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

Part 1: Overview

National foreword

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inside

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

Part 1: Overview

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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

Part 1: Overview

FOREWORD

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The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a Technical Report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC TR 62001-1, which is a Technical Report, has been prepared by subcommittee 22F: Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment.

This first edition of IEC TR 62001-1, together with IEC TR 62001-2[1], IEC TR 62001-3[1] and IEC TR 62001-4, cancels and replaces IEC TR 62001 published in 2009. This edition constitutes a technical revision.

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[1] To be published.

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

a) Clauses 3 to 5, 7 to 9, 17, 20, Annexes A and C to E have been expanded and supplemented;

b) Annexes C and F on the definition of telephone interference parameters and voltage sourced converters have been added.

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

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

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

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

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

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

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

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

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

INTRODUCTION

IEC TR 62001 is structured in four parts:

Part 1 – Overview

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

Part 2 – Performance

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

Part 3 – Modelling

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

Part 4 – Equipment

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

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

Part 1: Overview

1 Scope

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

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

The scope of this document covers AC side filtering for the frequency range of interest in terms of harmonic distortion and audible frequency disturbances. It excludes filters designed to be effective in the Power Line Carrier (PLC) and radio interference spectra.

The bulk of this document concentrates on the "conventional" AC filter technology and line-commutated HVDC converters. The changes entailed by new technologies are also discussed.

2 Terms and definitions

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

2.1
specification
document which defines the overall system requirements for an AC filter and the AC system environment in which it operates

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

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

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

2.2
customer
organization which is purchasing the HVDC converter station, including the AC filters

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

2.3
contractor
organization which has the overall responsibility for delivery of the HVDC converter station, including the AC filters, as a system

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

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

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

2.4
branch
arm
set of components (capacitor, inductor, resistor), either in singular or interconnected arrangement, which may be isolated off load for maintenance

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

SEE: Figure 22

2.5
sub-bank
one or more branches which can be switched (connected or disconnected) on load for reactive power control

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

SEE: Figure 22

2.6
bank
one or more sub-banks which can be switched together by a circuit breaker

SEE: Figure 22

3 Outline of specifications of AC filters for HVDC systems

3.1 General

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

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

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

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

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

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

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

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

3.2 Boundaries of responsibility

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

In this respect there are two extreme approaches.

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

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

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

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[2] Numbers in square brackets refer to the Bibliography.

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

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

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

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

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

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

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

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

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

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

3.3 Scope of studies

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

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

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

These essential studies would normally comprise the following:

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

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

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

3.4 Scope of supply

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

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

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

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

3.5 Technical data to be supplied by contractor

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

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

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

3.6 Alternative proposals by bidders

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

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

4 Permissible distortion limits

4.1 General

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

These possible adverse effects are as follows.

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

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

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

However, due to

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

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

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

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

4) special criteria.

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

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

4.2 Voltage distortion

4.2.1 General

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

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

4.2.2 Voltage distortion – Definitions of performance criteria

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

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

where

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

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

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

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

where

N is the maximum harmonic order considered.

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

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

4.2.3 Voltage distortion – Discussion and recommendations

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

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

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

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

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

4.2.4 Voltage distortion – Determination of limits

4.2.4.1 General

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

4.2.4.2 Voltage distortion – Determination of limits without detailed studies

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

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

b) specified limits on THD are in the range of 1 % to 4 % (no typical value);

c) specified limits on D are in the range of 2 % to 4 % (most typically 4 %).

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

Where a customer

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

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

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

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

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

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

4.2.4.3 Voltage distortion – Determination of limits with detailed studies

Determining suitable distortion limits by means of detailed studies requires more work at the specification stage but is likely to result in a cheaper AC filter design, with an optimal filter solution relative to the harmonic characteristics of the AC system, and avoid an unnecessarily complex filtering scheme which may impose undue constraints on the HVDC system design and operation. The methodology can be applied to respect either IEEE or IEC recommended limits. CIGRE has published a technical paper on limitation of harmonic distortion for MV and HV power systems [10] based on electromagnetic compatibility.

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

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

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

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

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

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

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

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

It is important to note here that the limits so defined are related to the particular network conditions, and this should be considered in the design of the AC filters. As an example, a stricter limit, defined to control an amplification problem, may correspond to a limited part of the total harmonic impedance locus computed at the point of coupling. Similarly, 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 provides all the necessary data for the filter optimization: AC system configurations, line data, remotely installed filters, earth resistivity, frequency dependent equivalent models at the end nodes, tolerances, etc. The data should also consider the future evolution of the network. This approach would require more work for the bidders, and they would possibly have to develop additional computer tools, but it would avoid the above mentioned inconsistencies. It would also entail considerable effort by the customer to prepare all the necessary data, and lengthen the time required for the tendering process. Unless the bidder defined exactly how each component in the network should be modelled, each bidder could derive different harmonic impedances, depending on the representation used for network components, in particular loads, transformers and transmission lines.

4.2.5 Voltage distortion – Pre-existing harmonic levels

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

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

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

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

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

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

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

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

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

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

4.2.7 Treatment of interharmonic frequencies

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

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

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

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

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

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

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

IEC TR 61000-2-1 [11] discusses interharmonic sources and some possible effects. IEC TR 61000-3-6 considers the impact of interharmonics on low voltage systems, and indicates the need for specific limits due to possible interference with ripple control systems, lighting flicker and other problems. It recommends a planning level of 0,2 % for individual interharmonics. Other applicable standards or guidelines may need to be taken into account.

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

4.3 Distortion limits pertaining to the HV and EHV network equipment

4.3.1 HVAC transmission system equipment

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

4.3.2 Harmonic currents in synchronous machines

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

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

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

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

To allow the bidder to calculate the harmonic currents flowing in the generators, the specification should give the required data, such as system configuration component models, generator and transformer frequency dependent reactances, operating conditions to be considered, etc.

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

4.3.3 Nearby HVDC installations

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

4.4 Telephone interference

4.4.1 General

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

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

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

4.4.2 Causes of telephone interference

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

4.4.3 Telephone interference – Definitions of performance criteria

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

4.4.4 Telephone interference – Discussion

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

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

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

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

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

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

4.4.5 Telephone interference – Determination of limits

4.4.5.1 Telephone interference – Determination of limits without detailed studies

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

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

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

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

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

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

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

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

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

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

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

4.4.5.2 Telephone interference – Determination of limits with detailed studies

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

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

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

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

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

4.4.6 Telephone interference – Pre-existing harmonic levels

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

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

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

4.4.7 Telephone interference – Limits for temporary conditions

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

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

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

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

4.5 Special criteria

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

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

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

5 Harmonic generation

5.1 General

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

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

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

5.2 Converter harmonic generation

5.2.1 Idealized conditions

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

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

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

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

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

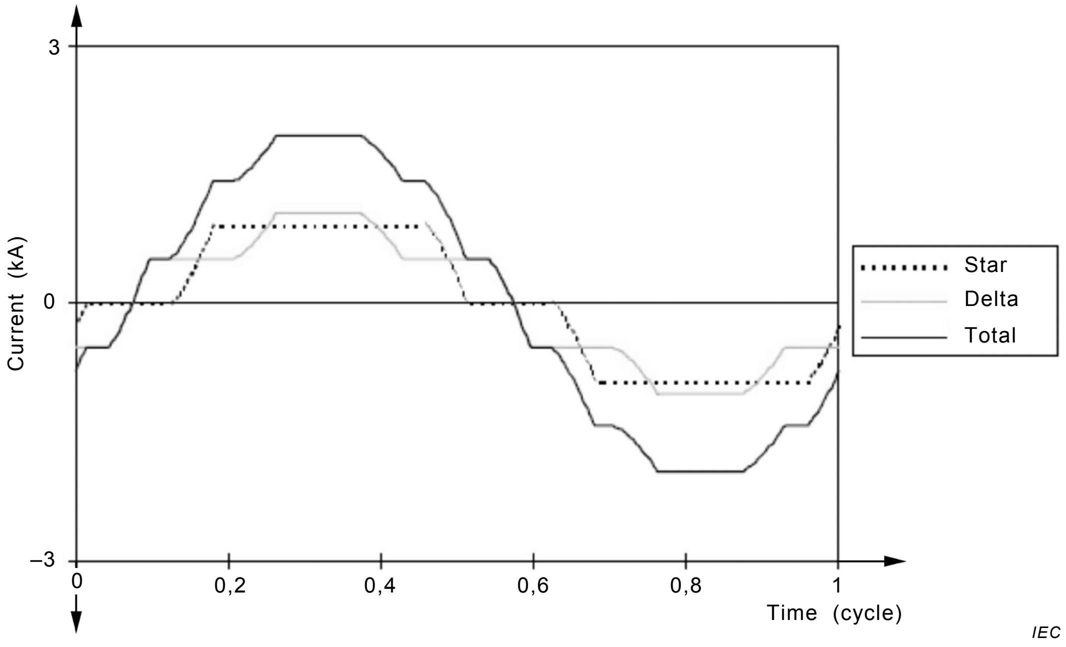


Figure 1 – Idealized current waveforms on the AC side of converter transformer

Parameters:

F = 50 Hz – AC network frequency;

U_{ac} = 230 kV – AC network voltage;

U_d = 500 kV – DC voltage;

I_d = 1 000 A – DC current;

X_l = 14 % – leakage reactance;

A = 15° – firing delay angle.

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

5.2.2 Realistic conditions

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

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

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

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

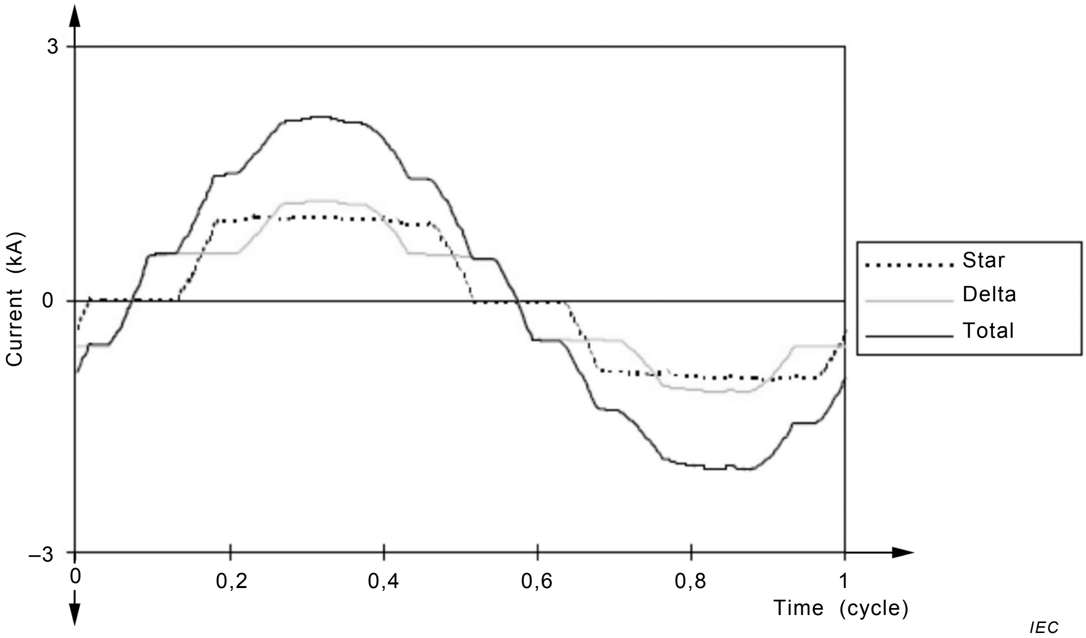


Figure 2 – Realistic current waveforms on the AC side of converter transformer including effect of non-idealities

Parameters as in Figure 1 but with:

- 1 % negative sequence fundamental voltage,

- 1 % second harmonic positive sequence voltage,
- 5 % (of Xl) leakage reactance unbalance between phases,
- ± 0,5° firing unbalance between star and delta groups,
- 50 Hz and 100 Hz components in DC side current.

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

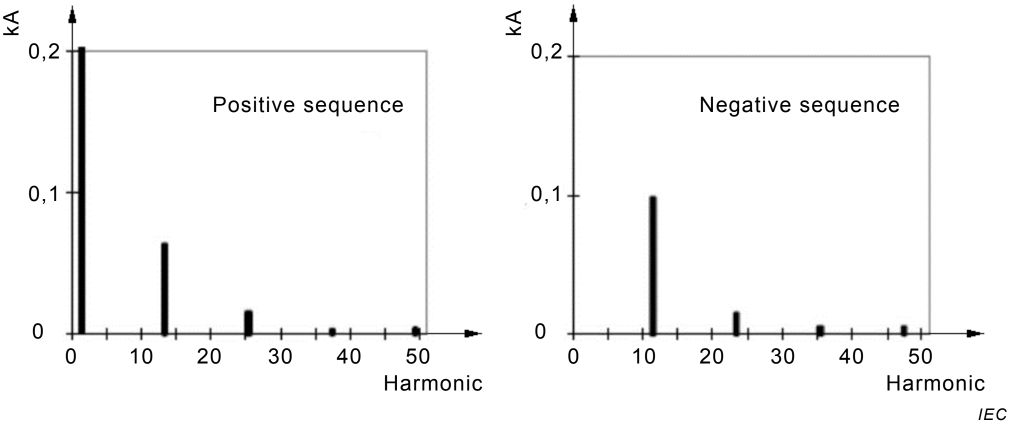


Figure 3a – Harmonic content of current waveform in Figure 1 (idealized conditions)

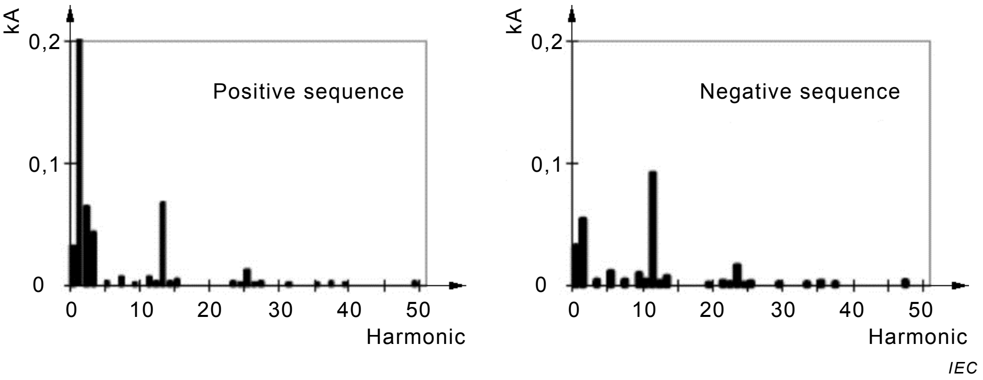


Figure 3b – Harmonic content of current waveform in Figure 2 (realistic conditions)

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

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

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

5.3 Calculation methodology

5.3.1 General

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

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

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

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

5.3.2 Harmonic currents for performance, rating and other calculations

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

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

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

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

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 cancelled 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 should 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 DC current unbalance between poles, particularly if extended DC 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 an 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 DC 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 DC power ranges

For most HVDC converter stations, as DC power transfer increases, additional AC filters are connected, both to mitigate the increased harmonic generation and to compensate reactive power. There is, therefore, usually a range of DC power for which a given set of AC filters may be connected. Within this range, those filters should perform adequately and not suffer overload, and so should be designed for the worst set of harmonic currents which can occur within the given range of DC power. It would not however normally be economical to design the filters to deal with harmonic currents corresponding to a higher DC 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 are calculated separately for each range of power at which a distinct set of AC 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 monotonically with DC power. Within each DC 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 monotonically 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 DC 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 DC power range. Initially, quasi-consistent sets of harmonics at steps of say 5 % or 10 % of DC power may be adequate, but later in the design process, as filter switching points are determined, the harmonic generation at these specific points should 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.

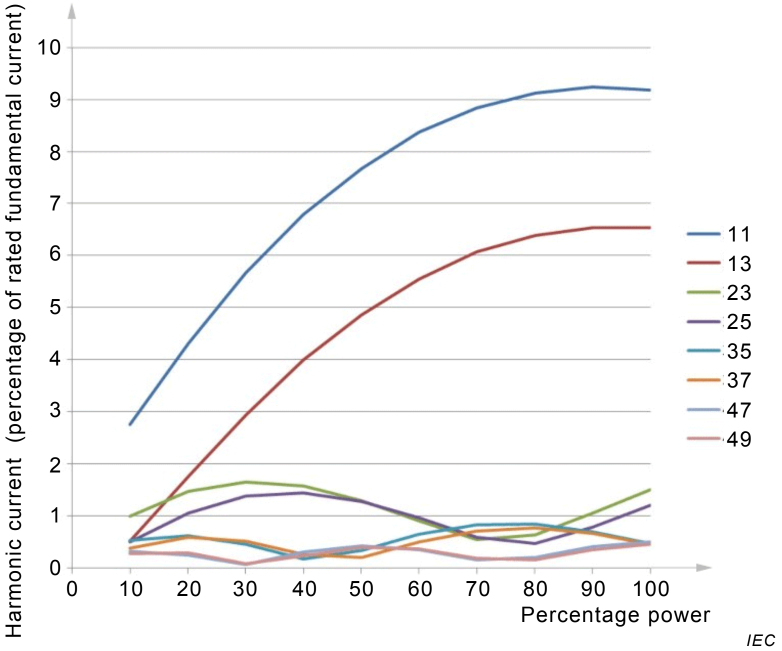


Figure 4 – Typical variation of characteristic harmonic magnitude with direct current

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 should be stated in the 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 DC power (or current) range is most usually used to create sets of harmonics, other deterministic factors such as DC voltage or firing angle could be used to group the harmonics in other operating modes such as

- reactive power control using DC 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 DC 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 are shown in Figure 4. The curves are based on the assumption of ideal DC current on the DC side of the converter and balanced perfectly sinusoidal voltages on the AC 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 should 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 AC system operation (to be requested in the specification if required), or may be associated with filter switching points and apply only to certain DC 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 in 5.4.2.

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. To use 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 should therefore be taken in the wording of the specification, so that it is clear that the calculation of characteristic as well as non-characteristic harmonics should take account of all asymmetries.

5.4.3 Converter equipment parameter tolerances

The 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 should 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 [11].

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 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 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, … $(12k-6) \pm 1$, that is, harmonics which are characteristic of each 6-pulse valve group but which are mutually cancelled in an idealized 12-pulse converter. In reality, incomplete cancellation occurs due to small differences between the two 6-pulse valve groups.

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

If, however, calculation is made on the basis of individual 6-pulse groups, then the 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 AC bus results in the introduction of harmonics of order $6k - 3$ where k is any positive integer, i.e. harmonics 3, 9, 15, etc., back into the same AC bus and via the DC system into the remote AC bus. The most significant is the 3rd harmonic. The amount of negative sequence component which is specified for the converter AC 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 AC 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 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 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 AC 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 DC system induced from parallel AC transmission are important, and cross the converter to give AC side direct current and positive sequence second harmonic. Both of these can result in DC 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 AC side of the converter transformer. Also DC or extremely low frequency current flow through the neutral of the transformers resulting from stray DC current from nearby electrodes or possibly geo-magnetically induced currents can result in a similar shift in magnetizing characteristics and increased harmonic generation.

The 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 AC 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 AC bus result in the generation of non-characteristic harmonic currents at two harmonics down or two harmonics up into the AC system. 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 AC side results in a harmonic on the DC side which in turn may result in another harmonic on the AC side.

