



BSI Standards Publication

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

Part 4: Equipment

National foreword

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TECHNICAL REPORT

**High-voltage direct current (HVDC) systems – Guidance to the specification and design evaluation of AC filters –
Part 4: Equipment**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.200

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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

Part 4: Equipment

FOREWORD

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

This edition includes the following significant technical changes with respect to IEC TR 62001:

- a) Clauses 10 to 16, 18, Annexes F and G have been expanded and supplemented.

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

Enquiry draft	Report on voting
22F/379/DTR	22F/385A/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- withdrawn,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.

¹ To be published.

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 4: Equipment

1 Scope

This part of IEC TR 62001, which is a Technical Report, provides guidance on the basic data of AC side filters for high-voltage direct current (HVDC) systems and their components such as ratings, power losses, design issues and special applications, protection, seismic requirements, equipment design and test parameters.

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.

It concerns the "conventional" AC filter technology and line-commutated HVDC converters.

2 Steady state rating

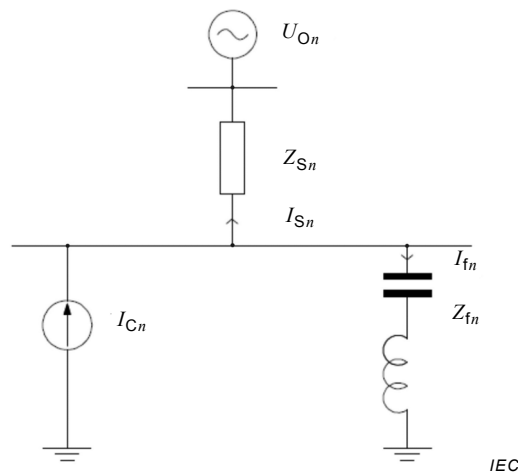
2.1 General

The calculation of the steady state ratings of the harmonic filter equipment is the responsibility of the contractor. Clause 2 gives guidance on the calculation of equipment rating parameters and the different factors to be considered in the studies. It is the responsibility of the customer to provide the appropriate system and environmental data and also to clarify the operational conditions, such as filter outages and network contingencies, which need to be taken into account.

2.2 Calculation method

2.2.1 General

Steady state rating of filter equipment is based on a solution of the following circuit which represents the HVDC converter, the filter banks and the AC supply system. See Figure 1.



NOTE The symbols used in this figure are explained after Formula (1).

Figure 1 – Circuit for rating evaluation

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

Using the principle of superposition, Formulae (1) and (2) can be used to evaluate the contribution to the harmonic filter current of order n from these two sources.

b) HVDC converter:

$$I_{fn}^i = \frac{Z_{sn}}{Z_{sn} + Z_{fn}} \cdot I_{cn} \quad (1)$$

where

- I_{fn}^i is the filter harmonic current from the converter;
- I_{cn} is the converter harmonic current;
- I_{sn} is the system harmonic current;
- Z_{fn} is the filter harmonic impedance;
- Z_{sn} is the network harmonic impedance.

c) AC supply network:

$$I_{fn}^{ii} = \frac{U_{on}}{Z_{sn} + Z_{fn}} \quad (2)$$

where

- I_{fn}^{ii} is the filter harmonic current from the system;
- U_{on} is the existing system harmonic voltage.

The definition of network impedance is described in 2.5.

To solve Formulae (1) and (2), the following independent variables need to be known.

- The harmonic current (I_{cn}) produced by the rectifier or inverter of the HVDC station. It is calculated for all harmonics (see IEC TR 62001-1:2016, Clause 5). This evaluation should consider the worst-case operating conditions which can occur in steady state conditions, i.e. for periods in excess of 1 min. The extreme tolerance range of key parameters, for

example converter transformer impedances or operating range of the tap changer, needs to be taken into account. Harmonic interaction phenomena as discussed in IEC TR 62001-3:—, Clause 3, should also be taken into account.

