters	Units
Rated harmonic frequency	Hz
Rated capacitance per phase (at +20 °C)	μF
Tolerance on rated capacitance	± %
Maximum variation of capacitance versus temperature	%/°C
Maximum total losses at rated voltage and rated temperature	W/k$_{var}$
Maximum dielectric losses at rated voltage and rated temperature	W/k$_{var}$
Variation of tand versus frequency	a
Rated voltage (U_N) across capacitor bank including harmonics	kV$_{rms}$
Harmonic voltage spectrum [b], steady state	n/kV$_{rms}$
Minimum voltage across capacitor bank excluding harmonics	kV$_{rms}$
Total current (including harmonics)	A$_{rms}$
Harmonic current spectrum [b], steady state	n/A$_{rms}$
Continuous voltage across capacitor bank for evaluation of sound power level including harmonics	kV$_{rms}$
Harmonic voltage spectrum for evaluation of sound power level	n/kV$_{rms}$
Maximum sound power level	dB(A)
Lightning impulse withstand level (LIWL)	
High voltage terminal to ground	kV
Low voltage terminal to ground	kV
High voltage terminal to low voltage terminal	kV
Switching impulse withstand level (SIWL)	
High voltage terminal to ground	kV

Capacitor design parameters	Units
Low voltage terminal to ground	kV
High voltage terminal to low voltage terminal	kV
Applied a.c. test voltage to ground (50 Hz or 60 Hz, 1 min.)	kV_{rms}
[a] The variation of tand with frequency from fundamental to the highest harmonic should be given as a graph or table.	
[b] The harmonic voltage or current spectrum is specified in terms of the order number and the rms-value of the individual harmonic voltages or currents.	

18.2.4 Capacitors: tests

Unless otherwise stated, routine tests and type tests should be performed in accordance with the relevant sections of standards IEC 60871-1(2005) and/or IEEE 18-1992 [57]. Tests on support insulators, where applicable, may be performed in accordance with IEC 60168 (1994) [15]. If the customer has additional specific requirements for special or "other" tests and for verification of equipment performance, then these should be stated.

Such requirements for example may include:

- Discharge test

A discharge test of the capacitor unit should be performed by charging the capacitor to a d.c. voltage equal to 1,7 to 2,5 times the rated voltage and discharging it by a short-circuit between the terminals. The d.c. voltage level to be used in the test should be agreed between customer and contractor.

- Measurement of capacitance dependence on frequency and temperature

- Impregnant test

The component supplier should propose tests to prove the adequacy of the chemical and electrical characteristics of the applied impregnant.

- Verification of acoustic noise

The contractor should demonstrate by analytical methods the expected total sound power level in dB(A) for each capacitor bank at fundamental and harmonic voltages as given in the electrical data list.

- Seismic qualification

To be performed by the contractor or his sub-contractor, if applicable (see Clause 15).

18.3 Reactors

18.3.1 Reactors: general

The standard usually applied for specifying a.c. filter reactors is IEC 60076-6 (2007) which contains a clause dealing with filter reactors. Further, ANSI/IEEE C57.16-1996 [63] will be an applicable standard for future filter reactor specifications. This standard contains a normative appendix specifically dealing with filter reactors.

Since the type of reactor applied in a.c. filters is usually air-core dry-type, the following information refers to this type of reactors only.

18.3.2 Reactors: design aspects

Usually the reactors are single phase with a winding designed for outdoor installation, for air cooling by natural convection. Therefore, all materials must be chosen so as to provide satisfactory withstand to the climatic and environmental conditions encountered at site. For reactors installed in areas of high urban based pollution or oceanic based salt pollution, care should be paid to the protection of the reactor winding against the adverse effects of electrolytic deposition. Under such operating environments, tracking can occur on the surface of a.c. stressed dry-type air core reactors. It is therefore recommended that if salt type pollution can occur, the reactors should be coated with special coating such as RTV single-component, low temperature curing silicone elastomer, having special hydrophobic properties to prevent water filming on the winding surfaces directly exposed to the environment.

The temperature class of the insulation material usually is either class B (130 °C) or class F (155 °C).

Dry-type air-core reactors do not have an iron core. Therefore, the magnetic field is not constrained and will occupy the space around the reactor winding. Although the magnetic field reduces in strength with increase in distance from the reactor, the presence of this field must be taken into consideration for the installation of dry-type air-core units. The extent to which care has to be taken is largely a function of kVA and is lower for low kVA units.

Usually the reactors are mounted on support insulators and support structures. The reason for providing support structures may be twofold, firstly to supply safety clearance for substation personnel to the equipment on high potential and secondly to provide sufficient magnetic clearances to the foundations on which the reactors are installed.

The dimensions of the electrical terminals of the reactor and the associated connectors should be kept as small as possible so as to avoid substantial eddy current loss due to the magnetic field of the reactor.

The support structure should be designed so as not to have shorted loops otherwise currents could be induced by the magnetic stray field of the reactor. Grounding of the support structure should be accomplished without creating closed loops in the grounding system.

If necessary, the winding may be designed with intermediate tap positions for inductance variation in steps. Tap position setting is done off-circuit, by hand, without affecting the reactor's main terminal connections.

Usually the filter circuits would require the use of reactors with Q-values at harmonic frequencies much lower than the "natural" reactor Q-factor. This may be achieved by connecting a resistor in the circuit with the reactor to damp the filter response. Usually the resistors are connected in parallel with the reactors. An alternative to the use of a resistor is the addition of a de-Q'ing structure on the reactor, that can reduce its Q-factor. The de-Q'ing structure typically consists of several coaxially arranged short-circuited metallic rings which couple with the main field of the reactor. The induced currents in the closed rings dissipate energy and thus lower the Q-factor of the reactor.

If the reactors are equipped with lightning arresters they should be mounted so that the pressure relief valve does not impinge on the reactor.

Special attention should be drawn to the winding design so as to meet acoustic sound power levels as specified in the technical specification. A sound power calculation may be requested for each unit (see Clause 16).

18.3.3 Reactors: electrical data

The Table 4 below is a checklist of data which could be used by the contractor for purchasing the equipment or to inform the customer of the design parameters.

Table 4 – Electrical data for reactors

Reactor design parameters	Units
Rated harmonic frequency	Hz
Rated inductance	mH
Tolerance on rated inductance (applicable for reactors without tapping range)	± %
Tapping range	± %
Step size	%
Q-value of reactor at fundamental frequency	
Q-value of reactor at rated harmonic frequencies	
Tolerance on Q-value at fundamental frequency	± %
Tolerance on Q-value at rated harmonic frequency [a]	± %
Current ratings	
Maximum continuous current, including harmonics	A_{rms}
Harmonic current spectrum [b], steady state	n/A_{rms}
Maximum temporary current, including harmonics	A_{rms}
Temporary harmonic current spectrum	n/A_{rms}
Duration	h
Currents for evaluation of sound power level	n/A_{rms}
Maximum sound power level	dB(A)
Transient current	
Amplitude	kA_{peak}
Time to crest	µs
Short circuit current, thermal [c]	kA_{rms}
Short circuit current, mechanical [c]	kA_{peak}
Duration [c]	s
Rated a.c. voltage (including harmonics)	kV_{rms}
Lightning impulse withstand level (LIWL)	
High voltage terminal to ground	kV
Low voltage terminal to ground	kV
High voltage terminal to low voltage terminal	kV
Switching impulse withstand level (SIWL)	
High voltage terminal to ground	kV
Low voltage terminal to ground	kV
High voltage terminal to low voltage terminal	kV
Applied a.c. test voltage to ground (50 Hz or 60 Hz, 1 min.)	kV_{rms}

a Tolerance on Q-value at rated harmonic frequency may be of significant importance (Clause 7).

b The harmonic current spectrum is specified in terms of the order number and the rms-value of the individual harmonic currents.

c If applicable.