A further factor which should be taken into account is harmonic current, or ripple, on the DC side. Harmonic currents on the DC side are transferred to the AC side as two harmonics:

a) a positive sequence harmonic, one harmonic up from the DC side harmonic; and
b) a negative sequence harmonic, one harmonic down from the DC side harmonic.

Ripple in the DC current normally consists of harmonics of order 12 k, where $k = 1, 2, \ldots$, plus possibly the second harmonic.

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

5.4.9 Back-to-back systems

A special case of harmonic interaction across the converter occurs in back-to-back HVDC systems [14]. In back-to-back systems, particularly those with low values of smoothing reactance, DC side harmonics are an important consideration. Back-to-back systems with low reactance or no smoothing reactors can introduce harmonics of one AC system frequency into the other. If the fundamental frequencies of the two AC 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 AC bus voltages. To establish a single set of harmonics which takes 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 AC 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 should 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 AC 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 AC systems, or interharmonics if the frequencies of the two systems are not identical.

5.5 Externally generated harmonics

The filter design should 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 compensator (SVC) (even if it has its own filters). The specification should require that any such source is to be taken into account when calculating both AC 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 AC drives, arc furnaces, power transformers, corona from AC lines, and consumer equipment, can result in a significant harmonic presence. The effect of harmonic sources from outside the station for considerations of filter performance is discussed in 7.1.6. Such sources are considered for the purpose of filter rating (see 9.2.1). The specification should 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 Filter arrangements

6.1 Overview

There are various possible circuit configurations which can prove suitable for AC side filters in HVDC converter stations. Clause 6 reviews these designs to give background information on the advantages and disadvantages of particular filter types.

Only shunt connected filters are considered in Clause 6.

The comments on particular filter designs apply to HV and EHV connected filters and equally to MV (medium voltage, $1 < U_n \leq 35$ kV) 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);
- AC 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 [6] can indicate typical filter solutions for particular schemes. However, 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 Clause 6 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.

6.2 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 6.4 and 6.5, 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 minimizes 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.

6.3 Classification of filter types

Many terms are employed to classify filters. In Clause 6, 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 Formula (6), 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 in 6.4.1 to 6.4.3 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 in 6.5.1 and 6.5.2, and include single tuned damped high pass (e.g. HP12) and double tuned damped high pass (e.g. HP12/24).

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 an 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, for example a 2nd order damped high pass (as in 6.5.1.1) or a 3rd order damped high pass (6.5.1.2).

6.4 Tuned filters

6.4.1 Single tuned filters

This is the simplest filter topology, consisting of a reactor connected in series with the capacitor bank. Figure 5 shows the circuit arrangement and the impedance/frequency response for a typical 11th harmonic tuned filter.

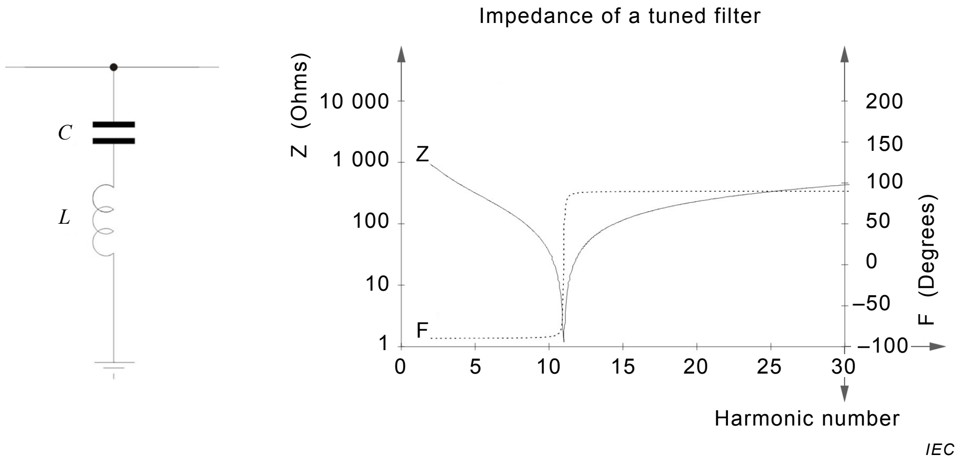


Figure 5 – Single tuned filter and frequency response

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,

$$2\pi f_0 n L = \frac{1}{2\pi f_0 n C} \tag{4}$$

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

$$Q=\frac{2\pi f_0 nL}{r}=\frac{\sqrt{\frac{L}{C}}}{r}, \qquad (6)$$

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 (11th, 13th, 23rd, 25th, etc.).

Because the effectiveness of the filter relies upon Formula (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, Formula (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, Formula (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	

6.4.2 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 6 shows two typical circuit arrangements and the impedance/frequency response for a typical 11/13th filter.

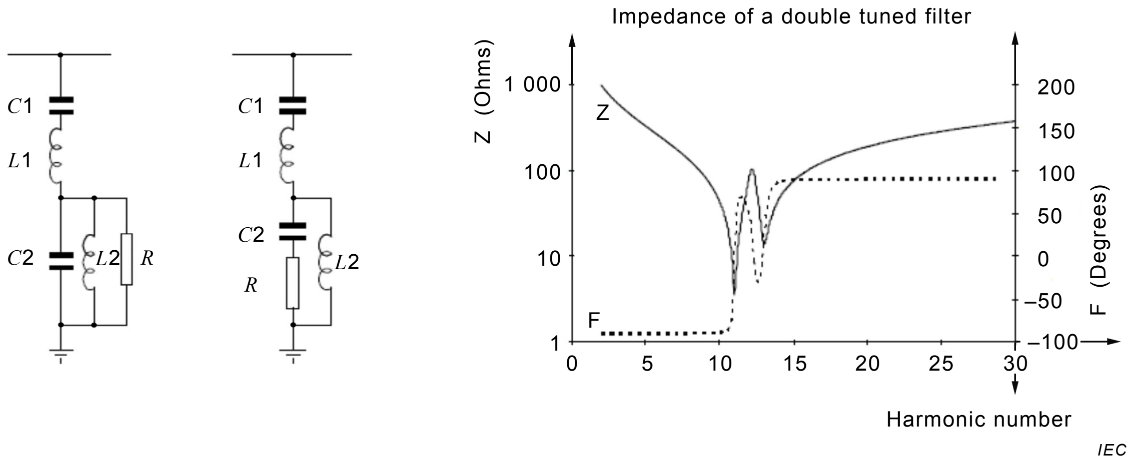


Figure 6 – Double tuned filter and frequency response

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 C1 and only one HV reactor L1; 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 6.4.1), 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 6.

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

6.4.3 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 7 shows the circuit arrangement and the impedance/frequency response for a typical 12/24/36th filter.

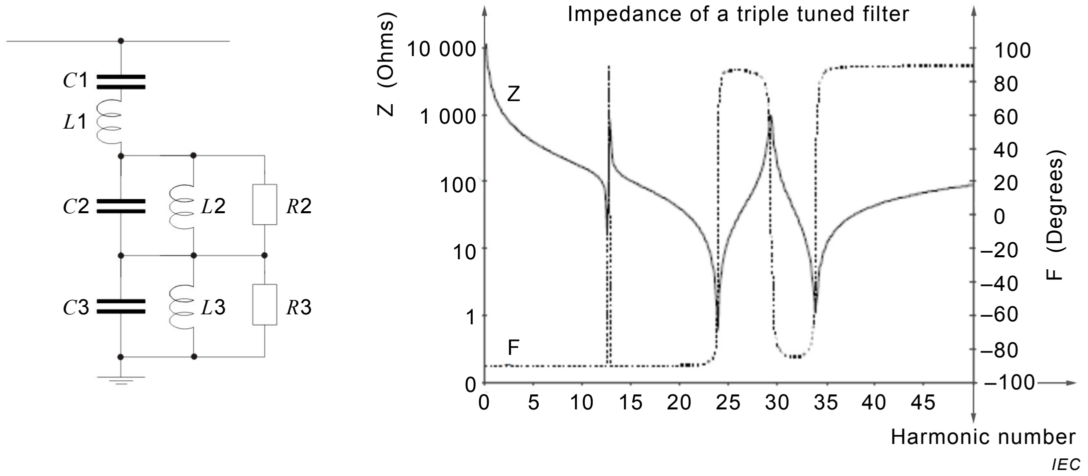


Figure 7 – Triple tuned filter and frequency response

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 offset 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 6.4.2.

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

6.5 Damped filters

6.5.1 Single tuned damped filters

6.5.1.1 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 8 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

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

NOTE This is the inverse of the definition of Q-factor for a filter where the resistance is in series (as in 6.4.1), the logic being that in both cases Q is a measure of the sharpness of tuning.

Figure 8 illustrates the effect of choosing a high quality factor Q (Curve Z1) or low Q (Curve Z2). Note the transition between capacitive and inductive impedance, i.e. the phase angle of 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).

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, for example 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, for example 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 costs 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

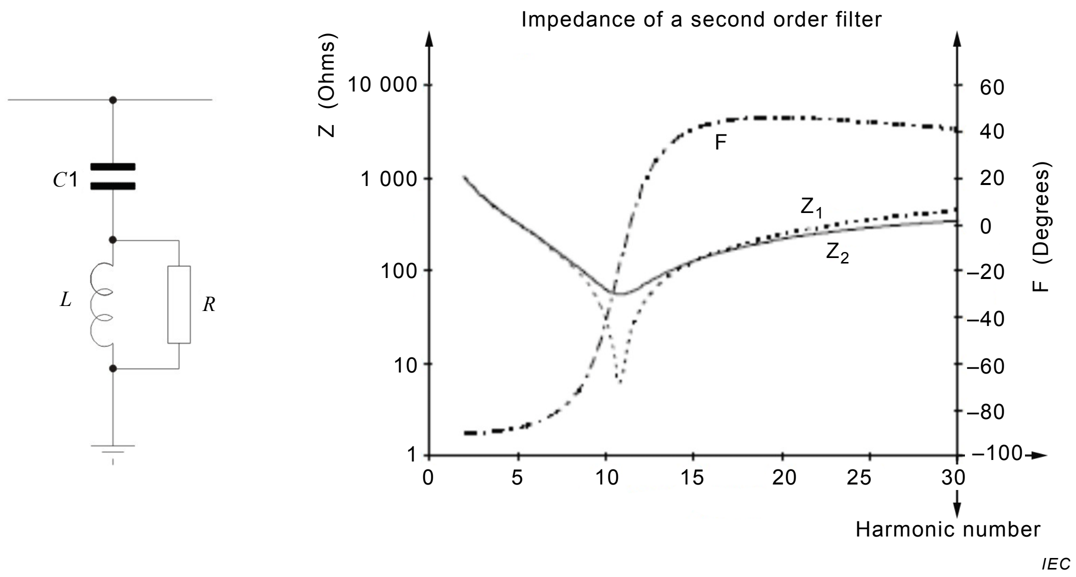


Figure 8 – 2nd order damped filter and frequency response

6.5.1.2 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 9. 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 9.

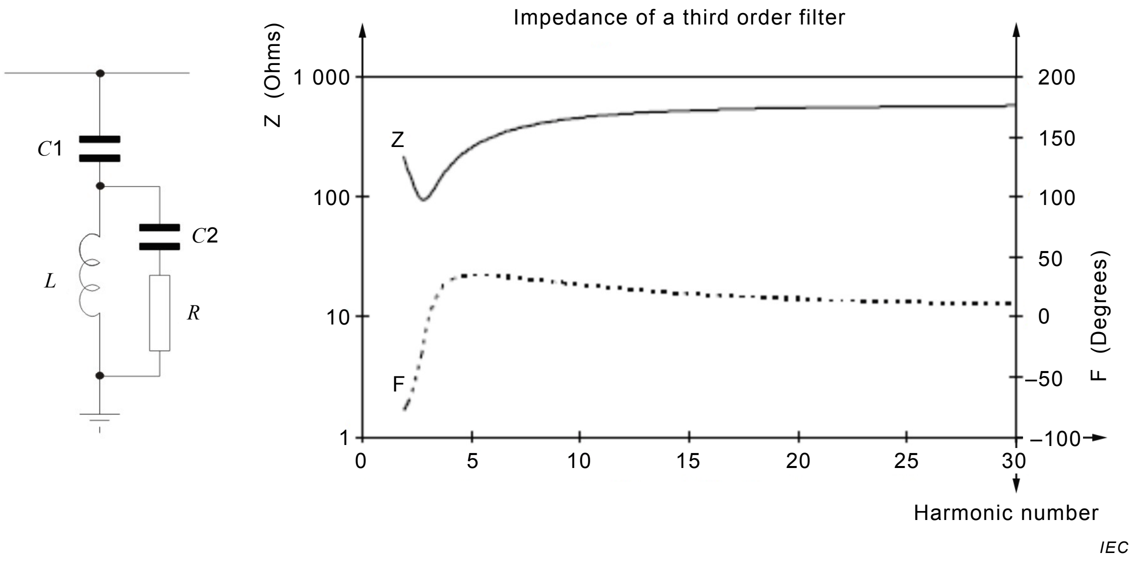


Figure 9 – 3rd order damped filter and frequency response

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 should 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:

	Advantages		Disadvantages
	As 6.5.1.1 plus:		As 6.5.1.1 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

6.5.1.3 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 10 shows the circuit arrangement and the impedance/frequency response for a typical 3rd harmonic filter.

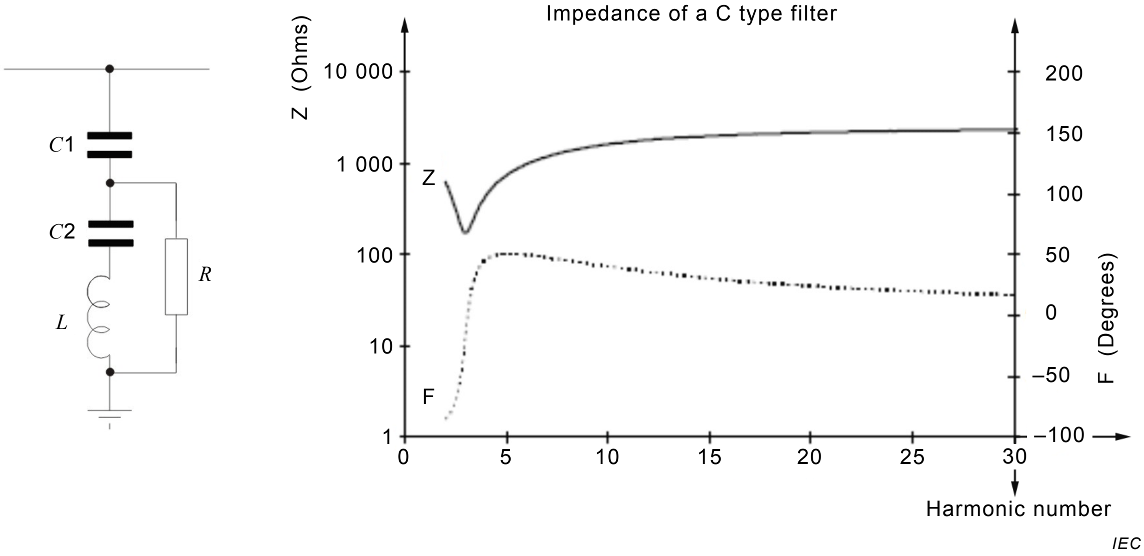


Figure 10 – C-type filter and frequency response

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 6.5.1.1 plus:		As 6.5.1.1 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

6.5.2 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 11 shows the circuit arrangement and the impedance/frequency response for a typical 12/24th filter.

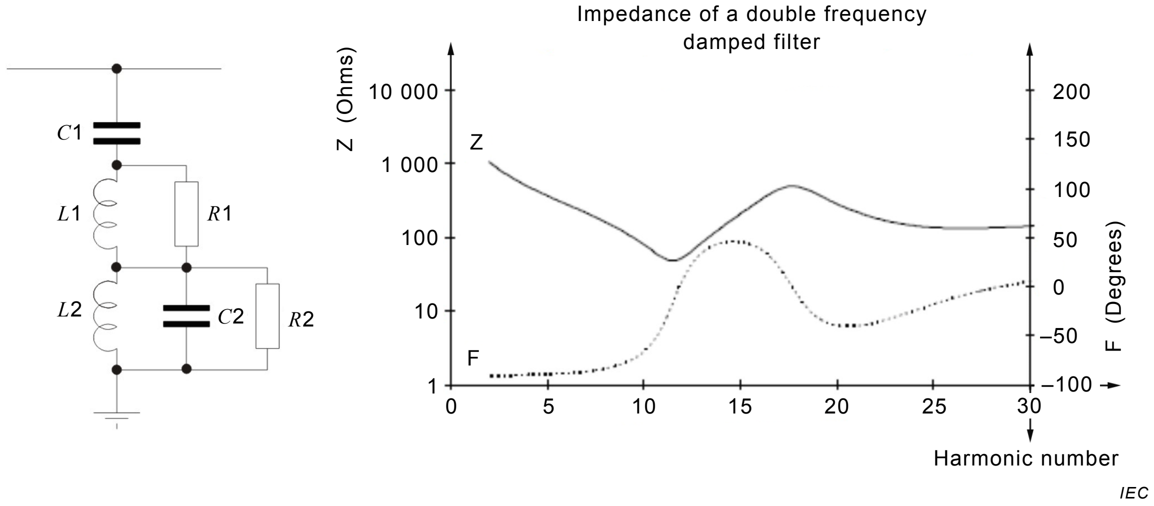


Figure 11 – Double tuned damped filter and frequency response

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

6.6 Choice of filters

From the advantages and disadvantages discussed in 6.2, 6.4 and 6.5, 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, for example 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.

7 Filter performance calculation

7.1 Calculation procedure

7.1.1 General

Filter performance calculations are central to the filter design process. Any prospective AC filter configuration should first be subjected to calculations to show what would be the performance under the defined conditions. However, due to other aspects to consider, such as rating and losses, 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 specification and assessed by the customer.

7.1.2 Input data

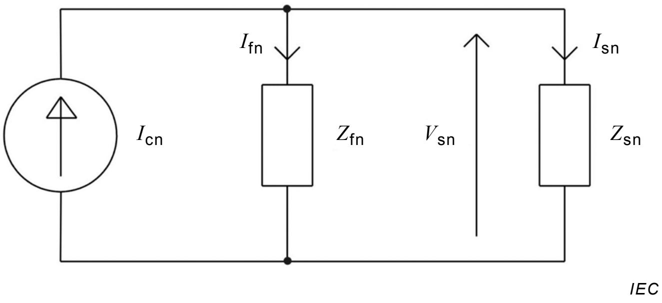
Normally, the customer defines the AC system harmonic impedance, voltage and frequency range, negative sequence voltage, reactive power exchange limits, operating conditions, ambient temperature range, pre-existing harmonics and the permissible distortion limits. The customer should consider possible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

7.1.3 Methodology

The methodology described below is the classical calculation procedure, which does not take into account the effects of AC-DC 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 modelled, calculations using the classical method may give substantially misleading results, especially for low-order non-characteristic harmonics. Subclause 5.4.8 discusses how such interaction may be included in the calculations.

The input data is used to construct a computer model, (Figure 12), which consists of a constant harmonic current source representing the HVDC converters, in parallel with the filters and AC system harmonic impedance.