- The pre-existing system harmonic voltage, as discussed in 2.2.2.
- The harmonic impedance of AC network (Z_{sn}), as discussed in IEC TR 62001-1:2016, 7.3. Note that different values of Z_{sn} can be defined for the calculation of I_{fn}^i and I_{fn}^{ii} , depending on how the pre-existing harmonic distortion is specified (see 2.2.3).

The harmonic impedance of the filter (Z_{fn}) needs to take account of the de-tuning and tolerance factors discussed in 2.4.

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 (interharmonics) will be at frequencies which are harmonics of the fundamental frequency of the remote AC system, and will be transferred across the link. Interharmonics may give rise to specific problems not found with true harmonics, such as

- a) interference with ripple control systems, and
- b) light flicker due to the low frequency amplitude modulation caused by the beating of a harmonic frequency with an adjacent interharmonic.

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.

The effect of interharmonics (see IEC TR 62001-1:2016, 4.2.7), although small, should also be taken into account in the calculation of filter component rating.

2.2.2 AC system pre-existing harmonics

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

To model a multiplicity of harmonic current sources in a detailed network model is impractical for the purposes of filter design. Therefore, it is proposed that a Thévenin equivalent voltage source is modelled behind the AC system impedance, as shown in Figure 1, to create an open circuit voltage distortion at the filter busbar, i.e. the level of distortion prior to connection of the filters. The magnitude of the individual harmonic voltages can be based on measurements or on the performance limits, but limited by a value of total harmonic distortion. This approach provides a more realistic assessment of the contribution to equipment rating caused by ambient distortion levels.

2.2.3 Combination of converter and pre-existing harmonics

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

$$I_{fn} = \sqrt{I_{fn}^{i^2} + I_{fn}^{ii^2}} \quad (3)$$

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

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

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

2.2.4 Equipment rating calculations

2.2.4.1 General

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

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

2.2.4.2 Capacitors

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

$$I_c = \sqrt{\sum_{n=1}^{n=49} (I_{fcn})^2} \quad (4)$$

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

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

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

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

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

$$U_m = \sum_{n=1}^{n=49} I_{fcn} \cdot X_{fcn} \quad (5)$$

where

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

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

A more realistic method is to use Formula (5) but to assume that only a limited number of harmonics are considered to be in resonance (e.g. the two largest contributions) and all other harmonics are evaluated against an open-circuit system or fixed impedance. However, this method still assumes that all harmonics are in phase, which will not be the case in practice.

In a further approach, all harmonics are assumed to be in resonance, but Formula (5) is modified such that only the fundamental and largest harmonic component are summed arithmetically. All other harmonic components of voltage are summed on an RSS basis and added arithmetically to the sum of fundamental and largest harmonic components to evaluate U_m . This "quasi-quadratic" summation thus takes account of the natural phase angle diversity between individual harmonic components:

$$U_m = U_1 + U_{no} + \sqrt{\sum_{n=2}^{n=49} U_n^2} \quad (6)$$

where

U_1 is the fundamental component;

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

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

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

$$U_m = U_1 + \sqrt{\sum_{n=2}^{n=49} U_n^2} \quad (7)$$

This is less conservative than the method used in Formulae (5) or (6), but has been substantially applied in practice and has proved adequate. The assumption of resonance at all harmonics, and the use of worst-case assumptions regarding tolerances in the calculations, provide some margin in the capacitor rating, which is assumed to cover the eventuality of phasor summation being more severe than is implied by Formula (7).

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

$$U_N = U_m / (1,0 \text{ to } 1,1) \quad (8)$$

However, the value of U_N calculated from Formula (8) should be at least equal to the maximum fundamental frequency voltage on the capacitor bank. If this is not the case, then the assigned U_N should be the maximum fundamental frequency voltage.

NOTE In the above definitions, U_n is used to denote a harmonic component ($n = 1$ to 49) and U_N is used to denote the capacitor bank rated voltage (as per IEC 60871-1).

When low voltage capacitor banks are installed in filters, for example in double or triple frequency filters, the rated voltages calculated as above may not be suitable. For such banks, the rated voltage may have to be increased to ensure that the banks can withstand the transient stresses, as discussed in 3.4.