18.3.4 Reactors: tests

Unless otherwise stated, routine tests and type tests should be performed in accordance with the relevant sections of IEC 60076-6(2007) or IEEE C57.16 [63]. Tests on support insulators, where applicable, may be performed in accordance with IEC 60168(1994) [15]. If the customer has additional specific requirements for special or "other" tests and for verification of equipment performance then these should be stated.

Such requirements for example may include:

- Acoustic noise

The contractor should demonstrate by analytical methods the expected total sound power level in dB(A) for each reactor at fundamental and harmonic currents as given in the electrical data list above. As shown in Clause 16, audible noise measurements based on fundamental frequency are of little significance.

- Seismic qualification:

To be performed by the contractor or his sub-contractor, if applicable (see Clause 15).

18.4 Resistors

18.4.1 Resistors: general

To date, there are no standards available which are specifically applicable for the resistors of HVDC a.c. filter circuits.

Since the type of resistors applied in a.c. filters is usually dry-type, the following information refers to dry-type resistors with air cooling by natural convection.

18.4.2 Resistors: design aspects

The resistors should be designed with negligible inductance and with low dependency of resistance versus harmonic frequencies.

The resistors are made of wires (grid type resistors), deployed metal sheets or cast metal elements. It is preferable to utilize active material with low variation of resistance vs. temperature so as to minimize the variation of the filter characteristic with working temperature at various loading conditions and ambient temperature.

Usually the resistor elements are mounted in an enclosure for protection against rain to avoid eventual harmful effects of rain water during any mode of operation. The enclosures should be designed so as to prevent the ingress of birds or other animals. Further they should be designed so as to allow simple opening for maintenance. Depending on the environmental site conditions it may be advisable to make the enclosures of stainless steel, or hot dip galvanized structural steel or corrosion resistant structural aluminium.

The enclosure should be electrically connected to one point of the resistor elements, typically the resistor mid-point.

For the electrical insulation of resistor banks consisting of several series connected modules, consideration must be given to the effects of non-linear transient voltage distribution. See the recommendation for lightning testing (see 18.4.4).

Bearing in mind that the temperature rise of the resistor elements may be considerably high (up to 600 °C), the choice of the insulation within a resistor module requires great care, since the high temperature of air will impact the insulation performance. The breakdown voltage of air at these high temperature levels may be reduced to typically 50 % of the value at ambient temperature. 'Chimney effects' of vertically stacked resistors also need to be accounted for.

Care should be taken for the design and the material selection of the electrical terminals to achieve adequate performance at high temperature. Furthermore, the high temperature rise of the resistors requires the internal and external electrical connections of the resistors to be made with sufficient sag so as to avoid undue mechanical stress by thermal expansion.

The recommended intervals between internal inspections during maintenance should be stated.

Usually the resistor enclosures are mounted on support insulators to provide the necessary electrical insulation to earth. The insulators may be mounted on a support structure for providing safety clearance for substation personnel to the equipment on HV potential.

Depending on the electric scheme and the power rating of the resistors, they may sometimes be incorporated in the reactor. In this case, a protective cover on top of the reactor winding may provide the necessary protection again rain water.

18.4.3 Resistors: electrical data

The Table 5 below is a checklist of data which could be used by the contractor for purchasing the equipment or to inform the customer of the design parameters.

Table 5 – Electrical data for resistors

Resistor design parameters	Units
Rated harmonic frequency	Hz
Rated resistance at rated current and frequency (at 20 °C ambient temperature)	Ω
Tolerance on rated resistance [a]	± %
Maximum inductance at rated harmonic frequency	µH
Current ratings	
Maximum continuous current, including harmonics	A_{rms}
Harmonic current spectrum [b], steady state	n/A_{rms}
Operating temperature at maximum continuous current, including harmonics	°C
Maximum temporary current, including harmonics	A_{rms}
Temporary harmonic current spectrum	n/A_{rms}
Duration	min
Operating temperature at maximum temporary current, including harmonics	°C
Transient current [c]	
Amplitude	kA_{peak}
Time to crest	µs
Energy	kJ
Rated a.c. voltage (including harmonics)	kV_{rms}
Lightning impulse withstand level (LIWL)	
High voltage terminal to ground	kV
Low voltage terminal to ground	kV
High voltage terminal to low voltage terminal	kV
Switching impulse withstand level (SIWL)	
High voltage terminal to ground	kV
Low voltage terminal to ground	kV
High voltage terminal to low voltage terminal	kV
Applied a.c. test voltage to ground (50 Hz or 60 Hz, 1 min.)	kV_{rms}

a The specified tolerance should include manufacturing tolerance and resistance variation with ambient and working temperature.

b The harmonic current spectrum is specified in terms of the order number and the rms-value of the individual harmonic currents.

c The resistor must endure the transient current after being permanently loaded with maximum continuous current.

18.4.4 Resistors: tests

In the absence of any standards for filter resistors, the following tests are suggested.

a) Routine tests

- Measurement of resistance

The resistance should be measured at power frequency and at rated harmonic frequency. The measured resistance corrected to minimum and maximum working temperature should be within the specified tolerance limits.

- Power frequency voltage withstand test

This test is performed to check the insulation of the resistor elements to the enclosure. For the purpose of this test, the electrical connections between enclosure and resistor elements if existing are removed and the test voltage is applied for 1 min between resistor elements and enclosure. Since the high operating temperature inside the enclosure will impact the insulation performance, the test voltage should be chosen to consider the effect of temperature, subject to agreement between customer and contractor.

In case of resistors consisting of several series connected resistor modules, the test voltage per module is reduced according to the number of series connected modules by taking into account manufacturing tolerances.

The insulation must not suffer flashover during the test.

b) Type tests

- Measurement of inductance

The inductance should be measured at power frequency and at rated harmonic frequency, with the resistor bank assembled as for service.

- Temperature rise test

The test should be made with thermally equivalent 50 Hz or 60 Hz current. If the resistance is independent from frequency within the range of specified harmonics, then the test current is the square root of the sum of the squares of the current at fundamental and harmonic frequencies.

If the resistance varies with frequency, then the calculation of the test current should be made according to the formula:

$$I_t^2 \times R_t = I_F^2 \times R_F + \sum_{n=2}^{m} I_{Hn}^2 \times R_{Hn} \qquad (28)$$

where

I_t is the equivalent test current (50 Hz or 60 Hz);

I_F is the maximum continuous fundamental current;

I_{Hn} is the maximum continuous n-th harmonic current;

R_t is the a.c. resistance at test current frequency, corrected to maximum working temperature;

R_F is the a.c. resistance at fundamental frequency, corrected to maximum working temperature;

R_{Hn} is the a.c. resistance at n-th harmonic frequency, corrected to maximum working temperature.

If the test facilities available cannot permit the resistor to be subjected to rated current, then the internal connections of the resistor may be reconfigured so that a power equal to the rated power can be achieved.

The test may be performed at any convenient ambient temperature. Loading of the resistor with the test current should be maintained for at least 30 min after steady state conditions are achieved. The temperature measured at the end of the test should be corrected to maximum ambient temperature and should not exceed the expected design temperature. The temperature of all resistor insulation (internal and, where relevant, external) should also be measured to assess its withstand capability.