Key

I_{cn}	injected harmonic currents from the converter
Z_{fn}	filter harmonic impedance
I_{fn}	filter harmonic current
Z_{sn}	AC system harmonic impedance
I_{sn}	AC system harmonic current
V_{sn}	AC system harmonic voltage

Figure 12 – Circuit model for filter calculations

The filter current may then be found from:

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

and the harmonic voltage distortion from:

$$V_{sn} = \frac{Z_{sn} \cdot Z_{fn}}{Z_{sn} + Z_{fn}} \cdot I_{cn} \quad = \frac{I_{cn}}{Y_{sn} + Y_{fn}} \tag{8}$$

where

Y_{sn} is the AC 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 should be calculated by the contractor for all harmonics (see 7.1.4). The system network harmonic impedance (Z_{sn}) is normally defined in the specification (see 7.3).

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

The specification should be clear as to whether harmonic currents are to be calculated considering the steady-state AC voltage range or nominal AC 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 AC voltage variation. Maximum harmonic current injection from the converters may therefore occur at minimum AC voltage conditions.

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

7.1.5 Selection of filter types and calculation of their impedances

During the course of the AC 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 6, including advantages and disadvantages of the respective filter type. Clause 6 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.

7.1.6 Calculation of performance

Using the model (Figure 12), different sets of harmonic currents corresponding to different DC current (or power levels) levels are applied and individual harmonic voltages appearing across Z_{fn} are calculated, under applicable and agreed network impedance conditions. The effect of AC 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 the 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 AC 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.

a) THD, TIF, THFF should be calculated with AC network impedance connected at the two harmonics which result in the highest value of that parameter, and at all other harmonics the AC system harmonic impedance should be considered to be an open circuit.
b) 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 AC network conditions, then the specified limits for these parameters should be correspondingly higher.

For IT and I_{pe} the following simple method could be used.

c) IT and I_{pe} could be calculated with a phase equivalent impedance modelled by a parallel connection of a resistance and a reactance. The reactance can be calculated from the fault level produced by the lines being modelled 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 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, 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 AC 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 specification. A recommended practice is to model Thevenin equivalents connected to the converter busbars, representing pre-existing harmonics from the AC 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.

7.2 Detuning and tolerances

7.2.1 General

Ideally, a filter would operate under conditions of perfect tuning. In reality, however, practical AC filters normally operate under detuned conditions to a greater or lesser extent. The specification should require that the following factors contributing to detuning should 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 6), the different factors will influence the performance to different degrees. 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.

7.2.2 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 should 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 should be given in the 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 should 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 7.5) 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 should 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 should 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 should 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 of filters should be considered. Most existing specifications have rejected seasonal tuning; however, seasonal tuning does offer the following advantages:

1) cheaper filter;
2) lower losses.

The disadvantages are the following:

- necessity of retuning every half year;
- cost of retuning (possible outage cost and labour cost).

7.2.3 Resistance variations

Variations in resistance of the resistors due to temperature changes in the resistor elements should 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.

7.2.4 Modelling

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 (see Annex D). Using this method, all filter component parameters are modelled 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. A formula for equivalent frequency deviation is shown in Annex D.

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, for example 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 AC side components, for example shunt capacitors, reactors, transformers or lines are included in the model, then their impedance may be modelled 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 modelling techniques, there is no reason for the equivalent frequency deviation to be used for other than possible rough initial calculations.

Consequently, the calculation techniques should model the frequency deviations and individual detunings of the components separately.

7.3 Network impedance for performance calculations

7.3.1 General

The network impedance is one of the most important parameters affecting AC 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 7.3.2 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 3.2).

The customer should therefore start 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 AC 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 [15], and a study of network impedance modelling techniques was undertaken by CIGRE JTF 36.05.02/14.03.03 [16]. 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 [15, 16]; 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 modelling 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 AC lines, bearing in mind that transpositions may not be effective at harmonic frequencies. The calculations should 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.

7.3.2 Network modelling 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 AC 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 AC 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:

$$Z_{\text{max}} = Z_{\text{max s.c.}} \cdot n$$

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

with phase angle of

0° to 80° for $n < 5$

± 75° for $5 \leq n < 11$

± 70° for $11 \leq n \leq 49$

where

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

$Z_{\text{min s.c.}}$ is the AC 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 greater effort should be 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 the need 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.

Advantages of impedance envelope diagrams:

- 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.

Disadvantages of impedance envelope diagrams:

- 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 Figures 13 and 14, some examples of envelope diagrams are shown and their relative merits evaluated. Other variations of diagrams than those shown are also possible.

7.3.3 Sector diagram

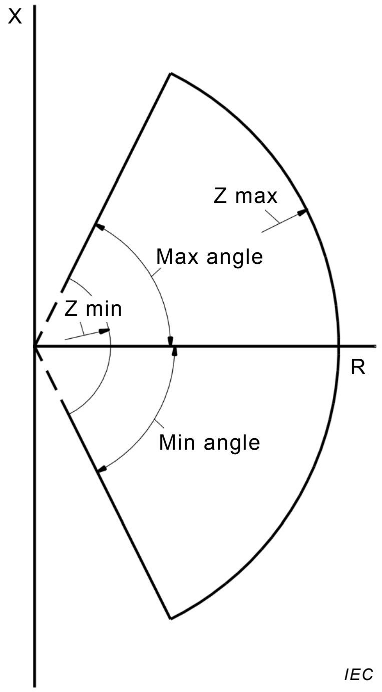


Figure 13 – AC system impedance general sector diagram, with minimum impedance

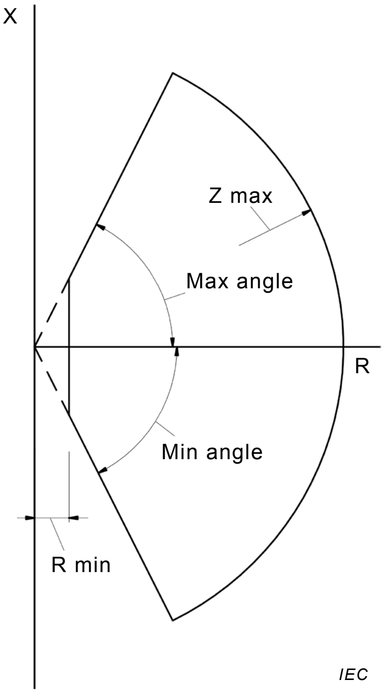


Figure 14 – AC system impedance general sector diagram, with minimum resistance

For the sector diagram maximum and minimum angle of the impedance should be given and also the maximum impedance. Either the minimum impedance (Figure 13) or the minimum resistance could be given as the lower limit (Figure 14).

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.
- Maximum and minimum 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 13):

- 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.

7.3.4 Circle diagram

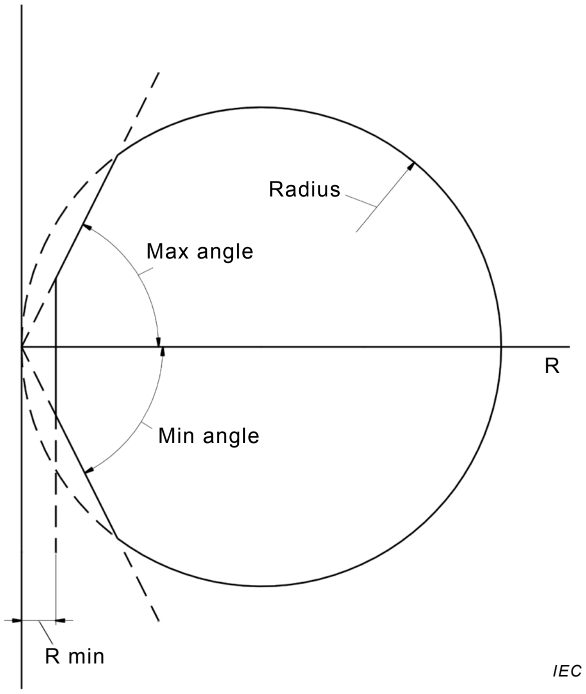


Figure 15 – AC system impedance general circle diagram, with minimum resistance

For the circle diagram (Figure 15), 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.

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.

7.3.5 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 AC filter design to the actual network conditions.

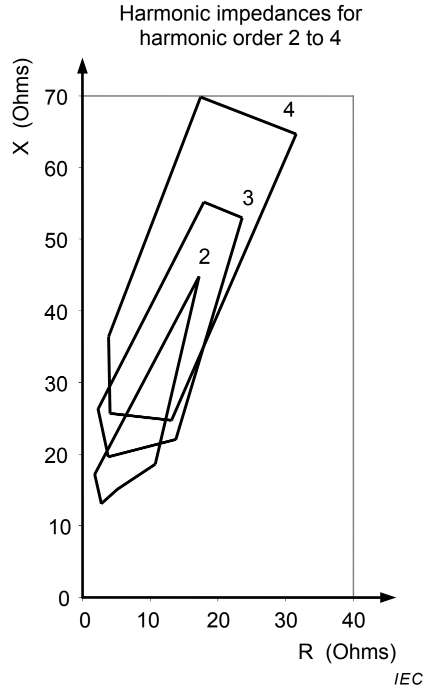


Figure 16 – Example of harmonic impedances for harmonics of order 2 to 4

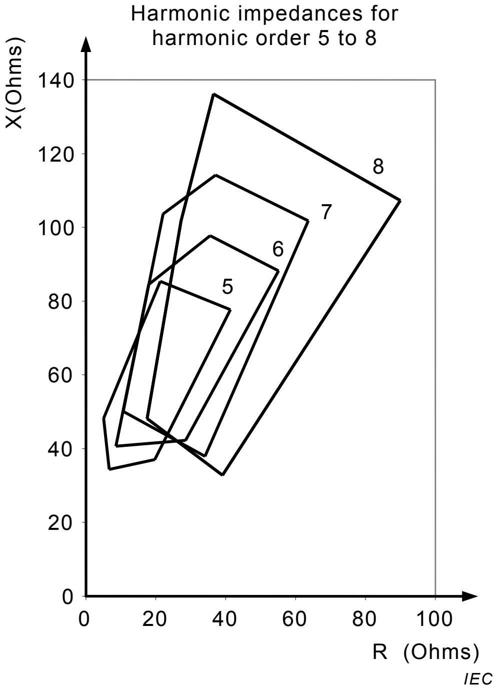


Figure 17 – Example of harmonic impedances for harmonics of order 5 to 8

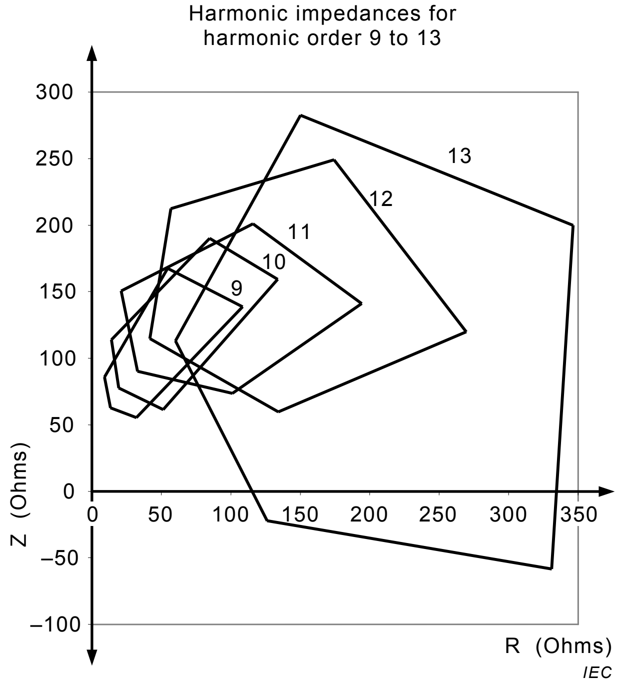


Figure 18 – Example of harmonic impedances for harmonics of order 9 to 13

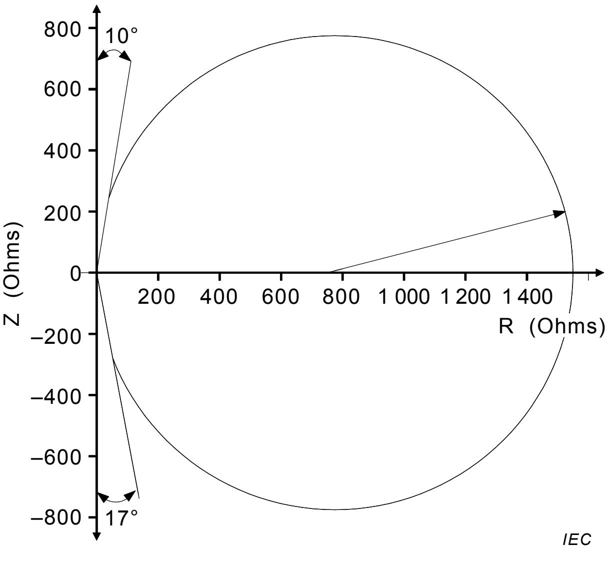


Figure 19 – Example of harmonic impedances for harmonics of order 14 to 49

Some examples are given in Figures 16 to 19. In Figure 19, the higher order harmonics (above 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.

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 modelling 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 modelling error.

Advantages of discrete polygon diagrams:

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

Disadvantages of discrete polygon diagrams:

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

7.3.6 Zero-sequence impedance modelling

If the filter performance parameters include a limitation on harmonic currents, in different phases, propagating into the connected AC network, the modelling method will be different. The harmonic source will be applied across the point of common coupling (PCC) from where the AC 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 modelled 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 modelling 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.

7.3.7 Detailed modelling of AC network for performance calculation

In some specific HVDC projects, it may be feasible and desirable to construct a detailed model of the connected AC 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 AC 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 AC line. In this case, the AC side impedance is dominated by the AC 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 CIGRE WG CC02 [15].

If a detailed model is to be employed, a three-phase representation should be used, with accurate representation of the characteristics of the AC lines, transformers, generators and loads at harmonic frequencies, as discussed in 7.3 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 [15], it is unlikely that the accuracy of the detailed model will be sufficient, and for these frequencies the normal impedance envelope should be used.

7.4 Outages of filter banks and 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 and/or sub-banks has been necessary due to 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 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 fulfil the RAM (reliability, availability and maintainability) requirements, the contractor will in many cases have to consider filter redundancy. It should be noted 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 should 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 AC filters, the customer should, taking into account the nature of use of the HVDC scheme, consider including the following exceptions to fulfilment 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 DC 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 AC 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 fulfil 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.

7.5 Considerations of probability

The usual calculation method for the determination of AC 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 AC 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 AC 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 (AC voltage level, AC 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 TR 61000 series (IEC TR 61000-3-6), is to characterize the system disturbance and equipment immunity levels as probability distributions (see Figure 20). 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 [9] and CIGRE [5] 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 criterion 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. [5].

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 with 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 puts 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, for example 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, AC voltage unbalance, harmonics in AC 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 AC filter performances is therefore desirable but a great deal of work would be needed to achieve this goal.

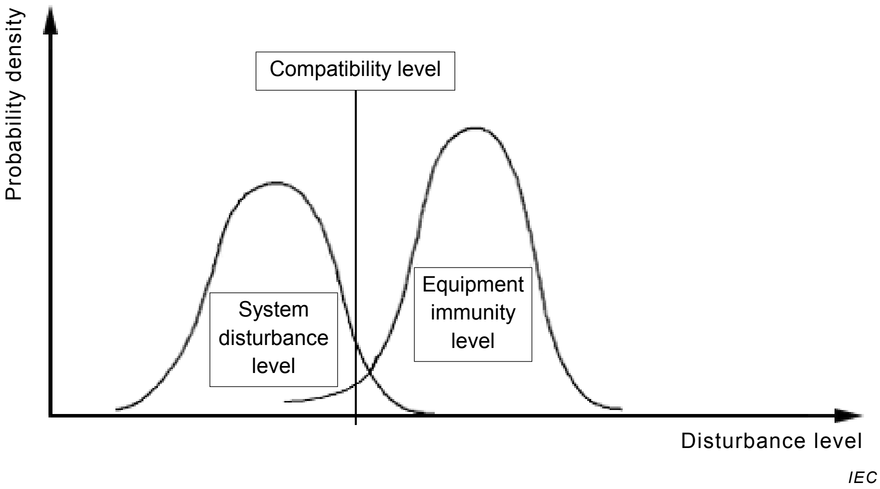
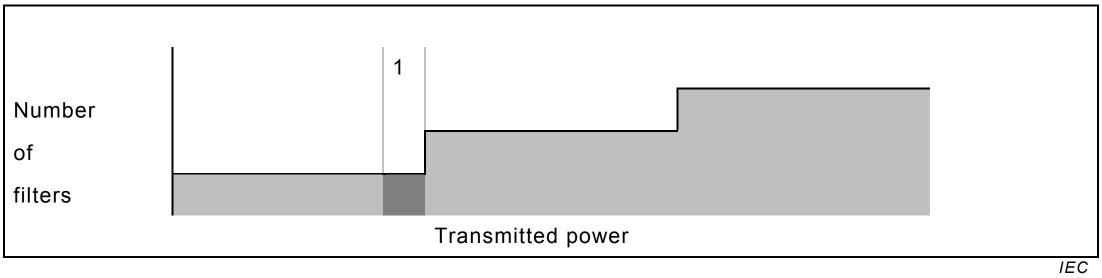


Figure 20 – Illustration of basic voltage quality concepts with time/location statistics covering the whole system (adapted from IEC TR 61000-3-6:2008)

It may be adequate for certain installations that the performance requirements are met, for example, for 95 % of the operating time. 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 21. 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 filters is not justified.



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

Figure 21 – Example of range of operation where specifications 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 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.

7.6 Flexibility regarding compliance

One purpose of the specification is to ensure that the contractor delivers an AC filter which satisfies the customer’s performance requirements. However, some of the criteria might be somewhat arbitrary (say, 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 AC 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.

7.7 Ratings of the harmonic filter equipment

The calculation of the steady-state ratings of the harmonic filter equipment is described in IEC TR 62001-4:2016, Clause 3 in detail. The calculation method incudes the effects of pre-existing harmonic distortion on the AC system and their combination with the converter harmonics for each harmonic order from 2nd to 50th inclusive. The calculation of the total filter current 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.

The effect of transient stresses on filter ratings is also taken into account in IEC TR 62001-4:2016, Clause 4 by using a transient analysis computer program. 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. 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. From the results of the studies the overall insulation co-ordination of the filter can be derived.

Audible noise limitations and the relevance to AC filter design are considered in IEC TR 62001-4:2016, Clause 8. The treatment of audible noise limitation in the specification can be significant, and the issue may also be prominent during bid evaluation discussions and the subsequent project design. Sound active components of AC filters are analysed, sound requirements are specified and acoustic noise reduction measures are recommended.

8 Filter switching and reactive power management

8.1 General

The design of the AC filters is closely linked with the reactive power management of the HVDC converter station. Clause 8 discusses the impact of the reactive power compensation and control on the AC filter design, and on the strategy for switching the AC filters. It indicates points which should be carefully considered by the customer in preparing a specification. Background material relating mainly to the reactive power absorption capabilities of the HVDC converters is contained in Annex E.

8.2 Reactive power interchange with AC network

8.2.1 General

An AC 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 busbar voltages is termed the reactive power absorption and supply capability, respectively, at that bus. A typical permitted reactive interchange capability of a system is shown by Curve 4 ($q_{\mathrm{ac(limit)}}$) in Figure E.1. This feature of the AC network has a strong influence on the design of reactive compensation equipment and AC filters associated with an HVDC converter.