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

$$Q_c = \sum_{n=1}^{n=49} I_{fcn}^2 X_{fcn} \quad (9)$$

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

$$Q_c' = U_N^2 / X_{fc1} \quad (10)$$

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

2.2.4.3 Reactors

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

$$I_1 = \sqrt{\sum_{n=1}^{n=49} I_{fn}^2} \quad (11)$$

$$Q_1 = \sum_{n=1}^{n=49} I_{fn}^2 X_{fn} \quad (12)$$

where

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

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

$$U_1 = \sqrt{2} \sum_{n=1}^{n=49} I_{fn} X_{fn} \quad (13)$$

During routine switching and when the filter is subjected to fast-fronted surges, very high transient stresses can appear across the reactors. As discussed in Clause 3, these need to be allowed for in the reactor design and hence included in the equipment specification.

2.2.4.4 Resistors

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

$$I_r = \sqrt{\sum_{n=1}^{n=49} I_{fn}^2} \quad (14)$$

The power rating of the resistor is therefore

$$P_r = \sum_{n=1}^{n=49} I_{fn}^2 R \quad (15)$$

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

$$U_r = \sqrt{2} \sum_{n=1}^{n=49} I_{fn} R \quad (16)$$

This figure, U_N , should become the basis for the determination of the creepage distance for resistor internal support insulation (see also 2.2.5). Although the choice of an arithmetic summation of fundamental and harmonic voltages appears to be unduly pessimistic and in conflict with the general approach to insulator creepage distances, the internal insulators are subjected to unusual operating conditions. The effects of atmospheric pollution can result in significant built-up of deposits on insulator surfaces which are not subject to washing by rainfall. During normal operation the insulators experience elevated temperatures, typically 100 °C to 300 °C, increasing the risk of surface flashovers. Maintenance has typically been performed on an annual basis, but some customers are now extending maintenance intervals to 3 years. Thus a conservative approach on the above basis for internal insulation creepage may be necessary.

During routine switching of damped filters and under fast-fronted surge conditions as discussed in Clause 3, the resistors can experience very high stresses. These predicted stress levels need to be included in the equipment specification.

2.2.5 Application of voltage ratings

The voltage ratings for the equipment as defined above can be used to define the minimum level of the maximum continuous operating voltage (MCOV) for surge arresters. The full duty on the surge arresters will be determined from the studies described in Clause 3.

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

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

2.3 AC network conditions

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

2.4 De-tuning effects

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

- Equipment tolerances: The extreme guaranteed range of tolerances should be used for rating studies. Unlike other effects considered here which are subject to cyclic variation, any effects due to manufacturing tolerance will persist for the equipment's lifetime.
- Frequency variation: Whereas normal anticipated frequency variations should be used for performance, extreme variations should be considered for rating. These extreme conditions may be specified as continuous or for specific time periods. The former will define continuous ratings whereas the latter will define short time overloads.
- Temperature variation: Whereas maximum and minimum average temperature should be considered for performance studies, absolute maximum and minimum temperatures should be considered for equipment rating. As discussed previously, the temperature will affect the capacitance value and hence will de-tune the filter. In addition, cold temperature conditions are of particular importance for capacitor banks, especially for energization conditions.
- Tap position on reactors: Adjustable taps are often provided on reactors for tuned filters to offset capacitor tolerance effects. The effect of tap position on the tuning of the filter and its subsequent rating should be considered.
- Capacitor unit failure detection schemes normally have three set levels: alarm only (1st stage), alarm plus impending timed trip (2nd stage) and instantaneous trip (3rd stage). Capacitor bank rating caters for the loading condition when operating under the 2nd stage alarm. In some cases, only a 2 stage scheme will be implemented, and rating needs only consider the 1st alarm stage.
- When multiple tuned banks of the same type are installed, it is important to consider possible circulating currents between the banks due to differences in tuning. Such currents will need to be considered for filter equipment rating. However, measures to control this effect, such as the use of paralleling buses, can be used if the filter layout is suitable.