- Lightning impulse test

The test should be made with both negative and positive polarity applied to the high voltage terminal with the low voltage terminal earthed. The wave form should be standard lightning impulse wave 1,2/50 µs. Due to low resistance shorter wave tails may be acceptable. Since the high temperature of air inside the enclosure will impact the insulation performance, the contractor or his sub-contractor should verify the impulse voltage performance at high temperature by suitable methods (either by test or by calculation) approved by the customer.

In case of resistors consisting of several series connected resistor modules, the impulse voltage test should preferably be performed on the complete resistor bank with all modules connected in series. If this is not practicable due to laboratory limitations, the impulse voltage test may be performed on a per module base. The contractor should demonstrate that the test voltage per module includes a sufficient margin to account for the non-linearity of the transient voltage distribution of the resistor bank.

The insulation must not flash over during the test.

- Verification of short-circuit performance

The contractor or his sub-contractor should verify by calculation and/or by test that the resistor may withstand the mechanical and thermal stresses imposed by the specified transient current.

- Seismic qualification

To be performed by the contractor or his sub-contractor, if applicable (see Clause 15).

18.5 Arresters

18.5.1 Arresters: general

It is assumed that only gapless metal-oxide surge arresters will be used for overvoltage protection of the a.c. filters.

It is recommended that the arresters comply with the documents IEC 60099-4 (2004), IEC 60099-5 (1996) and CIGRE Working Group 33/14-05 [52].

The customer should require the contractor to provide all surge arresters necessary for the a.c. filter overvoltage protection, based on the minimum protective margins for the different transient overvoltages.

Arresters are usually connected to the a.c. filter bus and across specific filter components. These filter components may be simply a reactor or a combination of capacitors, reactors and resistors all connected between the filter's high voltage capacitor and earth. The customer should require the contractor to present the position of the arresters in the filter circuit and their respective technical data in the arrester overvoltage protective scheme.

The surge arresters should give consistent protection of their associated equipment against overvoltages resulting from lightning or switching surges, any faults external to the a.c. filter and other system disturbances.

The electrical data of the individual arresters such as rated voltage, continuous operating voltage, protective characteristics and energy absorption capability should be indicated by the contractor and confirmed by the contractor's system studies.

18.5.2 Arresters: design aspects

The customer may or may not indicate a preference for arresters designed with housings made of polymeric material.

The arrester may be of single-column or multi-column design.

The customer may require arrester accessories such as:

- arrester discharge counter and/or tele spark gap to record the number of arrester impulse discharges. Filter energization should usually not activate the discharge counters.
- leakage current device to monitor the arrester leakage current.

It is not recommended to provide leakage current monitoring devices for arresters used in a.c. filters because of the following reasons:

- modern arresters made with state-of-the-art technology do usually not require leakage current monitoring;
- leakage current is of low significance for arresters connected across filter components when the arrester's actual continuous operating voltage is low compared to its maximum operating voltage;
- high level of harmonics in the arrester's operating voltage may lead the erratic results for leakage current monitoring.

18.5.3 Arresters: electrical data

The Table 6 below is a checklist of data which could be used by the contractor for purchasing the equipment or to inform the customer of the design parameters.

Table 6 – Electrical data for arresters

Arrester design parameters	Units
Continuous operating voltage [a]	kV_{rms}
Harmonic voltage spectrum [b], steady state	n/kV_{rms}
Rated voltage U_r	kV_{rms}
Nominal discharge current (8/20µs)	kA
High current impulse (4/10µs)	kA
Long duration current impulse (2 ms)	A
Line discharge class	
Maximum energy absorption capability (thermal) [c]	kJ
Reference voltage	$kV_{peak/\sqrt{2}}$
Reference current	mA_{peak}
Tolerance on sharing of reference current between columns of multi-column arresters or between arresters intended for parallel operation	
Residual voltage at nominal discharge current	kV
Residual voltage at 0,5 kA (30/60µs)	kV
Lightning impulse withstand level of arrester housing	kV
Pressure relief capability	kA_{rms}
Lightning impulse withstand level (LIWL)	
High voltage terminal to ground	kV
Low voltage terminal to ground	kV
Switching impulse withstand level (SIWL)	
High voltage terminal to ground	kV
Low voltage terminal to ground	kV
Applied a.c. test voltage to ground (50 Hz or 60 Hz, 1 min.)	kV_{rms}

a The continuous operating voltage U_c is the maximum permissible rms value of power frequency voltage, including harmonics, that may be applied continuously between the arrester terminals.

b The harmonic voltage spectrum is specified in terms of the order number and the rms-value of the individual harmonic voltages.

c The value to be specified refers to the total energy absorbed by the arrester at two long duration current impulses according to IEC 60099-4(2004).

18.5.4 Arresters: tests

Unless otherwise stated, routine tests and type tests should be performed in accordance with the relevant sections of IEC 60099-4(2004). Tests on support insulators, where applicable, may be performed in accordance with IEC 60168(1994). If the customer has additional specific requirements for special or "other" tests and for verification of equipment performance then these should be stated.

18.6 Instrument transformers

18.6.1 Voltage transformers

The customer may require the contractor to provide inductive voltage transformers connected in parallel to the a.c. filter capacitors. The main purpose of such voltage transformers is to rapidly discharge the capacitors (usually in less than 0,5 s rather than around 5 min achieved with the capacitor discharge resistors), after the filter has been switched off. This is accomplished by the voltage transformers becoming saturated during discharge resulting in considerable discharge current (up to about 15 A peak), whereas during normal operation the current of the primary winding is typically less than 2 mA and the impact on the dissipation factor of the capacitor bank by the voltage transformers is negligible. The advantage of fast capacitor discharge is to alleviate the voltage stress across the open filter bank breaker, and to permit rapid re-energization of the filter without overstressing its components.

The voltage transformers for this particular application must be designed to comply with the thermal and mechanical stresses imposed by the discharge of the filter capacitors through the voltage transformer. The standard applicable for inductive voltage transformers, IEC 60044-2(1997) [3] however, does not fully cover this application. It is therefore advisable that the contractor and customer agree on an equipment specification including discharge requirements described by the discharge energy and duty cycle and specifying details how to prove the discharge withstand capability of the voltage transformer.

Voltage transformers connected to the converter bus, used for overvoltage and unbalance protection of the converter station as well as for providing the voltage signal for the converter control, are considered to be external to the a.c. filter equipment and are therefore not discussed in this technical report.

18.6.2 Current transformers

18.6.2.1 General

The current transformers of the a.c. filters are part of the filter protection system as described in Clause 14.

Current transformers for short-circuit current and overcurrent protection of a complete filter circuit are usually arranged at the filter bank feeder or at the earth side of the concerned filter circuit. For unbalance protection they are arranged in the bridge arm of parallel branches. For protection of individual components, current transformers may be connected in series with specific filter components.

IEC 60044-1(1996) [2] is applicable for specifying current transformers for a.c. filters.

18.6.2.2 Current transformers: design aspects

Current transformers at the feeder side are usually of oil insulated design. The type of construction may be either live-tank (head) type, or dead-tank (hairpin or eyebolt) type. The CIGRE Report 57 of Working Group 23-07 [51] provides information on the design, construction, monitoring and quality assurance of oil insulated instrument transformers.

The customer may specify requirements on the transient performance of current transformers. For example, it may be required that a current transformer is of low reactance (low leakage flux) design. In this case, the assessment of the transient performance of a current transformer can be simply made by measurement of the voltage / current characteristic at secondary winding, with the primary winding open. If the transformer is not a low reactance design, then a direct measurement of accuracy must be made at the accuracy limit current (special test). This is a major problem since the test current can be very high and such test sets are very uncommon. For further details reference is made to IEC 60044-6 (1992) [5].

The customer may specify minimum requirements for the creepage distance of the insulators and for cantilever load.