8.2.2 Impact on reactive compensation and 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 AC filter design, and result in

a) installation of less reactive power compensation equipment,
b) simplified and less expensive AC filters,
c) less AC filter/capacitor switchgear,
d) simplified AC switchyard layout

and, usually of lesser importance,

e) simplified controls,
f) lower energy requirement for AC bus arresters,
g) 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 AC 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 8.7 below.

Specification of a low value of the AC 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 DC power levels, especially if the interchange limits are restrictive.

The AC switchyard layout tends to become complicated when a large number of filters is to be accommodated within a specified limited space. In certain situations, for example hilly terrain and proximity to an 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 filters are used.

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

8.2.3 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 AC 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 AC lines. Because the variation of active power flow on the HVDC transmission will vary the active power flow on the parallel AC lines as well, and this variation in active power loading of the parallel AC lines will influence the reactive power interchange capability of the AC 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 AC filter design and costs, and so avoid choosing unnecessarily restrictive limits or “rounded-down” values.

8.3 HVDC converter reactive power capability

After having determined the allowable reactive power interchange with AC 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 E.1.

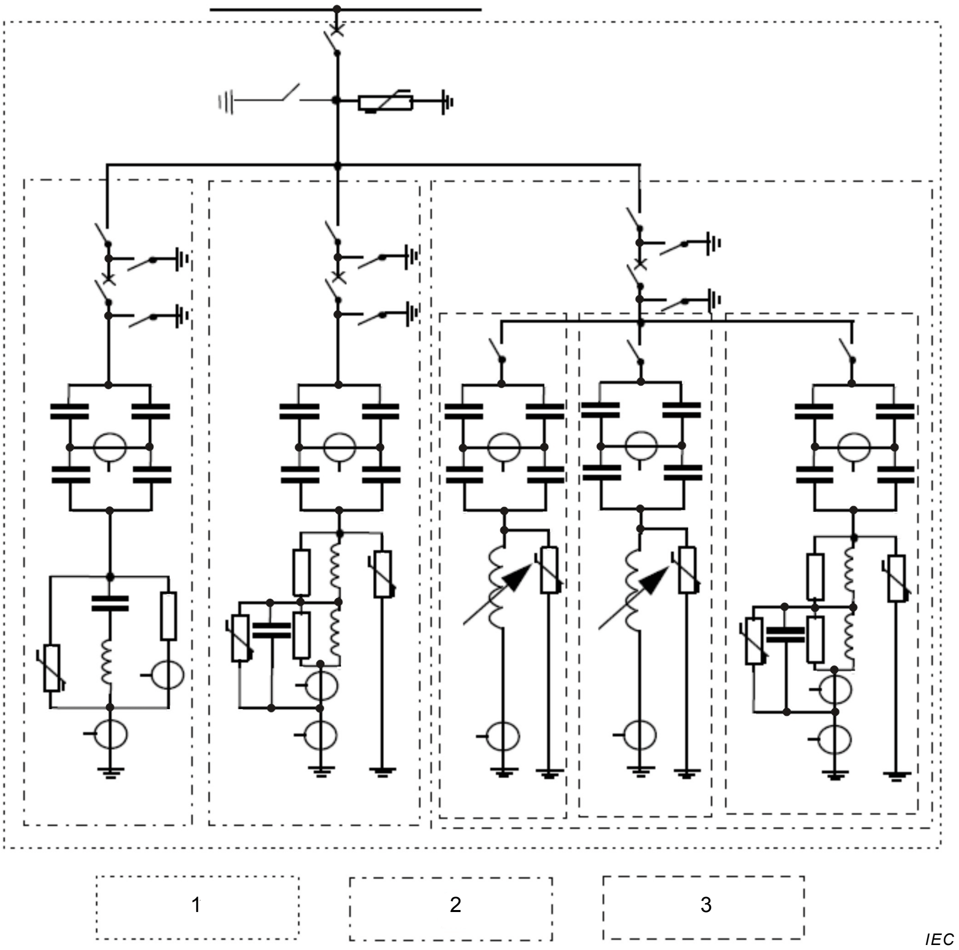
8.4 Bank/sub-bank definitions and sizing

8.4.1 General

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 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 should be able to continue.

The normally used definitions are given in 8.4.2 and a typical arrangement illustrating the definitions is shown in Figure 22.



Key

1 bank

2 sub-bank

3 branch

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

Figure 22 – Branch, sub-bank and bank definition

8.4.2 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 AC system fundamental frequency, commutating bus voltage and rated component values.

The effectiveness of a conventional passive filter in suppressing a particular harmonic 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 in 8.2.2.

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 an increased maintenance requirement on the switchgear.

On the other hand, a large step change in voltage could adversely affect the AC-DC 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 DC system, a factor which has to be considered. Consideration should also be given to other voltage controlling devices in the AC system, including generation, synchronous condensers, SVCs and automatically switched capacitors and reactors in the AC 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 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 DC power transfer due to commutation failure or DC 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 DC and the AC 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 AC 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 AC system where it is known that the AC system strength will increase shortly after the DC is installed, or
- where the converter AC bus is new, electrically remote from the existing AC system and is not servicing any local load.

As regards the transient step change in voltage, for frequent (in the order of 5 or more times per day) and less frequent (daily) switching operations, a transient voltage change of 2 % and 3 %, respectively, is quite normal. For very infrequent switching operations (5 to 10 per month), larger variations could be acceptable (say up to 5 %) but this should 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 control and thyristor valve 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 6).

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 optimization.

8.5 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 AC 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 AC system dynamics forcing the 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 busbar. 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-energize 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.

8.6 Converter Q-V control near switching points

The use of the HVDC converter to control the AC 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.

8.7 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 DC voltage. However, stringent reactive power export limits also require 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 AC 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 requirements more filters are required to be put into service, which could violate reactive power interchange limits with the AC network. However, operation at increased firing angles has certain disadvantages which are discussed in Clause E.1.

8.8 Filter switching sequence and harmonic performance

Filter switching-in points are determined by filtering and reactive power requirements as discussed above in 8.5. The type of filters to be used is decided by the stipulated filtering requirements and harmonic impedance of the AC 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 DC power levels.

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

Usually (except for possibly at low DC power levels), the switching-in points which would be required to satisfy performance requirements (the so-called “minimum filter” requirements) occur at higher DC 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 23. In this figure, the reactive power interchange with the AC network shown by Curve 1 is the actual reactive power interchange (q_{aintchng}) for a typical AC filter solution, whereas Curve 4 gives maximum permitted reactive power interchange ($q_{\mathrm{ac(limit)}}$) with the AC network. Curve 2 gives the converter reactive power absorption. The sub-bank/bank switching points are shown by Curve 3. Figure 24 gives a diagrammatic representation of these reactive power components.

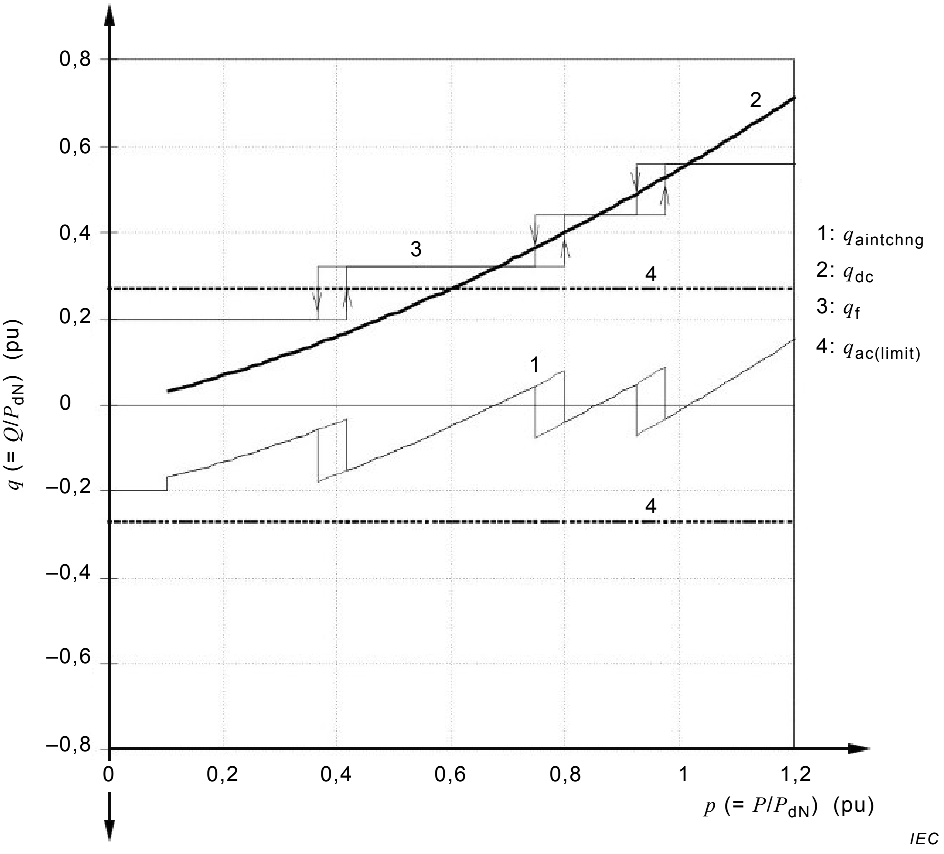


Figure 23 – Typical switching sequence

8.9 Demarcation of responsibilities

8.9.1 General

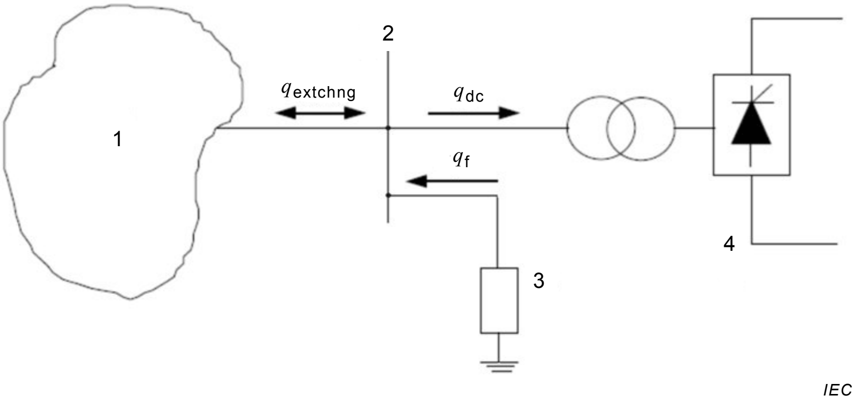
The customer and the contractor should be responsible for the activities identified in 8.9.2 and 8.9.3, respectively.

8.9.2 Customer

The customer should define the following in his 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 AC 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 AC bus.
- Maximum limit on step change in voltage on switching of reactive power elements or AC filters.
- Any requirement on filter switching hysteresis.



Key

1 AC network
2 converter AC bus
3 AC filter/reactive power elements
4 HVDC converter

Figure 24 – Reactive power components

8.9.3 Contractor

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

9 Customer specified parameters and requirements

9.1 General

Clause 9 is intended to serve as a check-list for a customer preparing a specification, and gives a review of which essential parameters and requirements should be specified.

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.

9.2 AC system parameters

9.2.1 Voltage

The following voltages should be specified.

- The nominal system voltage, that is, the voltage by which the system is designated.

- Rated AC 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 AC 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, for example temporary overvoltages.

9.2.2 Voltage unbalance

The negative sequence component of AC 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 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 % [7]. If a converter is located in the close vicinity of a generating station, even lower values could apply.

9.2.3 Frequency

The following frequencies should be specified.

- The nominal frequency of the AC system.
- Steady-state frequency variations, that is, the ranges, in conjunction with the AC voltage steady-state ranges, over which the AC 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 should 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 AC system frequency may reach extreme values for limited periods. These excursions and their expected durations should be specified. Under such conditions, the AC filters should remain in service without damage but should not be required to meet the performance specified (for example, 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 variation within the +2 Hz to –3 Hz limits, an equivalent duration of only 10 min has been used for rating purposes).

9.2.4 Short circuit level

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

Different values of maximum short circuit level may be specified for different use, for example 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.

9.2.5 Filter switching

Maximum permissible voltage change at filter switching and the applicable minimum short circuit level should be specified. Normally, this parameter is specified as a percentage 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.

9.2.6 Reactive power interchange

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

9.2.7 System harmonic impedance

The AC system impedance at harmonic frequencies, to be used in filter performance and rating calculations, should be specified.

9.2.8 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 AC overhead lines.

9.2.9 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, for example effectively earthed or earthed via a coil.

9.2.10 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.

9.2.11 Creepage distances

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

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

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

9.2.12 Pre-existing voltage distortion

Pre-existing voltage distortion existing on the connecting AC bus should be specified as it should be taken into account in the AC 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 criterion 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, for example railway systems.

Determination of pre-existing voltage distortion is not easily done, but in IEC 60071-1 [17], IEC 60071-2 [18], IEC TR 60071-4 [19], IEC 60071-5 [20] 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.

9.3 Harmonic distortion requirements

9.3.1 General

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

9.3.2 Redundancy requirements

Redundancy requirements, if any, should be specified. This requirement shall if possible follow the customer’s normal philosophy, for example a mean time between failures (MTBF) value for either the DC 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.

9.4 Environmental conditions

9.4.1 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.

9.4.2 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 International Standards IEC 60507, IEC TS 60815, IEC 62271-1.

9.4.3 Wind

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

9.4.4 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.

9.4.5 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.

9.4.6 Isokeraunic levels

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

9.4.7 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.

9.4.8 Audible noise

Noise from AC 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.

9.5 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 AC 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 is used by a customer, these should be supplied where applicable. An example of such boundary limits is the magnetic field associated with reactors or personal safety.

9.6 Requirements for filter arrangements and components

9.6.1 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 exist, 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.

9.6.2 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.

9.6.3 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, the bidder should include in his bid a list of tests to be conducted.

9.7 Protection of filters

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

9.8 Loss evaluation

A capitalized loss factor should be specified for the optimization of filter design. The conditions under which filter losses are to be calculated should be clearly stated.

The AC filter losses are considered in IEC TR 62001-4:2016, Clause 5. The calculation of power losses in all AC filter components is described, and basic criteria for assessing AC filter losses are given. 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.

9.9 Field measurements and verifications

Field tests can be divided into sub-system and system tests. Such tests may be specified to verify component behaviour 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.

9.10 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.

10 Future developments

10.1 General

For clarity of presentation, this document has concentrated so far on “conventional” AC filter technology and harmonics from 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.

Clause 10 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 AC harmonic filtering in a customer’s specification for an HVDC project.

In general, the customer is advised to ensure that the 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 specification protects the customer’s interests in the areas of testing, reliability and availability, maintenance and guarantees.

10.2 New filter technology

10.2.1 General

New technologies which are currently being introduced into HVDC systems will, where applied, substantially alter many aspects of AC 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 AC 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 AC filter installations is becoming possible, where necessary, due to developments in encapsulated, compact filter design. These various aspects are discussed below.

10.2.2 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 AC 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-AC 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-AC 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 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 compensated converters (either CCC or CSCC) (see 10.3.2) 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 AC 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 25). The inductance of the main winding is varied by adjusting the level of direct current in the control winding. The control system (Figure 26) 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.

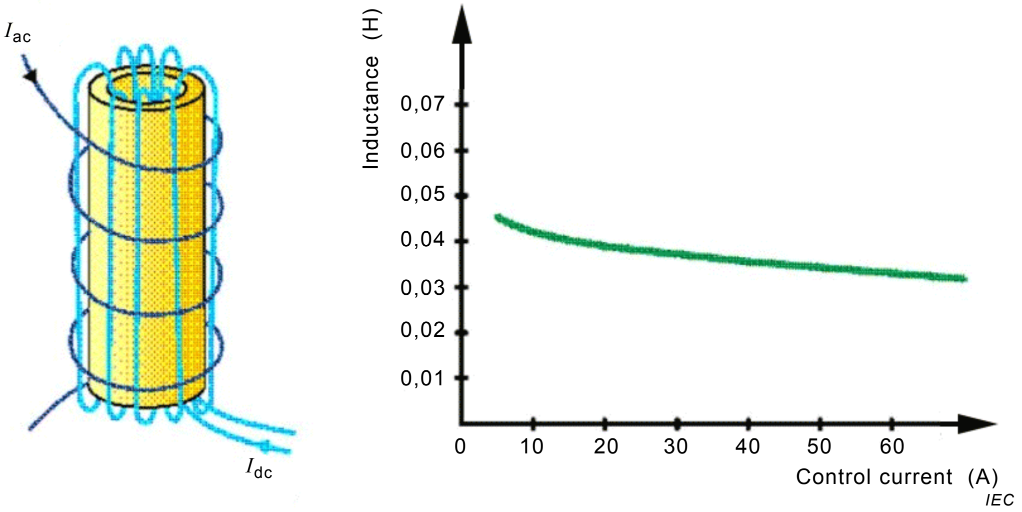


Figure 25 – Design principle of a self-tuned reactor using DC control current in an orthogonal winding

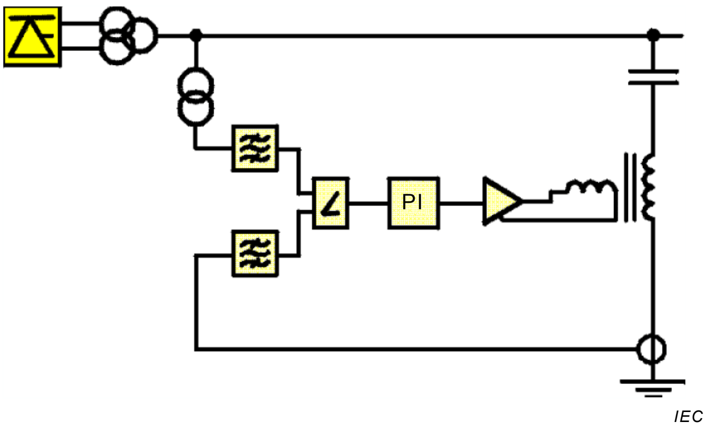


Figure 26 – Control principle for self-tuned filter

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 AC systems.

A number of factors should however be recognized.

a) 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.

b) Self-tuned reactors are only applicable to sharply tuned arms, and furthermore are generally only economical when applied to the 11th and 13th harmonics (or lower orders if filtering is required). Filtering for the entire range of higher order harmonics should still be achieved by damped high-pass filters, or possibly by conventional double-tuned damped branches.

c) The minimum size of a self-tuned filter branch is indirectly limited by the amount of harmonic current it is expected to carry, which is essentially the full harmonic generation of the HVDC converter (plus a contribution from pre-existing harmonics), divided among the number of branches tuned to that harmonic. As the filter branch Mvar size is reduced, the inductance of the reactor, and consequently the harmonic operating voltage over the reactor, should rise proportionally. This in turn determines the operating voltage of the protective arrester, and consequently the lightning impulse withstand level (LIWL) of the reactor. Limitations on the practical and economic maximum level of reactor LIWL will therefore determine the minimum possible size of the self-tuned filter branch. Series combinations of fixed and automatically variable reactors may be used to reduce the LIWL on the automatically tuned reactor, but this will increase the per unit adjustment range required.
d) As an extension of the above, the higher the AC system voltage of an HVDC scheme, the higher the inductance of the reactor will be, for a given Mvar size of filter branch. Although, for a given rated power of HVDC transmission, the harmonic current will be lower at higher voltages, this is a linear relationship, whereas the inductance will rise according to the square of the voltage ratio. Limitations on the minimum size of a self-tuned branch are therefore more likely to be an issue at very high AC system voltage levels.
e) Where parallel operation of self-tuned filter branches at the same harmonic is planned (for example, to reduce the harmonic current per branch, or for reasons of redundancy), the control problems associated with current sharing between the branches should be solved.
f) The range of inductance variation of a self-tuned reactor is limited by physical and economic considerations, and so operation in AC systems which suffer large variations in frequency may be problematic. Rating may have to consider the effects of abnormal frequency variations beyond the design range of variation of the self-tuned reactor.
g) The very high Q-factor of the self-tuned branches may result in unacceptable magnification of other non-characteristic harmonics near to the anti-resonance frequency of the self-tuned branches in parallel with the higher-frequency damped branches (i.e. in the range h15 to h20), and so force modifications in the design of the higher-frequency branches.
h) Audible noise levels higher than for comparable conventional reactors may be an issue in some applications.