2.5 Network impedance for rating calculations

The representation of the AC network harmonic impedance (Z_{sn}) for the purposes of equipment rating should be different from that used for predicting performance. As discussed in IEC TR 62001-1:2016, 7.3, a number of different distinct geometric shapes can be used to define the harmonic impedance for performance studies. This data should cover all normal and plausible contingency network operating conditions and load conditions anticipated throughout the lifetime of the equipment. For rating studies, a wider range of network conditions may be used to ensure that equipment ratings are adequate for the anticipated lifetime. This can be achieved by specifying larger search areas and/or increased system angles. It is important to ensure that realistic levels of minimum resistance are considered to avoid undamped resonance conditions occurring.

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

In some cases, the zero sequence impedance of the system may be required to evaluate the voltage unbalance on the converter bus following un-symmetrical faults, such as a line to earth fault. The resultant negative sequence voltage component is used for the purpose of short time (0,1 s to 1,5 s, depending on line protection philosophy and auto-reclose features) rating of low order, mainly 3rd, harmonic filters.

2.6 Outages

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

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

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

3 Transient stresses and rating

3.1 General

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

Such studies will require a transient analysis computer program, such as EMTP, ATP, NETOMAC or EMTDC², to model system parameters, including non-linear aspects such as transformer saturation and surge arrester characteristics. The results of these studies will indicate whether the calculated stresses exceed the equipment's capability. In such cases, the equipment rating will need to be increased to accommodate the predicted duty. Alternatively, surge arresters can be used to limit the transient duty on the equipment.

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

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

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

The transient studies discussed in Clause 3 are the responsibility of the contractor; however, the customer should define in the specification any minimum requirements for contract stage studies. For example, the customer should define any specific network and scheme operating conditions that are considered. Additionally, any fault scenarios to be studied should be stated together with details of any auto-reclose schemes that operate on the supply network.

² EMTP, ATP, NETOMAC and EMTDC are examples of suitable products available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of these products.

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

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

- The first, as discussed in 3.2, comprises switching impulse studies such as routine filter switching, auto-reclose events, system faults and fault application/clearance involving DC link load rejection.
- The second group, as discussed in 3.3, includes fast fronted waveform studies, such as lightning strikes and bus flashovers which result in rapid discharge of capacitor banks.

3.2 Switching impulse studies

3.2.1 Energization and switching

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

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

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

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

Typical examples of the transient waveforms which occur during routine filter switching are shown in Figures 2 and 3:

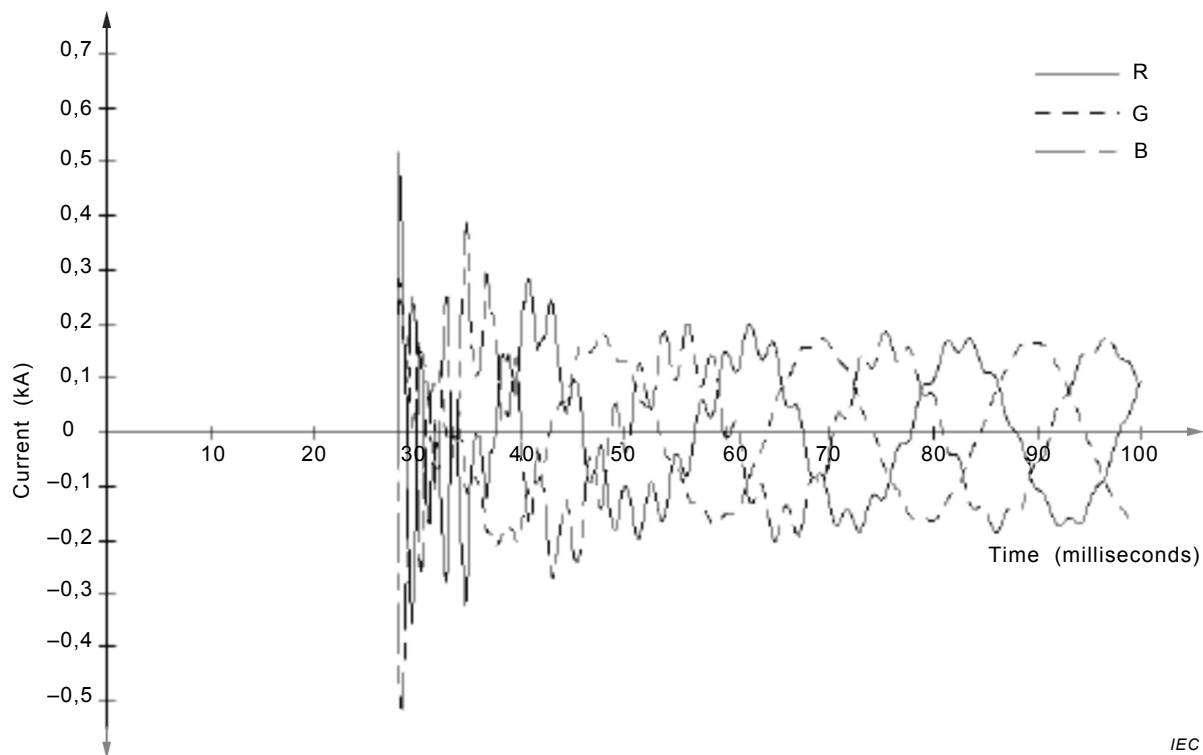


Figure 2 – Inrush current into a 12/24th double-tuned filter

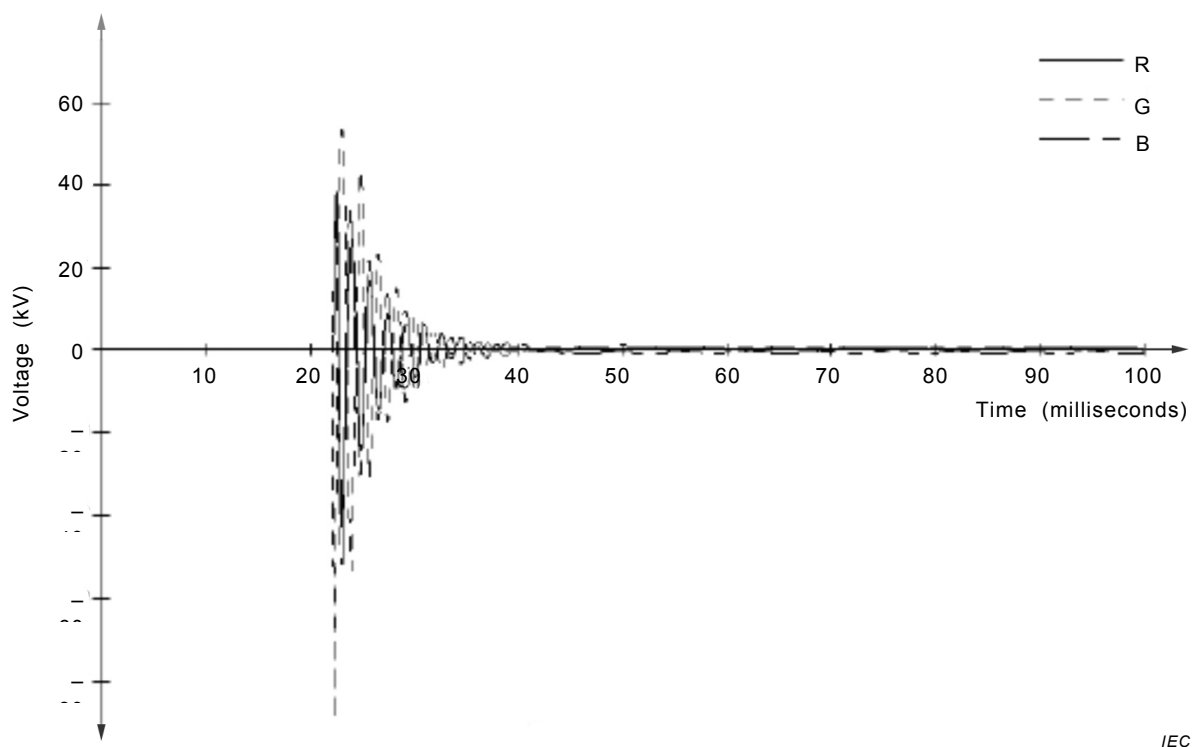


Figure 3 – Voltage across the low voltage capacitor of a 12/24th double-tuned filter at switch-on