Earth side transformers are commonly designed with solid insulation.

The current transformers may be mounted on a support structure for providing safety clearance for substation personnel to the equipment on HV potential.

18.6.2.3 Current transformers: electrical data

The Table 7 below is a checklist of data which could be used by the contractor for purchasing the equipment or to inform the customer of the design parameters.

Table 7 – Electrical data for current transformers

Current transformer design parameters	Units
Rated frequency	Hz
Highest voltage for equipment	kV_{rms}
Current ratings	
- Primary winding	
Maximum continuous thermal current	A_{rms}
Harmonic current spectrum [a]	n/A_{rms}
Short time current rating	A_{rms}
Harmonic current spectrum [a]	n/A_{rms}
Duration	msec
Transient current rating	kA_{peak}
Time to crest	µs
- Secondary winding	A_{rms}
Maximum continuous thermal current	A_{rms}
Core details	
Measuring cores	
Number of cores	
Turns ratio	
Rated burden	VA
Accuracy class	
Instrument security factor (FS)	
Protection cores	
Number of cores	
Turns ratio	
Rated burden	VA
Protection class [b]	
Accuracy limit factor	
Insulation requirements to earth	
Power withstand voltage (1 min)	
Primary winding (wet, if applicable)	kV_{rms}
Secondary winding	kV_{rms}
Lightning impulse withstand level of primary winding	kV
Switching impulse withstand level of primary winding (if applicable to the voltage class)	kV

[a] The harmonic current spectrum is specified in terms of the order number and the rms-value of the individual harmonic currents; usually not applicable to unbalance transformers.

[b] See IEC 60044-6(1992) [5]. Further data may be required depending on the specified protection class.

18.6.2.4 Current transformers: tests

Unless otherwise stated, routine tests and type tests should be performed in accordance with the relevant sections of IEC 60044-1(1996) [2]. Tests on support insulators, where applicable, may be performed in accordance with IEC 60168(1994) [15]. If the customer has additional specific requirements for special or "other" tests and for verification of equipment performance then these should be stated.

Such requirements for example may include:

- Verification of transient current capability

The contractor or his sub-contractor should verify by calculation that the transformer will withstand the mechanical and thermal stresses imposed by the specified transient current.

- Seismic qualification

To be performed by the contractor or his sub-contractor, if applicable (see Clause 15).

18.7 Filter switching equipment

18.7.1 Filter switching equipment: overview

The switching of filter banks in general and those for HVDC systems in particular have not specifically been covered by any standard to date. The number of different situations, currents, superimposed frequencies and possible recovery voltages is difficult to bring under general rules for worst conditions. In general, the system stresses in normal operation and fault circumstances have to be determined during dedicated system studies, which normally form an important part of an HVDC project. The results of those studies will reveal if the stresses on the filter breakers will be covered by existing standards or if additional requirements are necessary.

As explained earlier a.c. filters are bi-functional: filtering harmonics and providing reactive power. Therefore, the duties and stresses of filter and capacitor bank switching equipment show many similarities. Due to the relatively high value of the inductance present in filter banks the amplitude of inrush currents will be mitigated and frequencies of transients will be lower. On the other hand, it should be realized that these relatively high inductances could cause overvoltages under (fault) conditions with a high rate of rise of the current. These overvoltages form part of the insulation co-ordination of the HVDC station.

For the above-mentioned reasons the listed design aspects in the following clause will be approached qualitatively. They should be considered as the main relevant items and as a guide in specifying filter switching equipment.

If applicable, two types of switching equipment could be distinguished: circuit breakers and HV (load) switches. The latter will be referred to as 'switch' hereafter. For economical reasons, the application of load switches could be considered in filter branches and sub-banks. The most significant difference with circuit breakers is the capability of the latter to break short-circuit currents, whereas a (load) switch can only break load currents and, occasionally, a limited value of short-circuit current, if specified. In general, the above implies the need for a circuit breaker in order to protect the bank as a whole against short circuit-faults. The consideration whether to apply breakers or switches depends, amongst others, on economics, the particular HVDC scheme and operational requirements.

Other switching equipment installed in filter banks, not primarily intended to switch currents, such as isolators and earthing switches, in general, do not need special requirements other than those related to conventional a.c. substations. For this reason they will not be discussed in this document.

18.7.2 Filter switching equipment: design aspects

Subclauses 18.7.2.1 to 18.7.2.3 are general aspects, Subclauses 18.7.2.4 to 18.7.2.9 are more specific for breakers and switches in filters.

18.7.2.1 Existing international standards

There are two main international standards dealing with circuit breakers, including test requirements for capacitive switching: IEC 62271-100 (2008) [32] and the ANSI/IEEE C37 series [61]. For HV switches IEC 62271-104 (2009) [33] could be applied. However, the standards do not cover the requirements of a.c. filter bank switching. Therefore, installing an IEC/ANSI tested breaker does not necessarily ensure a good working, trouble-free installation.

18.7.2.2 Environmental conditions

Reference can be made to IEC 62271-1(2007) and Clause 17 of this technical report. For circuit breakers, special considerations are recommended in relation with outdoor ambient temperature (see 17.4.1), pollution (see 17.4.2) and seismic requirements (Clause 15).

18.7.2.3 System parameters

Important a.c. system parameters, in relation with the present case, are:

- nominal system voltage, voltage range and special voltage requirements beyond the limits of the steady state range, as mentioned in 17.2.1. Any temporary overvoltage conditions under which the filter should be disconnected, should also be specified;
- nominal power frequency;
- short circuit power level;
- duration of short circuit;
- system earthing;
- existence of other parallel connected capacitor and filter banks;
- the ratio of X/R;
- insulation levels.

HVDC system parameters are important as well since the Thévenin equivalent to which the breaker or switch is connected together with the filter bank is also dependent on the HVDC converter, with control characteristics playing a role in the load rejection behavior, etc.

18.7.2.4 Continuous current

The continuous current consists of a superposition of the reactive current at power frequency and the harmonic currents the filter in question is drawing from the a.c. system under all specified conditions. In general, this load current will have a relatively low rated value as compared to breakers/switches in the main power circuit. However, it should be realized that, due to the mentioned super-imposed current harmonics, more zero-crossings than those due to the fundamental frequency alone could occur. Their occurrence is relevant to the current breaking capacity in normal operating conditions. It is recommendable to specify the specific purpose of the breaker/switch explicitly.

18.7.2.5 Short circuit current of the circuit breaker

The rated short circuit capability should be at least equal to the system short circuit level as defined in 18.7.2.3 and must take into account future development.

If a short circuit occurs at the connections between the breaker and filter full short circuit current has to be interrupted by the circuit breaker. In case of faults, such as flashovers, inside the filter branch, the fault current through the breaker will be more or less reduced by the remaining filter impedance, depending on the location of the fault.

A switch will be able to carry the short circuit current for only a limited time; however, as noted in 18.7.1, a limited short-circuit breaking capability might be available.

18.7.2.6 Switching duties and sequences

Depending on the particular station scheme, and due to operating conditions, fault recovery strategies, etc. switching duties and sequences of a circuit breaker different from those specified in standards are possible. It is recommended to specify such duties.

In some exceptional cases, a fault inside the filter bank can occur during switching of normal load current. This case, though rare, causes an extra stress and therefore could be specified as a special duty of the breaker.

The rated switching duty of a load switch, in general, is limited to an opening and closing-opening operating sequence.