The customer’s specification should consider taking into account the recent developments in self-tuned reactor technology, in the following respects.

1) The bidders should be permitted to offer self-tuning, either as their main design or as an alternative. The customer may wish to ensure that a conventional solution is also offered, in which case this should be clearly expressed in the specification.
2) No part of the specification should indirectly preclude the use of self-tuning.
3) The bidders should be asked to prove their ability to deliver a tested and reliable self-tuned solution.

In the subsequent design assessment stage, customers should be aware of the various factors listed above in relation to the offered design.

10.2.3 Single-phase redundancy

It is common for a specification to require a complete redundant three-phase filter bank or branches to be included in the installation, to ensure continued fulfilment of performance criteria and availability of transmission in the event of a filter component failure. Normally, this can be achieved with limited extra cost, as the amount of shunt capacitance involved may anyway be required for reactive compensation purposes.

However, with the series compensated converter and self-tuned reactor concept, the reactive power requirement is largely supplied by the series capacitors, and the only justification for shunt filter banks is for filtering purposes. A series compensated converter station may in fact need only one self-tuned filter branch in order to satisfy harmonic performance requirements. In this context, alternative means of providing redundancy may become more economically attractive.

One alternative is to provide only a single phase of redundant components, with suitable switching to allow it to be connected in place of any one failed phase of a filter. If three circuit breakers or fast disconnect switches are provided for the redundant branch (one connected to each phase of the filter bank), then very fast switching to replace any faulted phase is possible (Figure 27). Alternatively, slower connection can be achieved at a lower price using one circuit breaker (or disconnect switch) and three isolators.

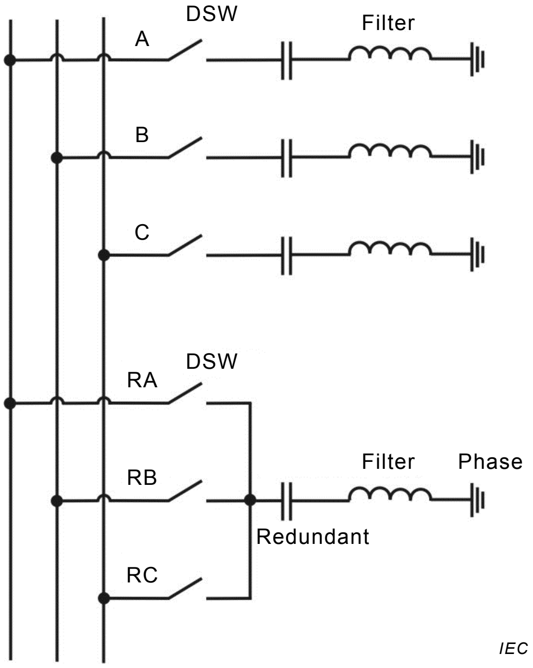


Figure 27 – One method of switching a redundant single phase filter

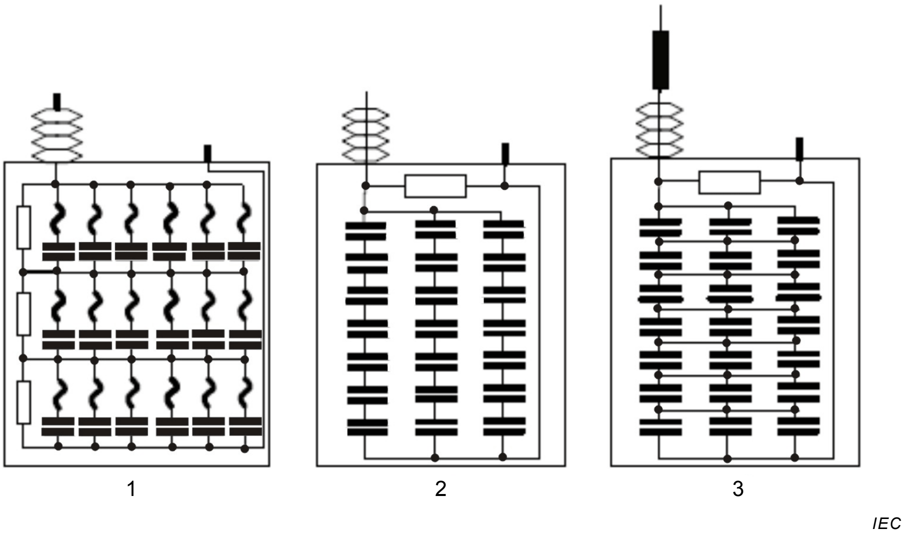
This concept may of course also be applied to conventional filter installations, if it is economical to do so. This will depend on the exact filtering performance and reactive power requirements of the scheme.

The customer should be aware of this possibility when preparing the specification, and permit bidders to offer single-phase filter redundancy, at least as an alternative. In the design evaluation phase, the customer should decide whether offered solutions provide the level of security he requires. Issues of protection, interlocking and switching speeds should be carefully examined.

10.2.4 Fuseless capacitors

Significant improvements continue to be made in capacitor technology, with the use of improved dielectrics and construction techniques offering higher kvar per unit volume, reduced costs, and increased reliability.

One of the more important developments has been that of the fuseless capacitor. The most suitable design for use in filters has an internal construction consisting of a several parallel strings, each string consisting of a large number of series-connected elements (Figure 28). There are no parallel connections between the strings, except at both ends of the capacitor unit. The construction of each element using aluminium foil interleaved with modern all-film dielectric material is such that a short circuit within an element creates an electrically good, welded joint between the two foil electrodes of the failed element. A single element failure results in only a limited release of energy, insufficient to damage adjacent elements or release significant amounts of gas, and has a limited influence over the total capacitance of the unit and the voltage distribution over the remaining healthy elements.



Key

1 internal fuse

2 fuseless

3 external fuse

Figure 28 – Fuseless capacitor design compared to internal and external fused units

The fuseless design offers a more economical construction of capacitor, with fewer parallel elements and interconnections, than in an internally fused design. A further advantage is that the discharge energy developed at the failure spot is limited. This reduces the risk of damage to adjacent elements and other insulation components if a failure occurs in the outer turns of the wound element. It is especially attractive for the high voltage filter capacitors. However, it may not be suitable for low voltage, small capacity filter banks because one element failure would cause a large voltage stress on the relatively few remaining healthy elements.

The customer's specification should permit the use of fuseless capacitors, but require the bidder to prove their reliability, and to provide a suitable capacitor bank protection capable of detecting an excessive number of failed elements.

10.2.5 Active filters

Active filters have been used on the DC side of several recent HVDC schemes [21, 22], and can now be regarded as a maturing technology in that context. However, their application on the AC side of an HVDC converter is currently at a relatively early stage of development.

The principle of active filters is to use a large, power electronic amplifier to generate a harmonic current or voltage signal which is injected into the HV circuit in such a way that it cancels the harmonics generated by the HVDC converter. A sophisticated control system is necessary to measure the harmonic distortion and control the magnitude and phase of the injected signal. Physically, the active filter equipment can all be pre-assembled in the factory and located in a container-like structure in the AC filter enclosure.

Certain aspects, however, make application to the AC side more difficult than application to the DC side.

a) The presence of the smoothing reactor on the DC side greatly reduces the DC side harmonics and so limits the harmonic power necessary to be generated by a DC side active filter. There is no equivalent on the AC side.

b) The AC filters are normally required to provide fundamental frequency reactive power compensation as well as harmonic distortion limitation.

There is, at present, no economic power electronic solution to provide both fundamental frequency reactive compensation and harmonic cancellation. Even if the active filter does not need to supply the fundamental frequency reactive power, the need to withstand the high fundamental frequency voltage for a shunt connected filter or to pass the high fundamental frequency line current for a series-connected filter still leads to an uneconomically high rating. Therefore, various hybrid solutions have been proposed to combine the advantages of improved performance and small physical size of the active filter with that of the low cost of the passive filter. The following are examples.

- An active filter connected in the neutral end of a passive tuned harmonic filter can improve filter performance and avoid resonances in a similar fashion to the automatically tuned reactor described above, but do so at selected frequencies without changing the overall frequency response;
- An active filter in the neutral end of a single passive high pass filter can achieve similar performance to three separate passive tuned and high pass filter arms;
- A fast switching pulse width modulated active filter in series with a power electronic static compensator (STATCOM) providing reactive power compensation can completely replace the passive filters.

Due to rapid technological development of PWM power amplifiers and DSP-based control systems, the price of active filters is falling rapidly and the available power rising. Application to the AC side of HVDC converters is likely to become an established option in the near future. Economical application of active filtering will probably be restricted initially to the higher order and non-characteristic harmonics which have a lower magnitude, or in combination with passive filters as a solution to particular AC system resonance problems.

As is the case for self-tuned filters, active filters may prove particularly attractive in conjunction with a series compensated HVDC converter, as in such applications the requirement for shunt reactive power is greatly reduced, and the function of the shunt filters is mainly to provide harmonic filtering. The use of active filters could enable the filtering requirements to be fulfilled while using a relatively small shunt filter.

A further advantage of active filters is that their frequency control can be modified with ease at any time to counteract new harmonic sources or possible resonance conditions which may arise due to developments in the AC network during the lifetime of the HVDC station.

The first application of an active filter on the AC side of an HVDC converter was commissioned at the Tjele station of the Skagerrak 3 link in late 1998. In this pilot scheme, the active filter was connected in series with an existing passive AC filter at its earth terminal, and employed fast switching insulated gate bipolar transistor (IGBT) converters rated at 0,6 MVA, with a frequency range covering harmonics 5 to 49.

The specification should permit active filters to be offered by the bidders, at least as an alternative, but should request proof that the offered technology is proven and reliable, and that adequate performance is guaranteed by field measurements.

10.2.6 Compact design

Conventional AC filters require a large space and, together with the associated switchgear, take up a high proportion of the area required by the converter station.

In certain locations, particularly in urban areas, the viability and cost of a proposed HVDC installation may be dependent on achieving a highly compact design of the converter station, and measures may have to be taken to reduce substantially the space taken by the AC filters.

The use of self-tuning reactors (see 10.2.2) is one means of substantially reducing the size of the AC filter installation, while still using otherwise conventional equipment and layout.

In Japan, the desirability of compact, earthquake-resistant filter equipment has been long recognized, and a prototype compact AC filter was tested in the early 1980s. More recently, a new design has been developed and tested for a compact 275 kV AC filter installation, using oil-insulated components totally encapsulated in a dead-tank. The capacitors are constructed as single-phase units, and the reactors, tap adjusters, resistors and arresters are encapsulated in one three-phase unit. All interconnecting buswork, including to the converter transformers, is enclosed in oil-filled busbar ducts.

The main advantages claimed for this design are that it reduces the ground area required to about one third of that required by the equivalent conventional design, and that it is more resistant to seismic activity – an important consideration in some locations. Protection of components from pollution, moisture and such risks as birds’ nests should reduce the risks of equipment faults. A possible drawback is the inaccessibility of components for maintenance, but with a highly reliable capacitor design this need not be a significant problem.

An alternative technology for compacting the design of AC filters would be to use gas (SF_6) insulation, with encapsulation of some, or all, components. While this is feasible, it has not been shown to be economical and not yet been applied to an HVDC scheme.

If a compact converter station design is an important issue, the customer should decide whether he wishes to accept such an encapsulated design, whether oil- or possibly gas-insulated. The specification should reflect the customer’s adopted approach, most importantly in those sections concerning testing, reliability and availability, maintenance and guarantees.

10.2.7 Other filter circuit components

10.2.7.1 General

A significant part of the cost of an AC filter is due to the circuit components needed for switching, isolation and for measurements, associated with each filter branch and/or bank. Apart from the cost of the equipment itself, there is a further cost related to the area required for installation and the equipment foundations.

New devices are becoming available which will substantially reduce the space requirements and cost of such equipment. Two examples are optical current transformers and compact switchgear.

10.2.7.2 Optical current transformers

In an optical current transformer, the secondary current from a current transducer is converted to a digital signal which is transmitted through optronics to the control and protection equipment. The current transducer can be of the conventional core type, or in some applications a shunt and/or a Rogowski coil may be used. Optical current transformers are very small and relatively maintenance free. They can be mounted directly on circuit breakers, disconnectors or other high voltage equipment.

10.2.7.3 Compact switchgear

Compact high voltage switchgear utilizes a switching unit which is built up from conventional switchgear components, combined into one unit per phase. A fully equipped switching unit typically has the following built in components:

- one circuit breaker,
- two disconnectors,
- two earthing switches,
- two optical current transducers.

The circuit breaker is the central component of the compact high voltage switchgear. The other components can be excluded from the fully equipped unit as required in different switchgear applications.

Compact switchgear has the following advantages:

a) less space required, reducing the cost for land and ground preparation;
b) one common foundation reducing the cost for civil works;
c) less erection work;
d) all control cables connected to one location, reducing the cost for cabling;
e) internal cabling is factory assembled and tested;
f) unit replacement system shortening time for maintenance outages.

10.3 New converter technology

10.3.1 General

Since the inception of HVDC transmission, converters have been of the three-phase, line-commutated Graetz bridge type, connected to the AC system through converter transformers, and with reactive compensation provided by shunt-connected capacitor or filter banks.

Other converter configurations have frequently been proposed in the literature, but only recently have practical installations been built and tested. Subclause 10.3 considers some alternative converter technologies and their impact on AC filtering requirements.

10.3.2 Series commutated converters

The reactive power absorbed by a line-commutated converter can be compensated by the connection of capacitor banks in series with each AC phase, rather than as shunt elements. This type of converter connection is known variously as a “series compensated converter” or “capacitor commutated converter (CCC)”. Normally, the term “capacitor commutated converter” is reserved for the configuration where the capacitors are connected between the converter transformer and the valves, whereas “series compensated converter” can cover both this and alternative configurations, with the capacitors connected on the AC system side of the converter transformer (Figure 29).

Series compensated converters have been studied and discussed for many years, but only recently introduced into practical HVDC schemes. Benefits of the series compensated connection include reduced total reactive compensation, improved performance and stability when connected to very weak AC systems and improved immunity to inverter end AC faults in transmissions where the discharge current from very long DC cables is an issue.

In the context of AC side harmonics and filtering, series compensation has the following implications.

- Harmonic current generation from the converter will be slightly greater than for a conventional converter operating under comparable load conditions, due to the reduction in overlap angle.
- The flexibility of operation of the series compensated design, especially in connection to weak AC systems, may mean that operation modes with high control angles are used, in order to achieve desired reactive compensation targets. Such operation may result in substantial increases in harmonic current generation compared with nominal conditions.

- There is normally no need to switch shunt reactive elements as DC load varies, as the bulk of the reactive compensation is varied automatically by the inherent nature of the series capacitor configuration. Therefore the AC filter bank(s) can be left connected over the whole DC load range.
- To gain optimal benefits from the series compensated converter, the size of the shunt connected filters should be as low as possible. The use of small, self-tuned filter branches is therefore an ideal combination with the series compensated converter. The high performance of the self-tuned branches also compensates for the increased harmonic generation of the series compensated converter.

If series compensated converters are to be considered, then the specification should be suitably worded, particularly in the context of reactive compensation, harmonic generation, and filter redundancy.

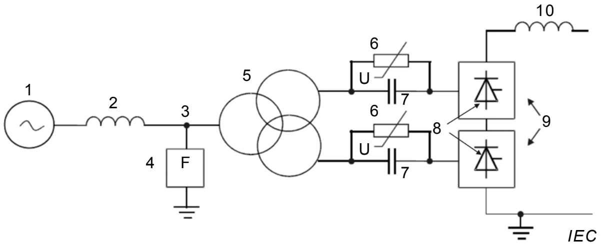
Bidders should be asked to demonstrate the adequacy of their methods of calculating the converter harmonic current generation.

The above listed aspects should be considered by the customer in discussions with the bidders and in evaluation of the offered designs.

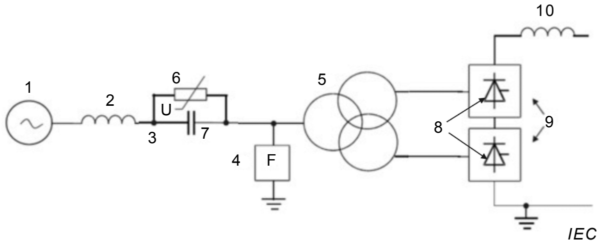
10.3.3 PWM voltage-sourced converters

Recent developments in power electronic devices have made possible the introduction of voltage sourced converters (VSC) using IGBT or gate turn-off (GTO) devices and pulse-width modulation (PWM), operating at levels of power and direct voltage suitable for power transmission purposes in the range of tens of megawatts up to approximately 150 MW [23, 24]. The circuit and waveforms of a DC link using voltage-sourced converters are shown in Figure 30. Detailed information on voltage sourced converters is given in Annex F.

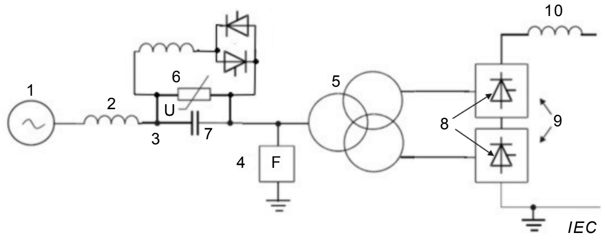
Because of the wide control range and turn-off capability, the reactive power consumption or generation of such converters can be controlled to any desired value within the operation range, virtually independently of the active power transmission. No external reactive compensation is therefore necessary.