3.2.2 Faults external to the filter

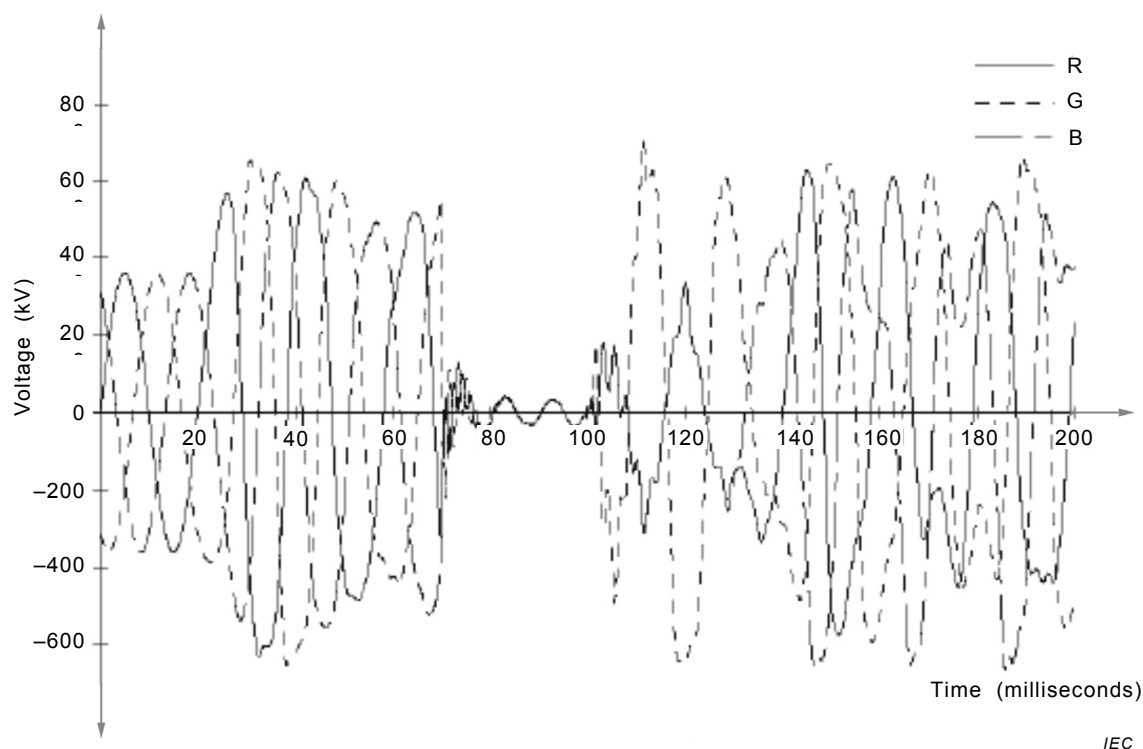
Faults on the AC supply network can encompass both isolated faults, such as line-line and three phase faults, and faults involving earth, whether single phase, two phase or three

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

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

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

Figure 4 illustrates a combination of fault conditions: at 25 ms, the HVDC converter is blocked resulting in a severe overvoltage on the main filter capacitor bank. At 70 ms, a 3-phase bus fault is simulated which is cleared at 100 ms, a reduced period to minimize computation time, resulting in a severe transient overvoltage on the capacitor bank.



IEC

Figure 4 – Voltage across the HV capacitor bank of a 12/24th double-tuned filter under fault conditions

3.2.3 Faults internal to the filter

The effects of faults within the filter will depend upon the type of filter and the electrical arrangement of the filter. Using a single-tuned filter, as an example, a line-earth fault at the HV terminal of the capacitor bank will apply the instantaneous DC voltage on the capacitor directly across the low voltage reactor and any surge arrester, as discussed further in 3.3.2. A line-earth fault at the capacitor LV terminal would simply bypass the reactor and result in very little change in current in the capacitor bank which is the predominant filter impedance.