18.7.2.7 Dielectric withstand of the arcing medium

Due to the relatively high number of switching operations, which are, in general, normal practice in HVDC-stations, it is recommended to require the breakers to have the lowest possible restrike-probability. Restrikes, occurring during switching operations of filter (and capacitor) banks can cause high overvoltages with relatively high frequencies. The occurrence of restrikes is strongly dependent on the moment of contact separation related to the next current-zero and the design of the breaker. In the old version of IEC 60056 (1987) breakers are assumed to be restrike free after (only) a limited number of tests without restrike. However, in the current version of the revised IEC 60056 (IEC 62271-100 (2008) [32], distinction has been made between breakers with low and very low expected restrike probability, even after a higher number of tests compared with old IEC 60056 (1987).

18.7.2.8 Number of switching operations

This criterion is important for the following two reasons:

- depending on the scheme, operating strategies, number of capacitor and filter banks (very) frequent switching may be normal practice. This imposes high mechanical stresses on the breaker/switch and therefore it is recommended to give due consideration to this aspect. In such cases, special-purpose switchgear could be considered;
- in case of a high number of switching operations, the probability of unfavorable arcing times will increase and with this, the probability of restrikes. In general, short arcing times tend to be more unfavorable than longer ones.

18.7.2.9 (Transient) recovery voltage (TRV)

The current interruption capability of switching equipment is highly dependent on the (transient) recovery voltage across the contacts after arc extinction. First of all, this voltage is dependent on the earthing of the neutrals of the a.c. system and the filter bank. The latter is generally earthed.

The relevance of the TRV-criterion in relation with HVDC is, in particular, determined by:

- the value of the temporary overvoltage (TOV) at load rejection (blocking of the converter),
- the strength/weakness of the a.c. system after recovery of a short circuit or commutation failure,
- possible saturation of the converter transformers during fault recovery,
- resonances with the a.c. system impedance during fault recovery,
- rate of discharge of the capacitor bank,
- switching strategies of other filter breakers in parallel,
- harmonics due to filter bank currents,
- a.c. filter arresters,
- a.c. bus arresters.

A sustained d.c. voltage across an opened breaker can influence the voltage withstand capability of some breaker types. Therefore, it is recommended to specify the discharge time constant of the filter banks. The discharge is dependent on the value of discharge resistors and the presence of (inductive) PT's.

System studies should prove if the TRV-stresses will exceed those specified in IEC and or ANSI/IEEE. In that case, additional tests are recommended.

As an alternative a breaker with a higher rating than the system voltage could be considered.

18.7.2.10 Making current

After closing on a filter bank, an inrush current will flow. The current is limited by the filter reactor. The inrush current from capacitor banks depends on the damping effects of the effective source impedance. The parallel operation of two or more shunt capacitor banks and/or filters, which are switched separately, may cause problems with very high unbalance currents during switching. When one bank is switched on, all the others already on-line discharge into the newly energized bank. The possibly very high transient current is damped only by the impedances in the discharging circuit.

With regard to the making current the following should be borne in mind:

- when closing on a filter bank prestrikes are probable, the amplitude and frequency of the subsequent inrush current will be determined by the parameters of the filter itself, the station configuration, the other banks actually connected to the bus and the a.c. system. During a prestrike, the inrush current will flow through the not yet closed contacts and the arcing medium for a certain time. Some types of breakers/switches could be sensitive to this phenomenon;
- inrush currents can cause overvoltages, the amplitude and frequency of which are determined by the above-mentioned parameters and the moment of prestrike;
- attention should also be paid to the transients in the a.c. system occurring when closing on a bank with (partly) charged capacitors;
- in order to meet the requirements the contractor could choose, if necessary, different means to limit inrush currents and overvoltages at closing of the breaker. These consist of the application of resistors or inductors or synchronous closing schemes. With synchronized switching, the circuit breaker closes at a optimal instant and thus inrush current and component stresses will be minimized. The performance of synchronous closing schemes is affected by the properties of the circuit breaker itself and the control interface. Since the breaker has to close around zero voltage sufficient margin has to be allowed for variations in voltage amplitude, system frequency, the presence of harmonic distortion. Further the closing accuracy will be affected by the stability of the closing time of the breaker and closing order of the control interface and measuring errors;
- breakers/switches should be capable of making a specified short circuit current when closing on a short circuit.

18.7.3 Filter switching equipment: electrical data

The Table 8 below is a checklist of data which could be used by the contractor for purchasing the equipment or to inform the customer of the design parameters.

Table 8 – Electrical data for filter switching equipment

Filter switching equipment parameters	Units
Rated voltage	kV_{rms}
Rated frequency	Hz
Rated normal current	A_{rms}
Insulation level to earth and across open switching device	
Rated a.c. voltage	kV_{rms}

Filter switching equipment parameters	Units
Lightning impulse withstand level	kV
Switching impulse withstand level (for rated voltage >300 kV)	kV
Rated short-time withstand current	kA_{rms}
Rated peak withstand current	kA
Rated duration of short-circuit	s
Rated short-circuit breaking current	kA_{rms}
Rated transient recovery voltage for terminal faults	a
Rated short-circuit making current	kA_{peak}
Rated operating sequence	
Rated single capacitor bank breaking current	A_{rms}
Rated back-to-back capacitor bank breaking current	A_{rms}
Maximum permissible switching overvoltage when switching capacitor banks	kV
Rated supply voltage of closing and opening devices and of auxiliary circuits	V_{dc} or V_{rms}
Rated supply frequency of closing and opening devices and of auxiliary circuits	Hz
Rated pressures of compressed gas supply for operation and for interruption	Mpa
Maximum deviation from closing time (if synchronous switching is used)	ms
[a] determined by several parameters - see IEC 62271-100 (2008) [32].	

18.7.4 Test requirements

Type tests performed in accordance with IEC and/or ANSI/IEEE may not always cover the real stresses of the present case. WG 13.04 is preparing a document on shunt capacitor switching [39]. As stated earlier, some of the stresses on breakers, in this case in HVDC stations, can exceed those specified in standards. It is therefore recommended to evaluate carefully the relevant criteria and compare the results of system studies with those in the standards. Additional requirements may be necessary.

These in particular refer to:

- the required number of switching operations in field conditions with regard to mechanical load and probability of restrike,
- switching duties and sequences,
- TRV-components, especially in relation with TOV-conditions in fault or special conditions.

The defined requirements in IEC and ANSI/IEEE regarding capacitive switching offer various possibilities for test circuits, test duties and test voltages to be chosen.

Because of the station scheme, operating strategies, specified fault conditions and a.c. system parameters the test requirements of the breaker/switch should reflect as closely as possible the actual situation.

If applicable, the accuracy of synchronous switching in relation to the affecting factors, mentioned in 18.7.2.10, should be verified by laboratory tests or otherwise by specific commissioning tests under real operating conditions. The test conditions should take account of influencing factors such as ageing, environmental conditions and the number of previous switching operations.

19 Field measurements and verification

19.1 Overview

This clause considers the tests which will be made during and after commissioning, to verify that the a.c. filter equipment and systems are functioning as required. Suitable specification of the technical and contractual aspects of such testing is important to safeguard the interests of the customer, and a clear definition of what is required is to the benefit of both customer and contractor.

The field tests can be divided into:

- equipment and subsystem tests which are performed before full voltage energization,
- system tests which cover all tests done after full voltage energization.

The complete system tests also include the off-site tests of the control system carried out on a simulator prior to its shipment to site.

Another test of interest in the context of a.c. filters is the measurement of pre-existing harmonic levels for the purpose of design and later for verification of performance.

19.2 Equipment and subsystem tests

19.2.1 General

The subsystem tests are performed without high voltage energization, and are usually carried out by the contractor.

The components of the filters are first verified for integrity: their nominal values of capacitance, inductance and resistance are measured and checked against their nameplate values. After final connections of the components, the overall behavior of the assembly is evaluated at low voltage operation.