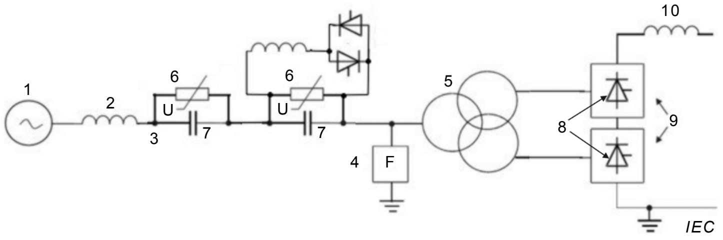
a) Capacitor commutated converter



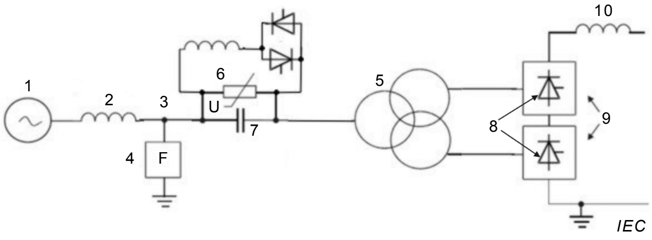
b) Uncontrolled series capacitor converter



c) Thyristor controlled series capacitor converter



d) Partly thyristor controlled series capacitor converter



e) Thyristor controlled series capacitor commutated converter

Key

1	AC system e.m.f.	6	overvoltage limiter
2	AC system impedance	7	capacitor
3	AC system bus	8	thyristors
4	AC filters	9	converters
5	converter transformer	10	DC reactor

Figure 29 – Various possible configurations of series compensated HVDC converters

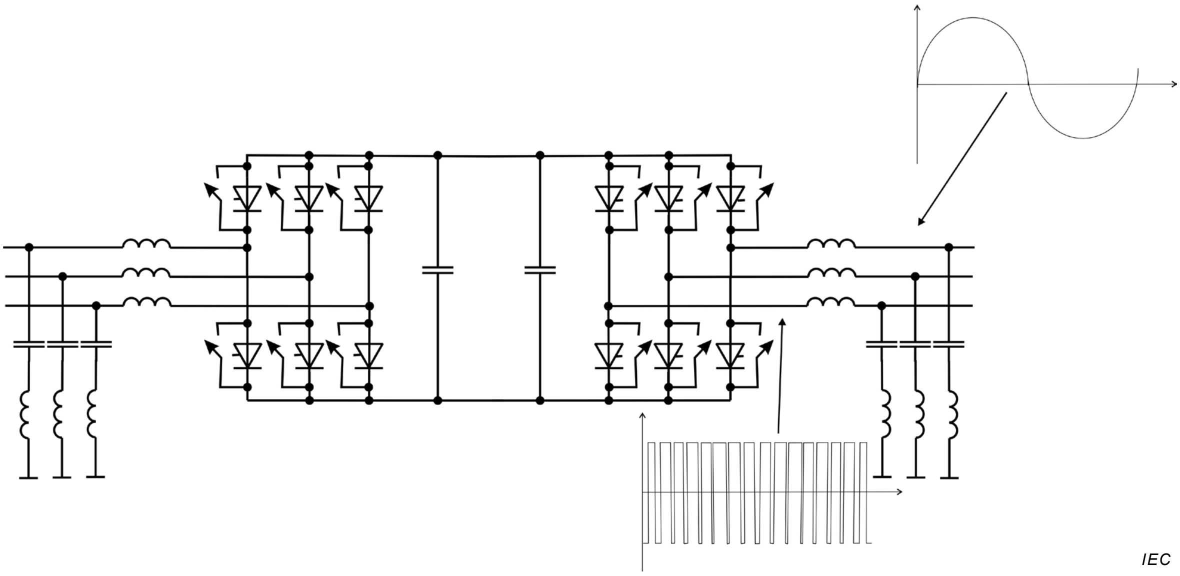


Figure 30 – Circuit and waveforms of a DC link using voltage-sourced converters

The magnitude of these high-frequency harmonics is such that a filter will generally be required, for example a high pass filter tuned to the switching frequency. The amount of required filtering is, however, expected to be relatively small.

The customer's specification should state the required harmonic performance limits and the reactive power interchange requirements for the converter station. It is probable that as experience is gained from this kind of converter, new requirements on filtering will evolve, in particular for higher frequencies. In the absence of such new requirements, it is believed that the normal performance requirements of a conventional specification can be followed, but taking into account a wider frequency range for telephone interference, such as 5 kHz instead of the typical 2,5 kHz to 3,0 kHz.

As any VSC applications in the near future will be limited to low and medium voltages, acceptable distortion limits should be set higher than those normally given for the high voltage systems of conventional HVDC. The AC system impedance model should also reflect the different characteristics of AC networks at higher frequencies and the higher damping typical of low- and medium-voltage systems.

If AC filters are required, they should follow the normal requirements of a conventional specification with respect to equipment specification, testing, loss calculation, audible noise and protection.

10.3.4 Transformerless converters

Proposals have been made for HVDC converters to be designed without converter transformers, thereby reducing the total cost of the installation, as well as the losses. A feasibility study has shown that such operation without converter transformers is technically feasible. However, no practical proposals for the implementation of such a scheme are known at present.

Without a converter transformer, the inclusion of a series-connected reactor in each AC phase is required to limit fault currents, and this provides a commutating reactance similar to that normally due to the converter transformer. The larger the fault limiting reactor, the lower is the AC harmonic current generation, but conversely, the reactive power consumption is higher. An optimal value of fault limiting reactance could be that value for which the shunt capacitive reactive power required was equal to the amount of AC filtering required to satisfy performance criteria.

The aspects of the specification concerning AC harmonics and filtering would be very similar to those for a conventional HVDC scheme.

10.3.5 Unit connection

“Unit connection” implies the direct connection of a 12-pulse HVDC rectifier to a particular generator (usually in the context of hydro generation), in isolation from the AC system. This has been the subject of much study [25], and some experimental connections have been tried and harmonic measurements made, but as yet no HVDC scheme has been designed on this basis.

With direct connection, no filters or reactive compensation should be required, thus permitting considerable cost savings. The generators should be dimensioned to withstand the full harmonic generation of the connected converter, and to operate at the required power factor. As generators are typically designed for around 10 % negative sequence component, and as actual negative sequence loading should be practically zero in the direct connection, this capability compensates for the increased harmonic loading. Normal generator designs should thus be capable of withstanding the harmonic stresses resulting from unit connection.

Assuming a short connection between generator and converter, there will be no problem of telephone interference, unless to internal communication systems within the power plant. The harmonic distortion on the intervening AC connections will however be substantial, and both connected auxiliary power equipment and measurement and protection apparatus should be designed to be immune to this.

The specification for such a scheme would concentrate, in the context of harmonics, on the implications of converter-generated harmonics for the design, rating, heating and vibration of the generator, and on definition of the amount of reactive power to be supplied by the generator.

10.4 Changing external environment

10.4.1 Increased pre-existing levels of harmonic distortion

The widespread introduction of power electronics into electrical equipment at all levels from domestic consumers to transmission grid has resulted in a substantial increase in the amount of harmonic generation throughout the supply system.

Much of this harmonic generation is not filtered effectively at source, and penetrates widely throughout the network.

The implications for HVDC schemes are various.

- In order to maintain acceptable harmonic compatibility levels in the system, the amount of harmonic distortion permitted to be generated by a new HVDC converter station may be reduced from levels which were previously regarded as acceptable, i.e. its “share” of the total permitted distortion will decrease.
- As the filters installed at an HVDC converter station are generally highly effective shunt devices, they provide a sink for harmoniccurrents from elsewhere in the AC system. This increases the required rating of the filter components, in some instances very significantly. The contribution of pre-existing levels of low order harmonics to the rating of 3rd harmonic filters can be substantial. The cost of rating components to allow for pre-existing harmonics will therefore tend to rise in future.
- Both of the above factors may give impetus to increasing use of series filters, which block the flow both of harmonic current from the converter station into the AC system, and of AC system harmonics into the shunt filters, and also to the introduction of active filtering on the AC side.

The definition of pre-existing harmonics is generally the responsibility of the customer. It is an aspect to which customers should pay particular attention in the preparation of specifications.

Trips or failures of filters due to overloading by pre-existing harmonics can be extremely costly, especially if they lead to loss of transmission capacity. It is difficult to prove or disprove that such overloading was in fact the result of pre-existing harmonics in excess of specified levels, and expensive contractual disputes between customer and contractor may result. Customers should be aware of the severe and increasing potential hazards in this area, and devote sufficient attention to the topic of pre-existing harmonics, both in terms of specifying realistic levels, and also of making the contractual responsibilities of both sides clear and explicit.

10.4.2 Developments in communication technology

Modern developments in communication technology are leading to the progressive replacement of metallic telephone conductors by fibre optic cables, the replacement of analogue by digital communication, and the widespread use of mobile cellular telephone systems. All of these developments tend to reduce the potential scale of interference from power lines to telephone systems, and in the long term future perhaps the problem will no longer be of relevance.

One implication of the availability of such technical solutions, which are immune to inductive interference at harmonic frequencies, is that in the event of actual interference occurring after an HVDC plant has entered operation, some form of local mitigation measure in the telephone connections to affected consumers should be technically possible, most probably at a cost below that of installing additional AC filtering at the HVDC station.

However, in the near-term future, there will still remain a very large amount of metallic telephone conductor in use, particularly at consumer level and particularly in rural areas and in developing countries, where many HVDC schemes are sited. It is therefore likely that limitation of telephone noise through the application of criteria such as TIF, THFF and IT will continue to be enforced in HVDC specifications for the foreseeable future.

10.4.3 Changes in structure of the power supply industry

In several countries or parts of countries around the world, one company has traditionally been responsible for both power generation and power transmission. When one organization is responsible for both the generation plants and the grid, optimal system configuration can be achieved by utilization of specific generators and grid configuration during both ordinary operation and during maintenance periods.

However, in various countries the responsibility for the generation units and the grid has been split between different generation companies and a power grid company. This decreases the possibility for one company to optimize the reactive power balance and ensure adequate system strength. The generating company could choose to have generation in another region, caused by the market situation, and not in the region where the HVDC station is located, resulting in lower short circuit level at the converter terminals. This could also lead to high reactive unbalance in the system due to new power flow in the grid. Furthermore, generation utilities may argue that they are not paid for delivering reactive power, and prefer to operate their machines at close to unity power factor in order to extend their life.

In addition, lack of co-ordination between the generation company and the transmission company related to maintenance could result in outage of generators and lines at the same time. This split of responsibility and a new market situation will make the cost of rotating reserve and reactive power more transparent. These developments may influence the AC filter specification for HVDC schemes as follows:

- a lower minimum short circuit level at converter terminals due to the high cost related to "buying" spinning reserve;

- less reactive power exchange with the AC system due to the high cost and difficulty related to "buying" reactive power.

Both the above implications may lead to more complex and expensive filter solutions due to a split of the whole into more switchable filter units. This will also result in more filter switching during operation.

In some cases, a SVC could be necessary in order to permit a possible filter solution and at the same time stabilize the voltage and reduce the voltage step at switching.

10.4.4 Focus on power quality

Power quality is increasingly the focus of attention throughout the world. Generally, such attention to power quality issues tends to result in a demand for lower levels of harmonic distortion and this could lead to more stringent filtering requirements.

However, the discussion will increasingly also take the cost of achieving improved power quality into consideration. This factor may tend to counteract demands for better supply quality.

It is unlikely that specified limits on harmonic performance criteria will become less stringent than at present, and quite possible that they will be tightened in future. The cost of achieving satisfactory harmonic filtering will also be increasingly under scrutiny. Such trends will increase the pressure for development of new converter and filtering technology.

Annex A
(informative)

Alternative type of procurement procedure

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

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

- The specific requirements will probably be more optimized for the project.
- During the negotiations, a common understanding of the various aspects of the specification is established between the customer and the bidders. This should result in less need for clarification after the contract is signed.

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

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

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

In this document, the term "specification" refers to the final definition of the customer’s requirements for a defined project, whether determined by the conventional approach or by this alternative negotiated approach.

Annex B
(informative)

Formulae for calculating the characteristic harmonics of a bridge converter

The formulae below give the characteristic harmonics of a line-commutated bridge converter, based on ideal assumptions of symmetrical conditions for a HVDC converter, with the direct current also ideally smoothed.

The user should treat the results of calculations using these formulae with caution, being aware that in reality numerous factors as discussed in Clause 5 both alter the magnitude of these characteristic harmonics, and create non-characteristic harmonics.

The magnitude of the line side harmonic converter current I_n, for each characteristic harmonic order n, is given by:

$$I_n = F_n \cdot \frac{U_{\text{valve}}}{U_{\text{line}}} \cdot N_{\text{b}} \cdot \frac{1}{n} \cdot \frac{\sqrt{6}}{\pi} \cdot I_{\text{d}} \tag{B.1}$$

where F_n is an attenuation factor given by:

$$F_n = \frac{1}{2\varepsilon} \cdot \sqrt{A^2 + B^2 - 2 \cdot A \cdot B \cdot \cos(2\alpha + u)} \tag{B.2}$$

with A and B being auxiliary functions:

$$A = \frac{1}{n+1} \cdot \sin(n+1)\frac{u}{2} \tag{B.3}$$

$$B = \frac{1}{n-1} \cdot \sin(n-1)\frac{u}{2} \tag{B.4}$$

and where ε is the relative inductive voltage drop due to commutation, given by:

$$\varepsilon = dx_N \cdot \frac{I_d}{I_{dN}} \cdot \frac{U_{dioN}}{U_{dio}} \tag{B.5}$$

For operation at nominal no-load direct voltage, the above formulae simplify to become:

$$I_n = F_n \cdot \frac{U_{valve}}{U_{line}} \cdot N_b \cdot \frac{1}{n} \cdot \frac{\sqrt{6}}{\pi} \cdot I_{dN} \tag{B.6}$$

and

$$F_n = \frac{1}{2dx_N} \cdot \sqrt{A^2 + B^2 - 2 \cdot A \cdot B \cdot \cos(2\alpha + u)} \tag{B.7}$$

where

I_n	is the AC system side harmonic current (A);
n	is the order of harmonics $n = (kp) \pm 1$, p = pulse number, $k = 1, 2, 3, \ldots$;
N_b	is the number of 6-pulse bridges comprising the converter;
U_valve	is the valve side transformer voltage rating at actual tap (kV);
U_line	is the AC line side transformer voltage rating at actual tap (kV);
U_dioN	is the nominal no-load direct voltage (V);
U_dio	is the actual no-load direct voltage (V);
I_dN	is the nominal direct current (A);
I_d	is the actual direct current (A);
ε	is the inductive voltage drop due to commutation (p.u.);
d_xN	is the relative inductive voltage drop at nominal conditions;
F_n	is the attenuation factor (p.u.);
α	is the firing/extinction angle of converter (°);
μ	is the overlap angle (°).

Annex C
(informative)

Definition of telephone interference parameters

C.1 General

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

C.2 Criteria according to European practice

The following criteria are commonly in use in countries following European practice.

a) Telephone harmonic form factor, THFF

$$\mathrm{THFF}=\sqrt{\sum_{n=1}^{n=N}\left(\frac{U_n}{U}\cdot F_n\right)^2} \tag{C.1}$$

where

U_n is the component at harmonic n of the disturbing voltage;

N is the maximum harmonic number to be considered;

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

$$F_n=\frac{p_n\cdot n\cdot f_\mathrm{o}}{800} \tag{C.2}$$

where

p_n is the psophometric weighting factor;

f_o is the fundamental frequency (50 Hz).

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

b) Equivalent disturbing current I_p is defined, according to CCITT, by:

$$I_\mathrm{p}=\frac{1}{P_{800}}\cdot\sqrt{\sum_f\left(h_f\cdot p_f\cdot I_f\right)^2} \tag{C.3}$$

where

I_f is the component at frequency f of the current causing the disturbance;

p_f is the psophometric weighting factor at frequency f;

h_f is a factor which is function of frequency and which takes into account the type of coupling between the lines concerned. By convention h_{800} = 1.

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

balanced component: $$I_{pe} = \frac{1}{16} \cdot \sqrt{\sum_{n=1}^{n=N} (n \cdot p_n \cdot I_n)^2} \quad \text{(C.4)}$$

where

I_n is the balanced component of the current in the phase conductors at harmonic n;

n is the harmonic order;

N is the maximum harmonic number to be considered;

h_f is set equal to f/800 Hz and is accordingly replaced by n/16 in the above formula. This frequency weighting is suitable for interference caused by earth capacitance unbalance of the telephone cable.

and

residual component: $$I_{rpe} = \frac{1}{16} \cdot \sqrt{\sum_{n=1}^{n=N} (n \cdot p_n \cdot I_{rn})^2} \quad \text{(C.5)}$$

where

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

The equivalent disturbing current has been used for few projects but there is no published information on specified limits. However, reference [5] provides some indicative figures for a typical transmission line, based on the Finnish experience. The figures are:

7 A < I_{pe} < 20 A

1 A < I_{rpe} < 3 A

C.3 Criteria according to North American practice

The following criteria are commonly in use in countries following North American practice.

a) Telephone interference factor, TIF:

$$TIF = \frac{\sqrt{\sum_{n=1}^{n=N} (U_n W_n)^2}}{U_1} \quad \text{(C.6)}$$

where

U_n is the single frequency RMS voltage at harmonic n;

N is the maximum harmonic number to be considered;

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

W_n is the single frequency TIF weighting at harmonic n:

$W_n = C_n 5 n f_0$

where

C_n is the C-message weighting factor;

n is the harmonic order;

f_0 is the fundamental frequency (60 Hz).

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

Typical requirements of TIF are between 15 and 50.

b) IT product:

$$\mathrm{IT}=\sqrt{\sum_{n=1}^{n=N}\left(I_n W_n\right)^2} \tag{C.7}$$

where

I_n is the single frequency RMS current at harmonic n;

N is the maximum harmonic number to be considered;

W_n is the single frequency TIF weighting at harmonic n: $W_n = C_n 5nf_\mathrm{o}$.

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

c) Equivalent disturbing current:

$$I_{eq}=\sqrt{\sum_{n=1}^{N}\left(H_n \cdot C_n \cdot I_n\right)^2} \tag{C.8}$$

where

I_n is the effective disturbing current at harmonic n (generally corresponding to residual mode current);

N is the maximum harmonic number to be considered;

C_n is the C-message weighting factor;

H_n is the weighting factor normalized to reference frequency (1 000 Hz) that accounts for the frequency dependence of mutual coupling, shielding and communication circuit balance at harmonic *n*.

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

$$I_n=\sqrt{\left(I_{rn}\right)^2+\left(K_b \cdot I_{bn} \cdot I_{bn}\right)^2} \tag{C.9}$$

where

I_rn is the total residual mode current at harmonic n;

I_bn is the balanced mode current at harmonic n;

K_b is the ratio of balanced mode coupling to the residual mode coupling at reference frequency.

The equivalent disturbing current has rarely been used as telephone interference requirement for an AC line feeding an HVDC system. In one instance of its application, limit values in the range 150 mA to 800 mA were specified. The equivalent disturbing current concept has also been used for DC transmission lines for which past experience has indicated that values in the 0,1 A to 1,0 A range are typical for normal operation.

C.4 Discussion

The American and European definitions are very similar. Indeed, the C-message and psophometric weighting factors are nearly identical. Except for these factors, the TIF and THFF differ only by a constant ratio of 4 000 (that is, 5 n f_o versus n f_o / 800).

Similarly, the American I_{eq} concept is a variation of the European I_p where the reference frequency and the weighting factor are changed to the American standard. The IT can be considered as a special case of I_{eq} for which the H_n factor is linear with frequency and normalized at 1 000 Hz. For this special case, the ratio between IT and I_{eq} is 5 000.

The linear frequency dependence assumption for H_n is generally considered adequate for standard telephone cable systems and typical exposure characteristics. However the IT concept is conventionally calculated with balanced mode harmonic currents only. The I_{eq} concept has the advantage of considering both balanced modes and residual mode induction and may be set to fit the needs of a particular project, where the linear frequency dependency assumption is not considered valid (due to high soil resistivity for example), by defining a H_n factor which reflects the particular project characteristics [4].

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

The definitions of TIF and THFF above, are as stated in [6] and use as a reference the total voltage derived as the root-mean-square sum of the fundamental and all harmonics. However, most HVDC specifications use instead the nominal fundamental frequency voltage, or the actual fundamental frequency voltage relevant to the operating conditions. Whichever is intended to be used should be stated clearly, for the reasons discussed in 4.2.3.