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

Although the fault conditions considered above are normally worst-case conditions for filter transient duty, for more complex filter configurations, other credible internal fault conditions would need to be studied.

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

3.2.4 Transformer inrush currents

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

Studies involving transformer inrush currents need to model the transformer in some detail including both linear and non-linear, for example saturation, inductances. The losses within the transformer, which will dictate the decay of inrush currents, should be modelled.

3.3 Fast fronted waveform studies

3.3.1 General

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

3.3.2 Lightning strikes

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

3.3.3 Busbar flashover studies

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

3.4 Insulation co-ordination

From the results of the studies described in 3.2 and 3.3, the overall insulation co-ordination of the filter can be derived. The need for surge arresters distributed within the filters will be determined. In most cases the choice between the arrester's protective voltage level and energy absorption capability and the voltage withstand capability of the protected equipment will be based on relative costs. Although low voltage station class arresters are relatively inexpensive, if significant energy absorption capability is required then parallel housings are needed and costs may be high. In such cases increasing equipment insulation levels may be the optimum solution.

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

There are a number of possible connection arrangements for filters with embedded surge arresters. Typical examples for double-tuned filters are shown in Figure 5.

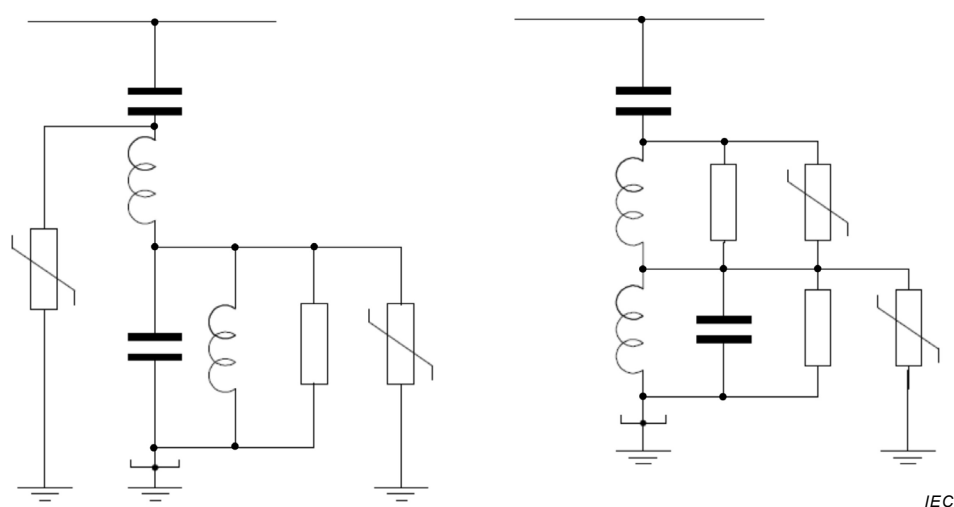


Figure 5 – Typical arrangements of surge arresters

The results of the lightning and switching impulse studies will confirm that the required margins between the equipment withstand levels and the corresponding surge arrester protective levels, according to IEC 60099-4 or the customer's specification, are achieved. Note that margins in excess of those normally specified by IEC 60099-4 will result in increased filter costs. The energy absorption duty imposed on surge arresters by lightning surges will normally be less than the energy arising from the fault conditions discussed in 3.2.

In the case of the double- and triple-tuned filters, the results of the fault studies or switching studies usually indicate that the maximum transient voltages on the low voltage capacitors greatly exceed the steady state ratings as derived in 9.2.2. As the cost of such banks is usually low, increasing the rated voltage such that overload capability complies with predicted maximum transient voltage can give an acceptable design without incurring the need for special designs of surge arresters.

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

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

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

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

4 Losses

4.1 Background

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

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

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

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

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

The customer should therefore be aware that by following the guidance of IEEE Std 1198 (now withdrawn), he may not obtain a realistic estimate of probable AC filter losses. Furthermore, as the losses pertaining to different AC filter designs vary substantially, he will also not be able to make a fair comparison of the designs offered by different bidders.