19.2.2 Fundamental frequency impedance and unbalance measurement

A single-phase low voltage supply (<1 kV) is applied in turn to each phase of the a.c. filters. The fundamental frequency voltage and current measurements permit the evaluation of the fundamental frequency impedance of the filter. Additionally, provided that the filter yard is not influenced by any other voltage source, the unbalance current can also generally be measured down to the microampere range. These results can be extrapolated to the rated voltage of the filter and compared to the contractor's calculations.

19.2.3 Frequency response curve

The purpose of this test is to obtain the impedance of the filter in the frequency range starting with the fundamental frequency up to usually the 50th harmonic. It will also permit selection of the final tap setting of the reactors in accordance with the desired tuning frequencies corrected for the conditions of the test, namely the ambient temperature.

The frequency curve may be obtained by applying the output of a signal generator to the filter through an amplifier. Filter voltage and current measurements taken across the complete frequency range give the impedance curve. However, this exercise is time consuming considering also that the voltage applied to the filter has to be monitored to ensure that it is reasonably free of distortion.

More sophisticated instruments will automatically control the injection signal and take the readings with probes tuned to the injection frequency in order to be more sensitive and less influenced by distortion.

Finally, this evaluation can be done by using a spectrum analyzer: its output noise signal is fed to the filter through the amplifier and the instrument, by means of Fast Fourier Transform (FFT) calculations, performs the transfer function directly on the voltage and current measurements. The instrument also provides a coherence function which may be regarded as a confidence criterion in the transfer function obtained.

19.3 System tests

19.3.1 General

The system tests complete the commissioning of an HVDC project and consist of the tests done at full voltage (including also the off-site tests of the control system). The subject of system tests has been well documented by a CIGRÉ Technical Brochure prepared by WG 14.12 [48], IEC/PAS 61975 is developed and will be published in the years to come [30]. For each test, this document gives the objectives, the preconditions, the procedures and the acceptance criteria.

The tests regarding the a.c. filter equipment and performance are treated in the referred Technical Brochure. The following paragraphs only summarize this information, adding more details on certain aspects concerning the measurements.

19.3.2 Measuring equipment

19.3.2.1 General

For the system tests, results are required in both time and frequency domains. The time domain measurements are usually provided by the transient fault recorder (TFR) and the sequence-of-events recorder (SER) while the frequency domain measurements are obtained from a harmonic analyzer.

19.3.2.2 Transient fault recorder and sequence-of-events recorder

The specification will often ask that these recorders be part of the equipment supplied by the contractor. The TFR is now based on digital technology and is used to analyze transients, which implies that the selected input scales are usually much greater than the nominal values. Since there are many variables to monitor around the converter, the limited number of TFR channels will normally not permit recording of more than one phase of each filter branch. Connection of the TFR might have to be reconfigured depending on the commissioning test being performed.

The SER gives a precise time-stamping and is therefore very useful to verify protective sequences and to co-ordinate measurement results with the prevailing equipment or system configuration.

19.3.2.3 Harmonic analyzer

Although the digital nature of the TFR would permit harmonic analysis, it cannot generally be used for filter performance evaluation: it is not sensitive enough because high input scales must be selected for transient purposes.

Harmonic performance evaluation of HVDC converters requires an instrumentation that is equipped with very good quality signal conditioners and analog-to-digital converters and which contains the necessary filters to prevent any aliasing. Very good harmonic analyzers incorporating all these features are now easily available or can be assembled from the various components. The whole measuring chain must have a very good signal-to-noise ratio (SNR). For example, a SNR of at least 80 dB is required in order to evaluate a TIF of 10 with the necessary precision.

The input channels of the analyzer should be synchronously sampled to allow evaluation of symmetrical components. Besides the integer harmonics, the harmonic analyzer should also provide the interharmonics (intermediate frequencies) which are useful to ascertain that the analyzer is functioning properly and that the measurements have been taken in steady state.

A personal computer (PC) should be used in conjunction with the harmonic analyzer in order to store the results of the analyzer, to calculate the various indices (TIF, THD, etc.) for which limits have been set in the specification and to help in the preparation of curves and reports.

IEC 61000-4-7(2002) [27] and its Amendment 1 (2008) describe the general requirements for harmonic analyzers depending on the application. Harmonics generated by HVDC converters will usually not fluctuate in steady state operation, especially if the interconnected a.c. systems are synchronous or if the d.c. line is very long. Therefore, when referring to the above standard, one should look for the requirements applicable to the measurements of quasi-stationary harmonics.

19.3.2.4 Current and voltage transformers

Conventional current and voltage transformers are suitable for the time domain measurements. Conventional current transformers are also suitable for harmonic performance evaluation since their first resonance frequency is usually above the range of interest. However, capacitive voltage transformers cannot be used because of their non-linear response at harmonic frequencies. Inductive voltage transformers are usually better but their frequency response should be verified prior to their utilization, and suitable corrections made if necessary. The possibility of measurement errors due to magnetic coupling from nearby components to inductive voltage transformers must also be considered, as there is evidence that this can introduce significant discrepancies at some harmonic frequencies.

If the permanently installed voltage transformers are found to be not suitable for harmonic measurements, the following alternatives can be considered:

- install special capacitive voltage dividers (dividers with a flat response for a large frequency bandwidth). An accuracy of 1 % is normally attainable with such devices;
- derive the harmonic voltages from the current flowing in an apparatus having a stable impedance. A good example is the capacitance of the PLC filters. A calibration test should be carried out before the actual harmonic measurements. Unless otherwise stated in the specification, an accuracy of 5 % to 10 % in the 0 kHz to 3 kHz frequency band should be sufficient.

19.3.3 AC filter energization

These tests are part of the converter tests. AC filters are energized one at a time and are soaked (left energized) for about 2 h. Using the TFR, the three-phase current and voltage waveforms should be recorded upon energization. The records should be analyzed to evaluate the effectiveness of the means of controlling transients. The steady state filter currents should be balanced. The steady state voltage variation can be used to evaluate the short circuit level as described in Clause E.3.

19.3.4 Verification of the reactive power controller

The reactive power controller should be verified in all its operating modes and this will therefore be done at various stages of the commissioning tests. It will be mostly verified using the operator's interface although the TFR and SER might be useful to analyze certain situations.

19.3.5 Verification of the specified reactive power interchange

This verification should be done for the operating conditions given in the specifications, for example: transmitted power level, mode of operation (rectifier or inverter), a.c. and d.c. voltage levels, maximum firing angles, etc. As there is usually a penalty attached to this requirement, the most precise current and voltage transformers (usually the billing ones) should be used.

The harmonic analyzer might be accurate enough for this measurement at fundamental frequency. If not, a power analyzer is the best instrument for the application.

19.3.6 Verification of the harmonic performance

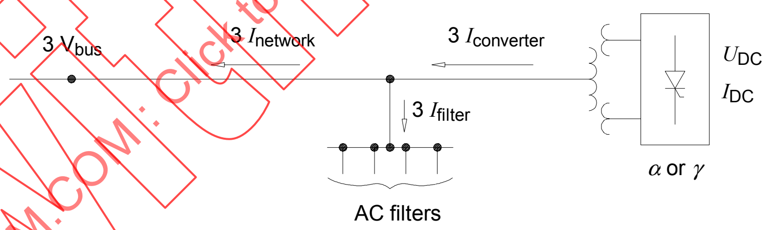
19.3.6.1 General

These tests are part of the steady state performance and interference tests. The objective is to establish the various harmonic levels for various operating conditions defined in the technical specification in order to verify that the specified levels are not exceeded during such conditions and that the levels remain acceptable under contingency modes. It should be understood that the measurement conditions will probably never correspond to the worst case conditions for which the filter design has been made.