The maximum harmonic order to consider for the calculation should be higher than that for the calculation of harmonic voltage distortion because of the relative weight of the higher harmonic orders and the coupling characteristics. Theoretically, up to 5 000 Hz should be considered; but, in practice, many specifications have asked for only up to the 50th harmonic (see 4.2.3).

Annex D
(informative)

Equivalent frequency deviation

For a single-tuned, high quality factor filter, an equivalent frequency deviation corresponding to the detuning may be defined as:

$$\delta = \frac{\Delta f}{f_0} + \frac{1}{2}\left[\frac{\Delta C}{C_N} + \frac{\Delta L}{L_N}\right]$$

or

$$\Delta f_{\mathrm{eq}} = \Delta f + f_0 \cdot \frac{1}{2}\left[\frac{\Delta C}{C_N} + \frac{\Delta L}{L_N}\right]$$

where

δ is the equivalent frequency deviation [p.u. of nominal, f_{n}];

Δf_{eq} is the equivalent frequency deviation [Hz];

f_0 is the nominal AC fundamental frequency (50 Hz or 60 Hz) [Hz];

Δf is the fundamental frequency deviation from nominal [Hz];

$\frac{\Delta C}{C_N}$ is the relative capacitance deviation from nominal [p.u];

$\frac{\Delta L}{L_N}$ is the relative inductance deviation from nominal [p.u.].

The maximum and minimum equivalent frequencies to be used for performance calculations will be:

$$f = f_0 \pm \Delta f_{\mathrm{eq}}$$

$$f_{\mathrm{max}} = f_0 + \Delta f_{\mathrm{eq}}$$

$$f_{\mathrm{min}} = f_0 - \Delta f_{\mathrm{eq}}$$

The performance requirements should be met for the frequency range from f_{max} to f_{min}. For conventional filter schemes, the highest harmonic level will usually be found for f_{max} or f_{min}.

Annex E
(informative)

Reactive power management

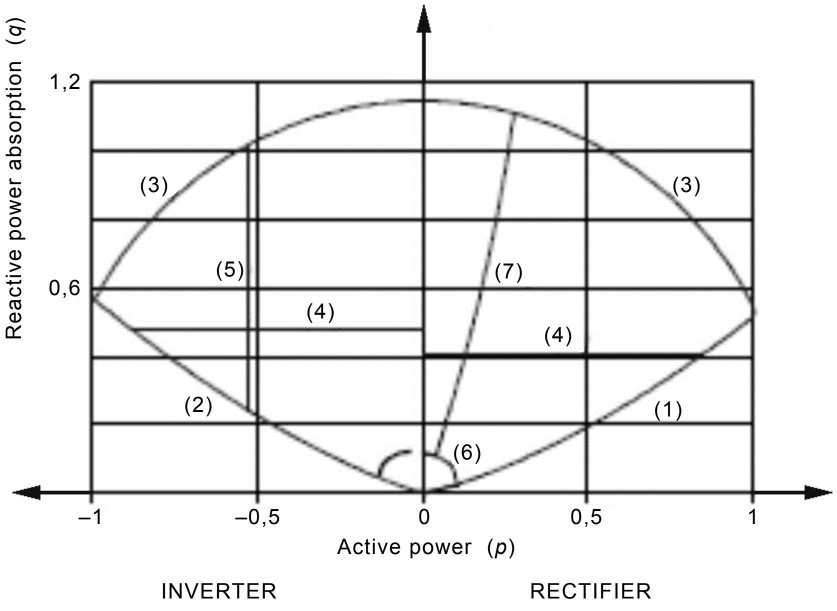
E.1 HVDC converter reactive power capability

E.1.1 Steady-state capability

The converter reactive power capability, which is a function of different operating parameters of the converter, is discussed in detail in [26]. Some relevant extracts from this reference are reproduced here.

For steady-state operation with increased reactive power, it is assumed that the operation goes on for an infinite time and the reactive power is controlled in such a way that it affects only one converter station or one AC network at a time. Also, the reactive power absorption capability in steady state is rather limited.

A natural property of a line-commutated converter is to absorb reactive power, whether operating as a rectifier or an inverter. Figure E.1 shows reactive power absorption capability of a converter under different control strategies. This diagram is valid for given voltage conditions of the AC network and the tap selected on the tap-changing transformer. Parameters p and q are per unit values related to the nominal active DC power.



Key

(1) constant DC voltage control and minimum control angle (α_{min})

(2) constant minimum control angle (γ_{min})

(3) constant DC current control

(4) constant reactive power control

(5) constant active power control

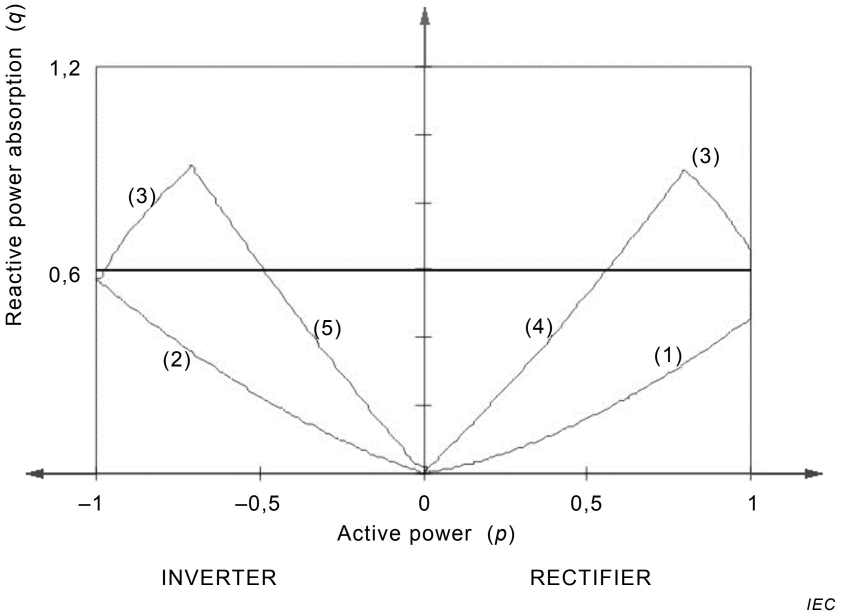
(6) minimum direct current

(7) maximum control angle (α_{max})

Figure E.1 – Capability diagram of a converter under different control strategies

Within the area enclosed by the curves (1), (2) and (3), the converter controls, in theory, can be made to act very fast, if necessary, in order to improve the operation of the combined AC/DC system. Additional control strategies, as shown in the figure, can be implemented to act on converter AC or/and DC variables to control the flow of active and reactive power, the AC voltage or the frequency.

Figure E.2 shows an example of the specially designed increased reactive power absorption capability of a converter designed for normally used control strategies. This represents a converter designed for an increased reactive absorption for α_{max} = 35°, γ_{max} = 40° and $U_{\text{diomax}} = 1{,}2U_{\text{dioN}}$. In this figure, the rectifier maximum limit is composed of the maximum ($\alpha+u$) curve, the maximum U_{dio} (ideal no-load direct voltage which is equal to $\frac{3\sqrt{2}}{\pi}U_{V,L-L}$) curve, the maximum apparent power curve, and the vertical line at p = 1,0 p.u. corresponds to the rated direct current. For the inverter, the maximum limit is defined by the maximum U_{dio} and the maximum apparent power curves and the minimum limit is the minimum γ curve.



Key

(1) constant DC voltage control and minimum control angle (α_{min})

(2) constant minimum control angle (γ_{min})

(3) constant DC current control

(4) maximum control angle (α_{max})

(5) maximum control angle (γ_{max})

Figure E.2 – Converter capability with γ_{min} = 17°, γ_{max} = 40°, α_{min} = 5°, α_{max} = 35° and $U_{\text{diomax}} = 1{,}2U_{\text{dioN}}$

From the above it is seen that a DC converter station can be designed to operate with very little reactive power injection into the connected AC network. However, the increased reactive power absorption mode of operation has the following disadvantages.

a) Increased control angles require that the AC voltage on the valve side should be increased, in order to retain normal DC voltage and full transmission capacity. This means the valves should be designed for higher voltage than for a normal optimum design. This will
    - have direct impact on the valve prices and converter losses as the number of thyristors and other components in the valves will increase,

- cause increase in commutation overshoots and hence increase in the cost of valve arresters,
- increase the cost of valve damping circuits as the components will have to be rated for higher power dissipation, and
- increase the valve cooling capacity as the cooling system will have to be designed for higher power dissipation.

However, even for long distance transmission, some of the reactive power control features described above can be made available without increasing U_{dio} and overdimensioning the thyristor valves. For example, an HVDC scheme can have certain overcurrent capability (even with redundant cooling system in service) and it could be designed in such way that DC voltage is not required to remain constant for this operating mode. Gezhouba-Shanghai, for example, has a DC voltage range between 475 kV and 525 kV for reactive power control mode up to nominal operation.

b) The increased reactive power at rated active power also means an increased apparent power and by this an increased rating of the converter transformer.

c) Operation with large control angles at rated current leads to an increased amount of harmonics on both the AC and the DC side, and this results in more expensive AC and DC filters.

d) Frequent variation of U_{dio} by stepping the tap-changer leads to increased demands for maintenance on the tap-changer. However, there could also be a possibility to operate HVDC converters at constant U_{dio} over the whole range of operation. This increases firing angles slightly in partial range, but the range of the tap-changer and expected cycles of tap-changer operation are lower and improve reliability and maintenance intervals.

E.1.2 Temporary capability

Transient or short time operation with increased reactive power consumption can be performed with much higher control angles because the HVDC valves are tested with 90° control angle and high current for a period ranging from 0,5 min to 1 min. Figures E.3 and E.4 show the reactive power absorption as a function of control angles for rectifier and inverter, respectively. These curves are calculated with constant I_{d} as a parameter and with $U_{\text{dio}} = U_{\text{dioN}}$. These curves show that the converter has about the same reactive power absorption at low DC current as for high DC current and normal control angles. This feature is very useful in situations such as those discussed in 7.4.

As the converter transformer tap-changer can not be operated in the duration of a transient, typically less than 5 s, the other converter station is also affected as the direct voltage is decreased when α or γ is increased. Thus, in order to maintain constant active power, the decrease in the direct voltage is compensated by an increase in the direct current.

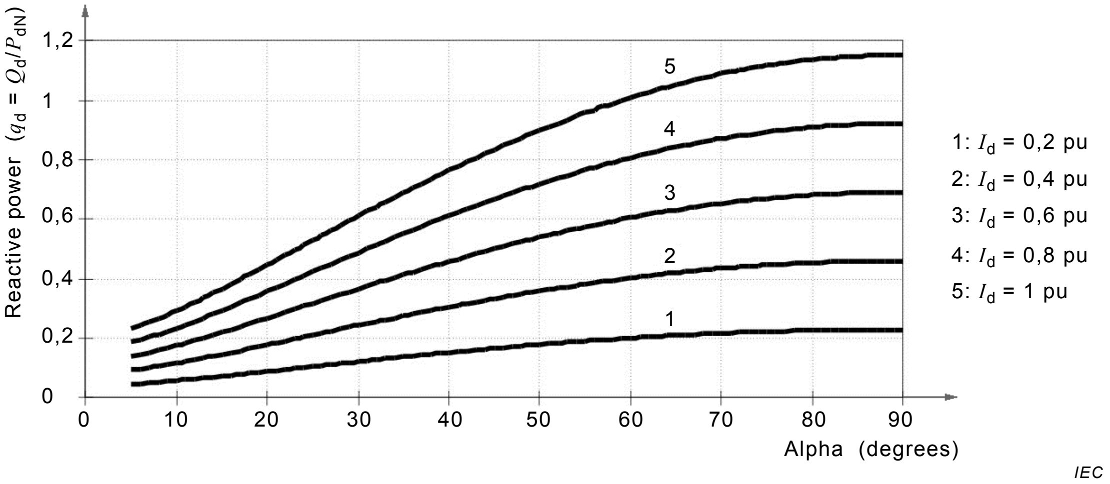


Figure E.3 – Reactive power absorption of a rectifier as a function of α with $U_{dio} = U_{dioN}$, d_x = 9,4 % and d_r = 0,2 %

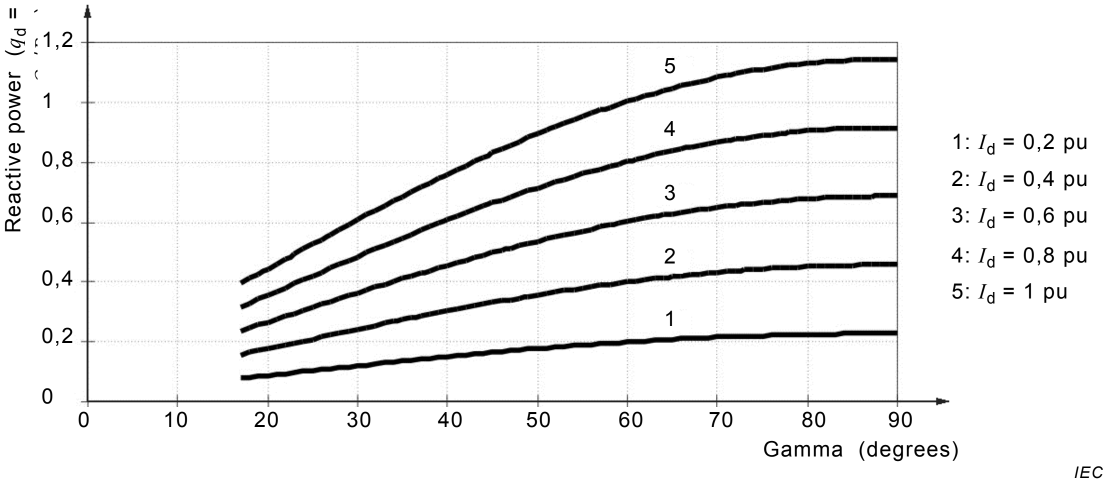


Figure E.4 – Reactive power absorption of a inverter as a function of γ with $U_{dio} = U_{dioN}$, d_x = 9,4 % and d_r = 0,2 %

E.2 Converter Q-V control near switching points

This kind of converter control, which makes use of temporary reactive power absorption capability of the converter as discussed in E.1, is required in the following situations:

- when the reactive power interchange is such that the export to AC system violates the specified limit at switching and narrow band of DC power around switching points under certain conditions such as maximum AC system voltage and frequency and positive capacitor tolerance;
- when the step change in voltage requirement is stringent;
- for smooth control of AC voltage, when this is to be controlled with the help of sub-bank/banks;
- for reducing temporary overvoltages.

Though technically it could be possible to meet the stipulated requirements in respect of the above by choosing smaller filter banks/sub-banks, economic reasons may not permit this. Instead, the converter is used to keep the step change in voltage and reactive power export within the stipulated limits. This is achieved by forcing the converter to temporarily increase its firing/extinction angles as simultaneously as possible with the switching event. Thus, if a sub-bank/bank is going to be disconnected, the total reactive compensation is reduced and a negative step in AC voltage will result. If the reactive absorption could be reduced at the same time, the total effect on the voltage would be small.

Such a procedure, which is of greatest interest for the inverter, requires that γ is suddenly decreased, which of course is not possible if the converters are operating in γ_{min} mode. However, if the sub-bank/bank switching is planned, it is possible to prepare for it by slowly increasing γ by a suitable amount and then, when the bank is switched off, γ is decreased again to the nominal value in a step. When a filter sub-bank/bank is switched in, no preparation is needed. The control angle γ can be suddenly increased to increase the converter reactive absorption when the sub-bank/bank is switched and then slowly brought back to its nominal value.

When the reactive power or the AC voltage is controlled by only using sub-banks/banks, the control is discrete and the converter reactive power is exactly compensated only in a limited number of points with the range from zero to rated power. The combination of sub-bank/bank switching and converter control, in such a way that the sub-bank/bank switching itself always gives reactive over-compensation which is completely or partially eliminated by converter control with increased α or γ, can be a practical solution when a low interchange of reactive power with the AC network is required.

E.3 Step-change in voltage on switching a filter

The step change in voltage, ΔU, at the commutating busbar after switching a filter sub-bank/bank is dependent on both the strength of the AC network and the control mode of HVDC converter. If ΔQ_0 is the reactive power in Mvar at nominal voltage, U_0, of the filter sub-bank/bank being switched and U is pre-switching voltage at the commutating busbar, then the resulting step change in voltage after switching of the filter sub-bank/bank will be given by:

$$\Delta U = \Delta Q_0 \left(\frac{U}{U_0} \right)^2 \cdot VSF$$

where VSF is the voltage sensitivity factor of the combined AC network and HVDC converter. VSF is defined as the incremental AC voltage variation, dU, due to a small reactive power, dQ, injected into the commutating busbar for a given active power level of the HVDC converter, i.e.

$$VSF = \frac{dU}{dQ}\,.$$

For the special case of a blocked HVDC converter, the above formula for ΔU will take the following form:

$$\Delta U = \frac{\Delta Q_0}{\left(S - Q_{c0}\right)} \cdot U$$

where S is three phase short circuit Mva at the commutating busbar and Q_{c0} is the total (including the Mvar of the filter sub-bank/bank being switched) filter sub-banks/banks Mvar at nominal voltage connected after switching.

This formula can also be used to estimate S by recording the pre-switching voltage, U, and post-switching change in voltage, ΔU as follows:

$$S = \frac{\Delta Q_0}{\Delta U} \cdot U + Q_{c0}$$

Annex F
(informative)

Voltage sourced converters

F.1 General

Since the late 1990s, a new class of HVDC converter has emerged, based on self-commutated semiconductor devices such as insulated gate bipolar transistors (IGBTs) instead of thyristors. The resulting class of converters is known as voltage sourced converters (VSCs) and differs fundamentally from line-commutated converters (LCCs, which are current-sourced) in several key respects.

VSC technology for HVDC is still relatively immature and is developing rapidly; nevertheless Annex F is intended to provide a short overview of the main types of VSC insofar as they are relevant for AC harmonic filtering.

Because of the wide control range and turn-off capability, the reactive power consumption or generation of such converters can be controlled to any desired value within the operation range, virtually independently of the active power transmission. No external reactive compensation is therefore necessary.

The harmonic spectra produced by a VSC are quite different to those produced by an LCC, generally tending to produce lower levels of low-order harmonics but higher levels of harmonics in the kHz region. Depending on the VSC technology chosen, some harmonic filtering may still be necessary. The amount of required filtering is, however, quite small compared with the needs of an LCC scheme.

The customer’s specification should state the required harmonic performance limits and the reactive power interchange requirements for the converter station. The AC system impedance model should also reflect the different characteristics of AC networks at higher frequencies and the higher damping typical of low- and medium-voltage systems.

In general, the normal performance requirements of a conventional specification can be followed, but taking into account a wider frequency range for telephone interference, such as 5 kHz instead of the typical 2,5 kHz to 3,0 kHz.

If AC filters are required, they should follow the normal requirements of a conventional specification with respect to equipment specification, testing, loss calculation, audible noise and protection.

F.2 Two-level converter with PWM

The first type of VSC used in HVDC was the "2-level converter" shown in Figure F.1. The circuit is conceptually similar to the classic 6-pulse Graetz bridge that forms the basis of a line-commutated converter. The main differences are that the valves consist of series-connected IGBTs (which can be turned both on and off) instead of series-connected thyristors (which can only be turned on) and the DC voltage is smoothed by a large capactor instead of the DC current being smoothed by a large inductor.