The following items therefore offer guidance to the customer, where appropriate, on how to define alternative conditions for calculating AC filter losses. It is suggested that the filter

losses should be calculated both under the nominal conditions of IEC 61803, and under the suggested alternative conditions described in 4.4 below, in order to provide all the information needed by the customer.

4.2 AC filter component losses

4.2.1 General

The AC filters comprise capacitive, inductive and often resistive elements, all of which contribute to the total losses of the converter station. As part of the filter design process, account will have been taken of the loss capitalization in choosing the number and type of filters required. Clause 6 in IEC TR 62001-1:2016 highlights the various advantages and disadvantages of tuned filters, which typically produce low losses, against damped filters which generally produce higher losses on a per Mvar basis.

Further discussion with respect to overall filter component costs, taking into account their losses, is provided in CIGRE WG 14.03.

4.2.2 Filter/shunt capacitor losses

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

Table 1 details the subdivision of losses within a typical all-film type capacitor unit.

Table 1 – Typical losses in an all-film capacitor unit

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

The above losses are typical; guaranteed values would be in the order of 20 % higher. Fuseless capacitors have similar dielectric, discharge resistor and connection losses to those stated above. In respect of externally fused units, the losses due to the external fuse are additional to those quoted. With improvements in the choice and design of dielectric, it is noteworthy that the losses in the capacitor unit discharge resistor now tend to dominate. The requirements and duty for such resistors are not within the direct control of the capacitor manufacturer, but are dictated by discharge time requirements imposed by international standards or the customer's own requirements. If an enhanced discharge requirement is specified then the losses as shown in Table 1 will be higher.

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

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

$$P_c = \tan(\delta) \cdot \sum_{n=1}^{n=N} I_{cn}^2 \times X_{cn} \quad (17)$$

where

- P_c is the filter capacitor loss;
- n is the harmonic number;
- N is the maximum harmonic order (typically 49);
- I_{cn} is the calculated current in the capacitor at harmonic order n ;
- X_{cn} is the capacitor reactance at harmonic order n ;
- $\tan(\delta)$ is the tangent of the capacitor loss angle.

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

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

4.3 Reactor and resistor losses

4.3.1 General

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

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

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

For damped filters, the choice of reactor Q factor at harmonic frequencies is generally unimportant in terms of achieving the required performance and optimal rating, leaving the filter designer a relatively free choice in specifying Q factor at fundamental frequency to satisfy the balance between reactor cost and losses. However, for double-tuned damped filters, the choice of reactor Q factor at harmonic frequencies requires careful optimization to

minimize the effects of circulating harmonic currents within the filter itself. Increasing the Q factor may in certain circumstances increase the harmonic losses in the reactors.

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

The power losses in the reactor can be determined by

$$P_l = \sum_{n=1}^{n=N} \frac{I_{ln}^2 \times X_{ln}}{Q_n} \quad (18)$$

where

P_l is the filter reactor loss;

n is the harmonic number;

N is the maximum harmonic order (typically 49);

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

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

Q_n is the reactor Q factor at harmonic order n .

4.3.2 Filter resistor losses

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

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

The power losses in the resistor can be determined by

$$P_r = \sum_{n=1}^{n=N} I_{rn}^2 \times R_n \quad (19)$$

where

P_r is the filter resistor loss;

n is the harmonic number;

N is the maximum harmonic order (typically 49);

R_n is the resistance in ohms at harmonic order n ;

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

4.3.3 Shunt reactor losses

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 is required to satisfy harmonic performance

requirements. The derivation of their losses is similar to that in conventional transmission system applications. It should be noted that in general their losses at harmonic frequencies are almost negligible in comparison to those at fundamental frequency.

4.4 Criteria for loss evaluation

4.4.1 General

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

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

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

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

These are discussed in turn in 4.4.2 to 4.4.7.

4.4.2 Fundamental frequency AC filter busbar voltage

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

4.4.3 Fundamental frequency and ambient temperature

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

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

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