19.3.6.2 Signals to be analyzed

To verify the a.c. side harmonic performance, the following signals should be brought to the harmonic analyzer (Figure 40). Suitable transducers, giving accurate reproduction of harmonics must be used (see 19.3.6.3):

- the three phase-to-earth bus voltages,
- the three a.c. system currents (or currents in separate a.c. lines if needed for IT evaluation),
- the three converter currents,
- the three filter currents,
- the converter firing angle,
- the d.c. side voltage and current signals.



IEC 1972/09

Figure 40 – Converter variables for harmonic performance tests

The d.c. side harmonic performance will usually be evaluated at the same time. The related signals will be added to the above list and this will dictate the required number of input channels for the analyzer.

Harmonic analysis will be performed on all the signals brought to the analyzer. This analysis is required for the a.c. signals in order to evaluate the harmonic factors (TIF, THD, etc.) and for the study of any abnormal condition. Harmonic analysis of the d.c. side voltage and current will be very useful to study any a.c./d.c. harmonic interaction. Although it is the average value of the converter firing angle which is usually of interest, harmonic evaluation should also be performed on this signal as the presence of a low order harmonic variation of firing angle could affect a.c. and d.c. side harmonics.

It should be noted that, with the availability of the measured three-phase voltage and current harmonic phasors, it is possible to discriminate the direction of harmonic current flow.

System frequency does not have to be explicitly recorded as it can be derived from the processing of the a.c. bus voltages.

19.3.6.3 Installation of the analyzer

In the past, the analyzer used to be installed for a very short period. It would be set up a few days before the specific harmonic performance tests and removed shortly after.

However, as instrumentation has become easier to obtain (cheap, effective, user friendly), it is advisable to install it at the very beginning of the commissioning tests, i.e. prior to the equipment energization. It should be set up to continuously take samples at regular intervals (every 30 s or so). Plots of the harmonic indices can then be produced and analyzed on a daily basis. Any abnormal harmonic level can be documented along with the converter and a.c. system operating conditions.

The benefits of this early set-up of the instrumentation are mainly:

- a very good evaluation of the pre-existing noise since the converters will not be continuously in operation during the commissioning period,
- an evaluation of the harmonic levels for a large number of converter and a.c. system conditions,
- a reduction of the duration of the testing period needed for the specific harmonic performance tests,
- the possibility of establishing statistics related to the harmonic indices.

19.3.6.4 Test conditions

It has been seen in the previous sections that the harmonic performance is influenced by a large number of factors. The harmonic performance tests should cover as many configurations as practically possible. These will usually be:

- the whole operating range of the converters including the overload range and operation at reduced HVDC voltage,
- various loadings of the a.c. system which should also result in various short circuit levels and a.c. system impedances,
- operation with normal a.c. filtering, with reduced filtering, and with the whole range of filters (or combinations of different filter banks) which might be connected at a given power level,
- all d.c. side configurations (as a d.c. side resonance can affect a.c. side distortion).

The other parameters such as system frequency, a.c. voltage level, voltage unbalance, etc. cannot usually be varied easily and therefore are taken as they occur.

If the instrumentation has been installed at the beginning of the commissioning tests, harmonic performance will be known for many configurations before the specific test period. The test period will be used only to cover the conditions which have not been experienced already or to review some conditions that would have proved troublesome before and would need more documentation.

For the specific harmonic performance measurements, taking samples at regular intervals (e.g. every 30 s) while slowly ramping the converters (around 1 p.u. power in 2 h) has proven more efficient than measuring only at fixed power levels. When using a ramp, it takes less time to cover the whole converter range and it gives much more information. Also, it always remains possible to come back to a specific operating point that would have resulted in abnormal harmonic levels. With such a slow ramp rate, measurements can still be considered to be carried out in steady state. Figure 41 is an example of measurements made during a ramp.

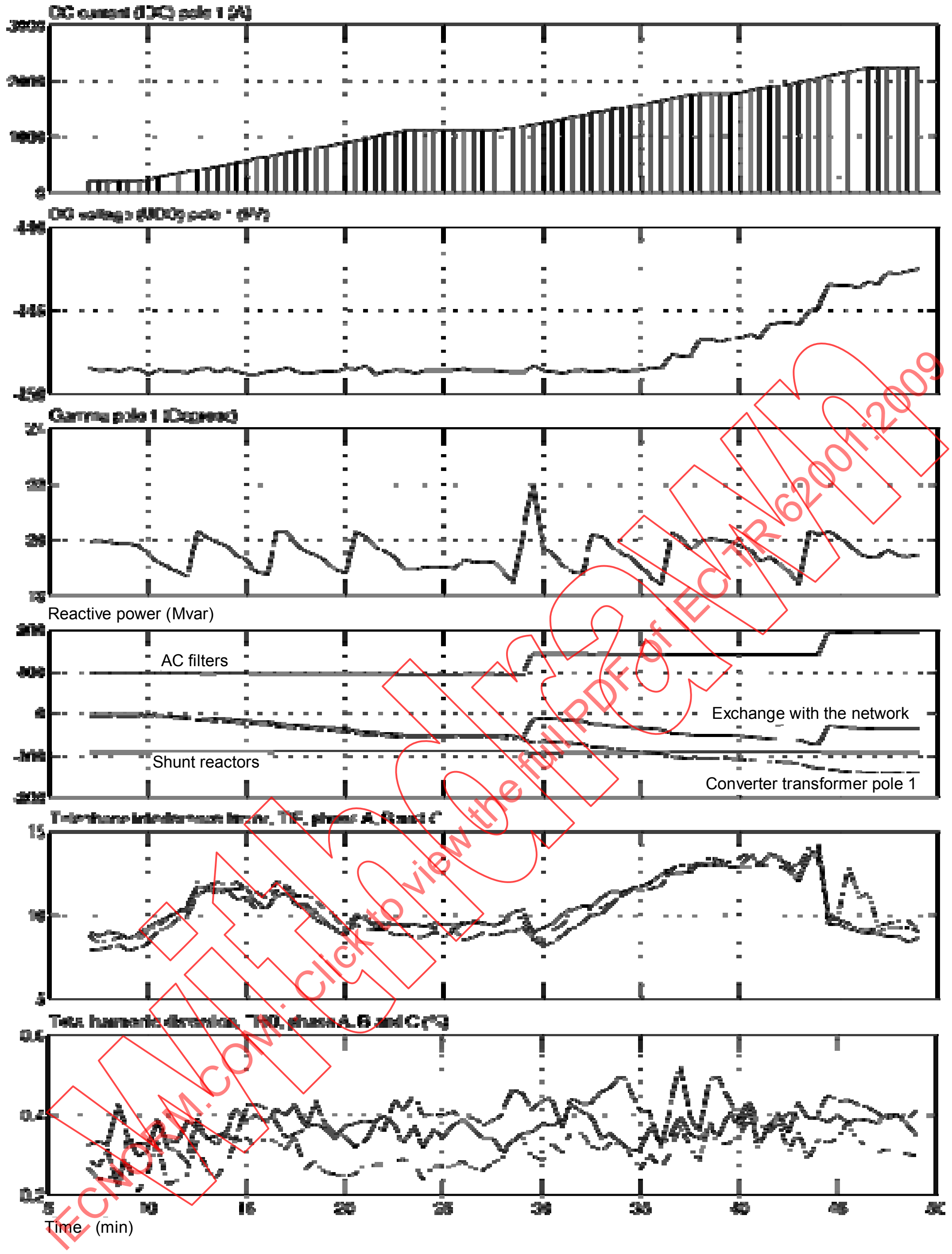


Figure 41 – Example of measurements made during a ramp of the converters

Although the specified harmonic limits will most likely not apply for operation with less than the designed number of a.c. filters connected, knowing the harmonic levels for these conditions can become very useful to the operating personnel in case of a filter outage.