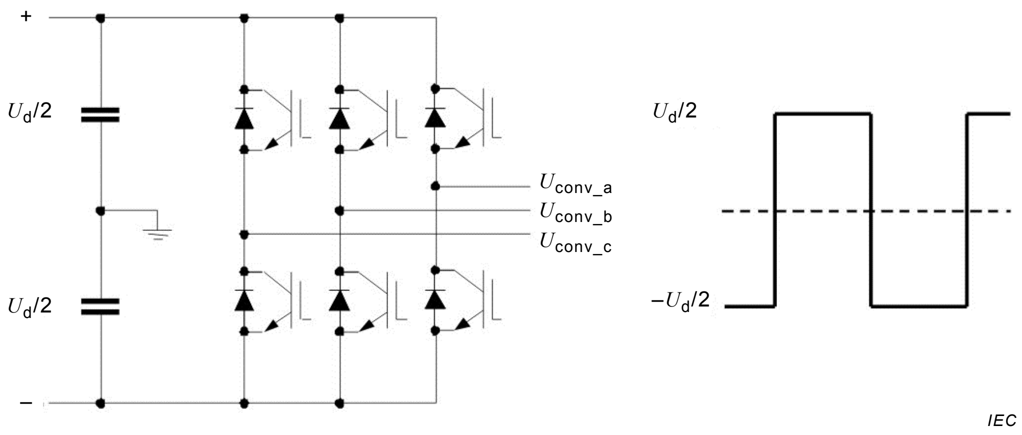


Figure F.1 – Simplified representation of a 2-level voltage sourced converter

The AC output of such a converter is a square-wave voltage that alternates between $+U_d/2$ and $-U_d/2$. If switched only at fundamental frequency, such a square-wave voltage would give unacceptably large amounts of odd characteristic harmonics, so to improve the harmonic voltage quality, pulse-width modulation (PWM) is used, as illustrated in Figure F.2.

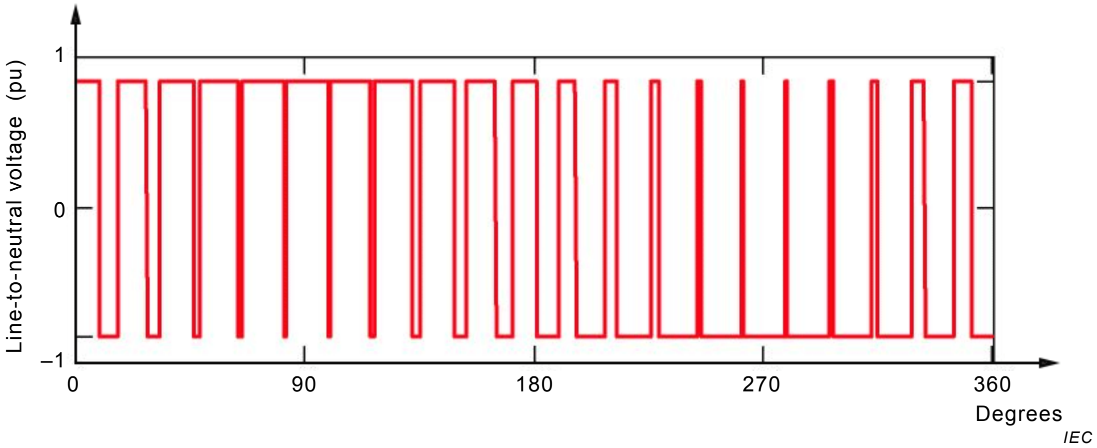


Figure F.2 – Single-phase AC output for 2-level converter with PWM switching at 21 times fundamental frequency

By setting the switching frequency sufficiently high, the residual high-frequency harmonics can become small enough for filtering not to be needed, but this comes at an unacceptable price in terms of power losses. Consequently, the choice of switching frequency is a compromise between losses and harmonic generation, with the optimum typically lying in the range 1 kHz to 2 kHz. With practical choices of switching frequency, the magnitude of these high-frequency harmonics is such that a filter will generally still be required, for example a high pass filter tuned to the switching frequency.

Despite the apparent similarity between the main power circuit of an LCC and that of a 2-level VSC, the harmonic spectra produced by the converters are quite different. With a 2-level VSC, the harmonics will, ideally, occur at and around multiples of the converter switching frequency. For example, if the switching frequency is 1,5 kHz, then the dominant or "characteristic" harmonics will occur in the vicinity of 1,5, 3,0, 4,5, ... kHz. The choice of PWM pattern will have an impact on the harmonic generation, for example on the phase and magnitude of the harmonics.

At present 2-level converters are still used for some VSC HVDC schemes with power ratings up to the low hundreds of megawatts, but for higher power ratings they have largely been replaced by multilevel converters (see F.4).

F.3 Three-level converter with PWM

In an attempt to improve on the poor harmonic performance of the 2-level converter, some HVDC schemes have been built with a variant, the 3-level converter, one example of which is shown in Figure F.3.

The AC output voltage of such converters is not limited to the two discrete values $+U_d/2$ and $-U_d/2$ but can also be in a third, zero state. As a result, the harmonic performance for a given switching frequency is slightly improved, but PWM is still required (Figure F.4). However, the converter is physically quite difficult to realize and the control is more challenging than that of the 2-level converter, so the uptake of this converter topology has been limited for HVDC.

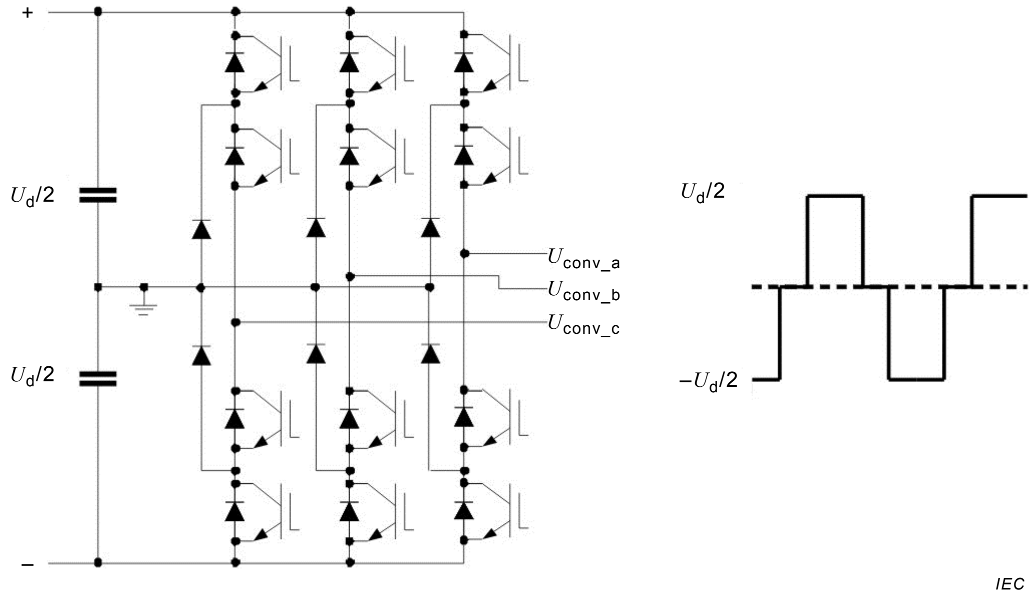


Figure F.3 – Simplified representation of a 3-level voltage sourced converter

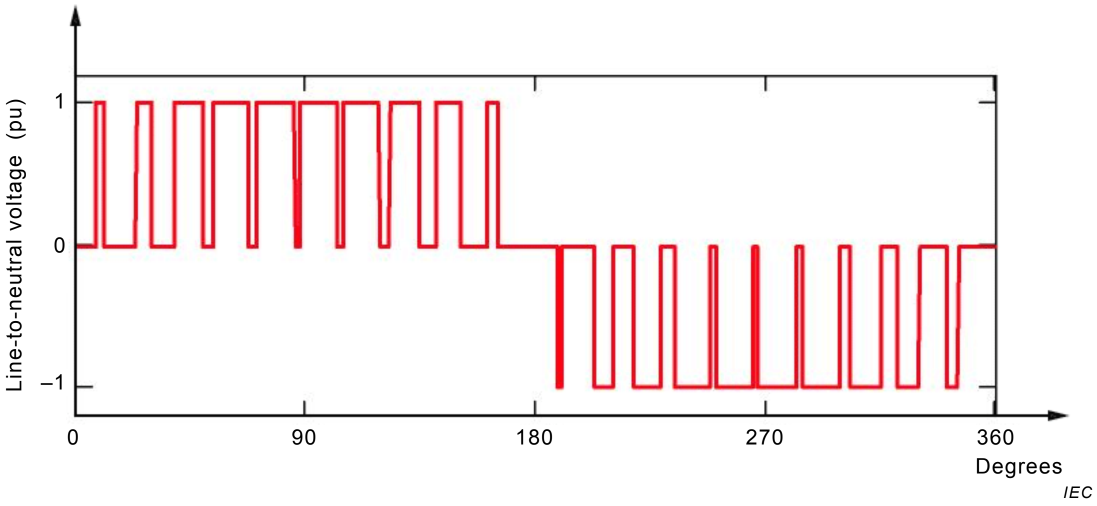


Figure F.4 – Single-phase AC output for 3-level converter with PWM switching at 21 times fundamental frequency

F.4 Multi-level converters

Various types of converter, collectively known as "multi-level converters" can produce more than three discrete AC voltage states. Of the many possible multi-level converters, the most promising for HVDC applications is currently the so-called "modular multilevel converter" (MMC) family.

In the MMC, each valve is a controllable voltage source (Figure F.5) instead of a controllable switch. These converters use a large number of relatively small, two-terminal controllable voltage sources connected in series in each valve. Two series-connected valves form a "phase unit" and are used to connect each AC phase to the DC terminals of the converter. Each phase unit can synthesize a stepped voltage waveform that can be controlled in amplitude and phase independently of the other phase units in the converter.

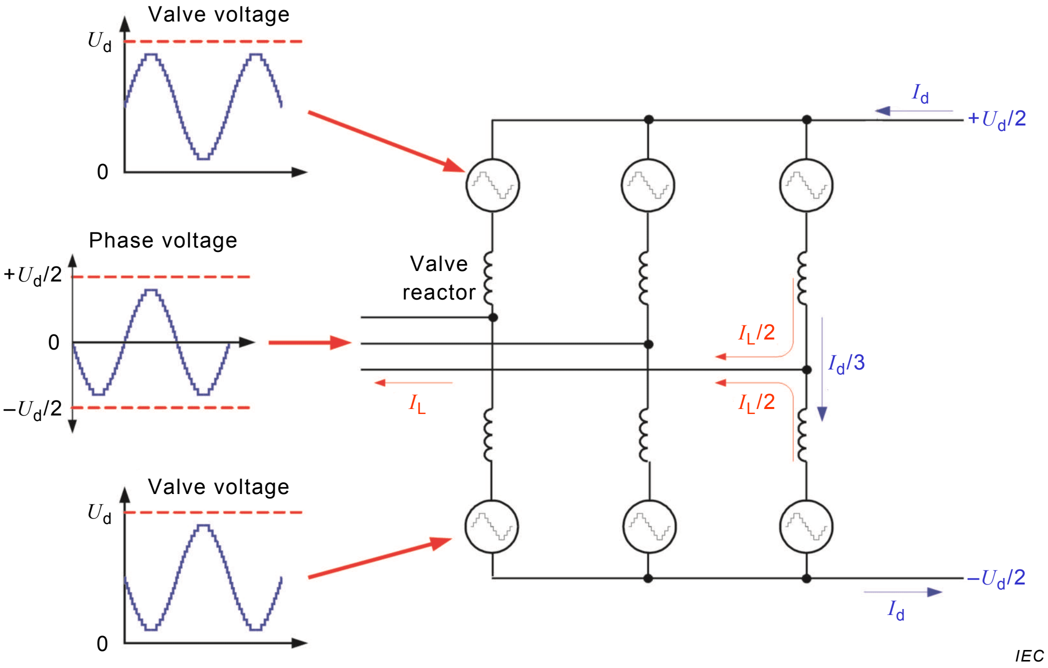


Figure F.5 – Basic operation of the MMC converters

The output voltage produced by each valve is an offset sinusoidal voltage with a mean value equal to half the DC line to line voltage, and the two valves in each phase unit are controlled such that the AC components of their output voltages are 180° out of phase. In this way, the sum of the two valve voltages is almost a pure DC voltage (equal to the DC line to line voltage of the converter), and the difference between the two valve voltages is an almost pure AC voltage representing the AC output voltage of the converter.

The sum of the two valve voltages in each phase needs to be controlled accurately, in real time, to be equal to the converter DC voltage. However, since the complete converter consists of three phase units connected in parallel to a common DC bus, "valve reactors" need to be connected in series with each valve in order to prevent excessive circulating currents between phases caused by the inevitable slight errors in controlling the DC voltages of the three phase arms.

Each building block of an MMC consists of either two or four controllable semiconductor switches and a large storage capactor which is either bypassed or inserted into the circuit depending on the states of the semiconductor switches.

Many MMCs use only single IGBTs as the switching elements, avoiding the need for direct series connection of IGBTs. In such cases, several hundred "submodules" are normally needed in series in each valve. The resulting AC voltage waveform can also have several hundred discrete states (depending on the modulation strategy chosen). The MMC can therefore produce very low levels of harmonics.

However, there is a variant of the MMC known as the “cascaded two level converter” or CTL. The CTL converter is distinguished from other types of MMC by using two or more IGBTs connected in series in each switch position. The CTL produces fewer, larger steps in the AC output voltage than MMC variants that do not require series connection, but the levels of generated harmonics are still low.

Figure F.6 shows the main differences between the MMC with submodules (without series-connection of IGBTs), and the CTL, illustrated for the most common variant of each type, the "half-bridge" configuration.

In general, the MMC family is capable of delivering excellent harmonic performance, depending mainly on the number of submodules or cells per valve and the modulation strategy used. As a result, in many cases, filtering is not required. Nevertheless, the need for a small amount of filtering, for example to prevent a resonance condition with the AC network, cannot be excluded until detailed studies have been performed.

F.5 Modelling of VSCs for harmonic filtering purposes

For the most part, the calculation processes established for designing AC filters for LCC HVDC schemes, as described in Clauses 6 to 9 can also be used for VSC schemes. However, there are some important differences compared with LCC schemes that need to be taken into account. The most significant of these are the following.

a) VSCs tend to produce harmonics at higher frequencies than do LCCs. With 2-level and 3-level converters, the harmonic spectra tend to be tightly bunched around multiples of the PWM (switching) frequency but with MMCs the spectra can be quite broad, with characteristics resembling "white noise" – although there can still be distinct peaks corresponding to the PWM frequency (where used) or the clock cycle of the controller. Because of this, it is usually necessary to consider a higher range of frequencies (for example, up to 5 kHz instead of 2,5 kHz). The modelling of the AC network harmonic impedance also needs to consider this higher frequency range.

b) With VSCs, the harmonic spectra are largely a consequence of the control principles and modulation strategy used, and as a result are highly specific to a particular manufacturer’s design. This is in contrast to an LCC, where the characteristic harmonics can be predicted quite easily from well-known equations.

c) With VSCs, the harmonics produced on the AC side are best modelled by a voltage source behind an inductance, in contrast to LCCs which are approximated by a harmonic current source. As a result, the way the penetration of harmonics into the AC system is modelled needs to be different, as illustrated in Figure F.7.

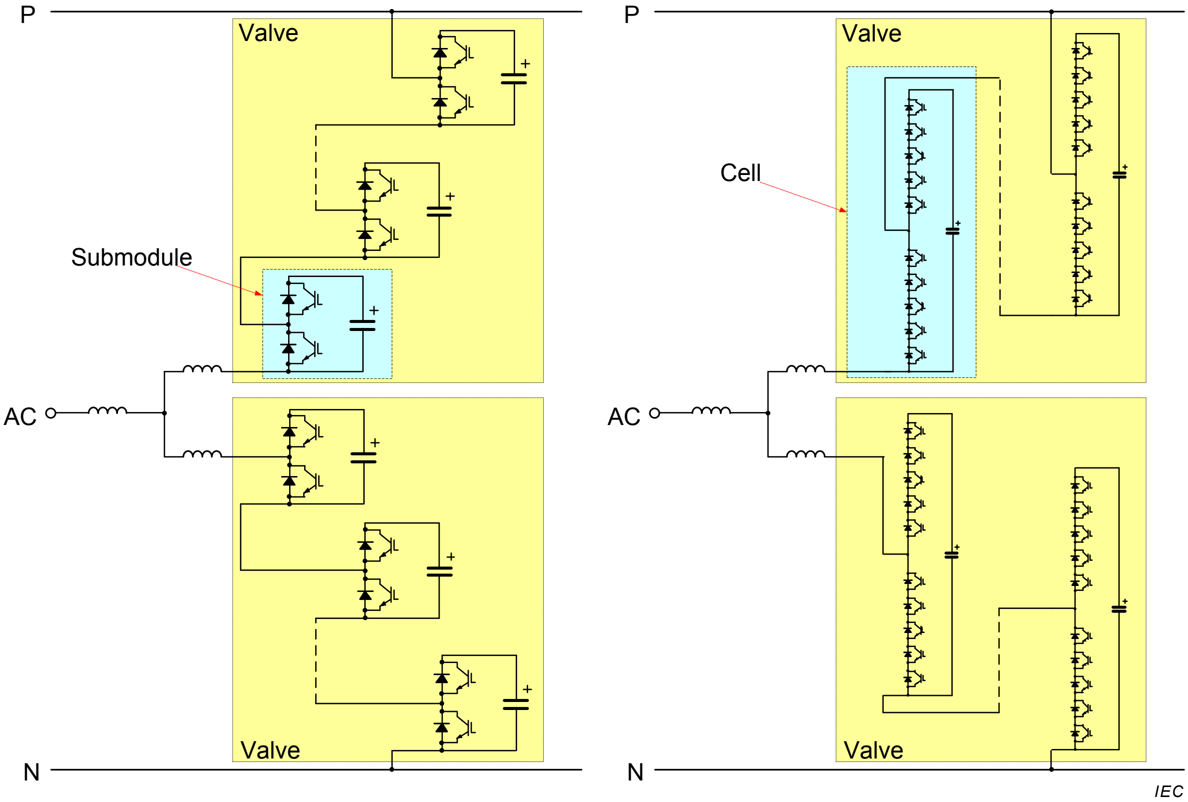


Figure F.6 – Phase unit of the modular multi-level converter (MMC) in basic half-bridge, without series-connected IGBTs (left) and the cascaded two level (CTL) converter with series-connected IGBTs (right)

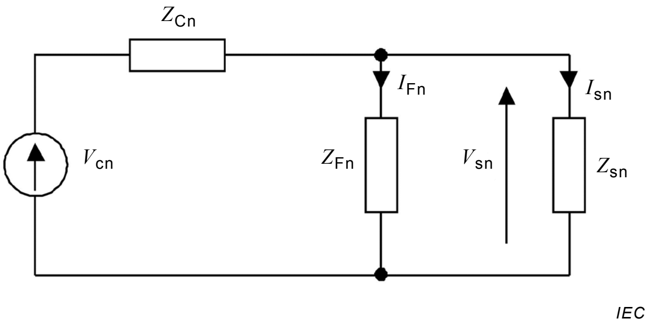


Figure F.7 – Representation of a voltage sourced converter as a harmonic voltage source behind an inductance

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