19.3.7 Verification of audible noise

The audible noise generated by the overall station (the a.c. filters are only one of many sources of audible noise) should be measured according to the specification, which should give the maximum allowable noise levels as well as the measuring procedures (for more information, refer to 16.3 and 17.4.8).

19.4 In-service measurements

19.4.1 General

The customer should consider what filter-related measurements, if any, he wishes to make during the normal in-service operation of the HVDC station. Provision should be made in the technical specification for supply of any equipment, instructions and training related to such measurements.

In most HVDC schemes, no special provision is made for such measurements. If any harmonic investigations are to be made after the completion of the system tests, these will usually employ specialized equipment and personnel provided by the customer.

However, in a few HVDC projects, the following categories of measurement have been considered or implemented, and the customer should consider these in relation to his own operation philosophy and capabilities.

19.4.2 In-service tuning checks

Normally, the only verification of filter tuning after the system tests will be the regular maintenance checks for failed capacitor units and verification of the integrity of other components. However, measurement of the tuned frequency of filters could be made during maintenance periods, using the same equipment and techniques as employed during commissioning tests.

19.4.3 On-line monitoring of tuning

In a very few HVDC schemes, equipment has been permanently installed to permit on-line monitoring of the tuning of a.c. filters, using measurements of the phase angle between currents and voltages at harmonic frequencies. A cubicle is supplied containing the harmonic analyzer and facilities to switch between signals from different filter branches.

19.4.4 Monitoring of IT performance

If harmonic current in outgoing lines is an important performance issue, the monitoring of the IT criterion (see 4.4) could be made on a regular, or permanent, basis by measurement of harmonic current in the lines using the normal line CTs connected to a harmonic analyzer.

19.5 Measurements of pre-existing harmonic levels for design purposes

As mentioned in Clauses 4, 8, 10 and 17, pre-existing harmonic levels have to be addressed in the specification to permit the proper design of the a.c. filters by the contractor. Therefore, the related measurements to establish these levels will usually have to be carried out at an early stage of the project. These measurements should cover a time span of at least a few weeks in order to obtain statistical figures. A longer period, ideally one year, would be desirable in order to take into account seasonal variations in generation and network topology.

The data obtained will typically only pertain to the amplitude of the bus voltage harmonics as it is difficult to measure the associated harmonic impedance. The final values specified for pre-existing harmonics should take into account the measured pre-existing levels corrected to include future a.c. system development.

20 Future developments

20.1 General

For clarity of presentation, this technical report has concentrated so far on “conventional” a.c. filter technology and harmonics from current-source line-commutated HVDC converters.

However, substantial changes in both the technology and the electrical system environment are taking place currently, and will continue to occur in the future. These changes will have an impact on many of the aspects of specification and design discussed in this document.

This clause outlines the developments which are happening at present, or can be foreseen in the near future, and indicates what impact these will have on the treatment of a.c. harmonic filtering in a customer's technical specification for an HVDC project.

In general, the customer is advised to ensure that the technical specification does not inadvertently include any restrictions or conditions, perhaps carried over from previous specifications, which preclude the bidders from offering solutions using new technologies which may be of benefit to the customer.

Customers may naturally be cautious about the application of new technologies, and should ensure that the technical specification protects the customer's interests in the areas of testing, reliability and availability, maintenance and guarantees.

20.2 New filter technology

20.2.1 General

New technologies which are currently being introduced into HVDC systems will, where applied, substantially alter many aspects of a.c. filter design. Foremost of these is the automatically continuously tuned reactor, especially when in combination with the series capacitor commutated converter. The first active filters have also been installed in a pilot scheme on the a.c. side of HVDC converters. Single-phase redundancy schemes offer lower capital costs. Capacitor technology is improving continuously, with significant advances being made in fuseless capacitor design. A large reduction in the area required for a.c. filter installations is becoming possible, where necessary, due to developments in encapsulated, compact filter design. These various aspects are discussed below.

20.2.2 Automatically tuned reactors

Since some of the earliest HVDC projects, it has been recognized that significant benefits could be gained if tuned filters could automatically correct for detuning due to frequency variation or component deviation.

In the design of conventional tuned a.c. filters, the worst case performance occurs under the conditions of maximum detuning, and the filter Q-factor has to be set low enough to provide damping and permit optimal filtering when the filter is fully detuned.

If, however, either the capacitor or the reactor of a tuned filter could be varied continuously, over a small range around nominal, then the tuning of the filter could be automatically adjusted to compensate for any detuning effects. With such near-perfect tuning, the Q-factor could be raised to a high value with minimal risk of filter-a.c. system resonance. The increased effectiveness of the filtering would allow the size of the filter banks to be reduced substantially. With no risk of magnification due to filter-a.c. system interaction, rated harmonic currents in the filter components would be reduced, and losses would also be significantly lower.

Such obvious benefits attracted designers to experiment with automatically tuned reactors in some early HVDC schemes, using mechanical methods. These experiments were, however, largely unsuccessful due to the dependence on moving parts, as well as control problems, and the concept of automatic self-tuning was not applied again until the late 1990s. Indeed, many technical specifications discouraged or forbade automatic tuning or even seasonal adjustment. Also, designers recognized that the bulk of the cost of a filter was in the HV capacitors, the total size of which was generally determined by reactive power, rather than filtering considerations.

Interest in the self-tuning concept has been re-awakened recently, however, partly due to developments in the component technology, and partly due to HVDC system considerations. New designs of automatically self-tuned reactors have been developed and are now a proven option for application in HVDC schemes.

The recent developments in the application of series commutated converters (see 20.3.2), has moved the location of much of the required reactive compensation from shunt-connected to series-connected capacitor banks, and therefore substantially reduced the amount of shunt compensation required. The remaining shunt-connected elements are therefore only required for filtering purposes, and in general, the smaller these are, the easier, cheaper and more flexible the design of the HVDC system is, particularly in the context of a.c. systems with low short circuit ratios.

Successful recent developments of the automatically self-tuned reactor have used a non-mechanical concept. The reactor is constructed around a core, which is magnetized orthogonally by an auxiliary winding carrying a controlled level of direct current (Figure 42). The inductance of the main winding is varied by adjusting the level of direct current in the control winding. The control system (Figure 43) measures the phase angle between the voltage over the filter arm and the current through it, at the desired harmonic frequency, and adjusts the control current to vary the inductive reactance with the target of achieving zero phase difference between the harmonic current and voltage, i.e. perfect tuning of the filter.

Long-term tests in trial installations have proved the practicality of the new design of automatically self-tuned reactors, and the first commercial installation is now in operation.

Although presently planned applications of self-tuned filters are for single-tuned shunt branches, it is possible that in the future, self-tuned reactors could be applied in double-tuned branches and / or in series filters.

The benefits of the use of self-tuned filters may be summarized as follows:

- reduction in the required size of shunt filter banks,
- near-perfect filtering at the tuned frequencies,
- elimination of need for separate resistor to reduce the filter Q-factor,
- reduction in losses,
- in combination with series compensated converters, enabling the application of HVDC links connected to very low SCR a.c. systems.

A number of factors must however be recognized:

- self-tuned reactors, and their control systems, are significantly more costly than conventional reactors of comparable size and rating, and so may not be the optimal solution in all cases.