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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

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Part 4: Equipment

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

This second edition cancels and replaces the first edition published in 2016. This edition constitutes a technical revision. This edition includes the following significant technical change with respect to the previous edition:

a) general updating of the document to reflect changes in practice;
b) Annex A deleted as its content is covered by IEC 61803.

The text of this Technical Report is based on the following documents:

Draft	Report on voting
22F/615/DTR	22F/622B/RVDTR

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

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

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 document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

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- withdrawn,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

INTRODUCTION

The IEC TR 62001 series is structured in five parts:

IEC TR 62001-1 – 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.

IEC TR 62001-2 – Performance

This part deals with current-based interference criteria, field measurements and verification.

IEC TR 62001-3 – Modelling

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

IEC TR 62001-4 – 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.

IEC TR 62001-5 – AC side harmonics and appropriate harmonic limits for HVDC systems with voltage sourced converters (VSC)

This part concerns specific issues of AC filter design related to high-voltage direct current (VSC) systems with voltage sourced converters (HVDC).

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 LCC (line-commutated converter) HVDC but much of this applies to any filter equipment for VSC (voltage sourced converter) HVDC.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at https://www.iso.org/obp
- IEC Electropedia: available at http://www.electropedia.org/

4 Steady state rating

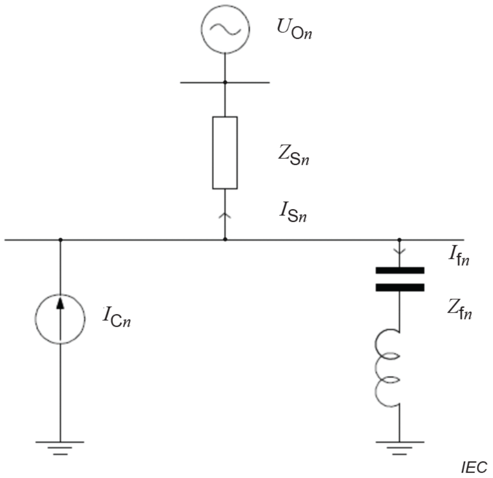
4.1 General

The calculation of the steady state ratings of the harmonic filter equipment is the responsibility of the contractor. Clause 4 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.

4.2 Calculation method

4.2.1 General

Steady state rating of filter equipment for an LCC HVDC system 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 in the key to 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, Formula (1) and Formula (2) can be used to evaluate the contribution to the harmonic filter current of order n from these two sources.

a) HVDC converter:

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

where

I^{i}_{fn} 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.

b) AC supply network:

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

where

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

U_{on} is the existing system harmonic voltage.

The definition of network impedance is described in 4.5.

To solve Formula (1) and Formula (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 [1][1] or CIGRE Technical Brochure 754 [2] for VSC using a harmonic voltage source). 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 [3] should also be taken into account.
- The pre-existing system harmonic voltage, as discussed in 4.2.2.
- The harmonic impedance of AC network (Z_{sn}), as discussed in IEC TR 62001-1 [1]. Note that different values of Z_{sn} can be defined for the calculation of I^{i}_{fn} and I^{ii}_{fn}, depending on how the pre-existing harmonic distortion is specified (see 4.2.3).

The harmonic impedance of the filter (Z_{fn}) needs to take account of the de-tuning and tolerance factors discussed in 4.4.

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 may either 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 [1]), although small, should also be taken into account in the calculation of filter component rating.

4.2.2 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. In many early HVDC projects this was accommodated not by direct calculation as shown in 4.2.1 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. Often 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.

IEC TR 61001-3 [3] contains a detailed discussion on alternative ways of handling pre-existing harmonics.

1 Numbers in square brackets refer to the Bibliography.

4.2.3 Combination of converter and pre-existing harmonics

As there is no fixed vectorial relationship between $I^{\mathrm{i}}_{\mathrm{f}n}$ and $I^{\mathrm{ii}}_{\mathrm{f}n}$, one option is that that these individual contributions to filter rating are summated on root sum square (RSS) basis at each harmonic:

$$I_{\mathrm{f}n} = \sqrt{I^{\mathrm{i}\,2}_{\mathrm{f}n} + I^{\mathrm{ii}\,2}_{\mathrm{f}n}} \tag{3}$$

Alternatively, the general summation law from IEC 61000-3-6 [4] may be used.

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.

4.2.4 Equipment rating calculations

4.2.4.1 General

The total filter current is derived as in 4.2.3 for each harmonic order of significant magnitude. Traditionally for LCC HVDC systems, the maximum harmonic order was generally taken as 49 or 50. However with the increasing prevalence of high power electronic equipment, higher values of the maximum harmonic order may be considered. For LCC 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.

The calculation of $I_{\mathrm{f}n}$ 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.

4.2.4.2 Capacitors

From the spectrum of currents in the capacitor bank ($I_{\mathrm{fc}n}$), the total RSS current can be calculated as

$$I_{\mathrm{c}} = \sqrt{\sum_{(n)-1}^{n=N} \left(I_{\mathrm{fc}n}\right)^2} \tag{4}$$

Typically, the capacitor unit bushings are the limiting factor for capacitor unit current.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

$$U_{\mathrm{m}} = \sum_{n=1}^{n=N} I_{\mathrm{fc}n} \cdot X_{\mathrm{fc}n} \tag{5}$$

where

$X_{\mathrm{fc}n}$ 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 components 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:

$$U_{\mathrm{m}} = U_1 + U_{no} + \sqrt{\sum_{n=2}^{n=N} {U_n}^2} \tag{6}$$

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.

$$U_{\mathrm{m}} = U_1 + \sqrt{\sum_{n=2}^{n=N} {U_n}^2} \tag{7}$$

This is less conservative than the method used in Formula (5) or Formula (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.

$$U_N = U_m / (1{,}0 - 1{,}1) \tag{8}$$

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 N) and U_N is used to denote the capacitor bank rated voltage (as per IEC 60871-1 [5]).

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 5.4.

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

$$Q_c = \sum_{n=1}^{n=N} I_{fcn}^{\ 2} \cdot X_{fcn} \tag{9}$$

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

$$Q_c' = U_N^{\ 2} / X_{fc1} \tag{10}$$

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.

4.2.4.3 Reactors

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

$$I_i = \sqrt{\sum_{n=1}^{n=N} I_{fln}^{\ 2}} \tag{11}$$

$$Q_l = \sum_{n=1}^{n=N} I_{fln}{}^2 \cdot X_{fln} \tag{12}$$

where

$X_{\mathrm{fl}n}$ 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 creepage voltage across the reactor should be specified as

$$U_\mathrm{l} = \sqrt{\sum_{n=1}^{n=N} \left(I_{\mathrm{fl}n} \cdot X_{\mathrm{fl}n}\right)^2} \tag{13}$$

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

4.2.4.4 Resistors

The thermal current loading can be expressed from the harmonic current ($I_{\mathrm{fr}n}$) spectrum as

$$I_\mathrm{r} = \sqrt{\sum_{n=1}^{n=N} I_{\mathrm{fr}n}{}^2} \tag{14}$$

The power rating of the resistor is therefore

$$P_\mathrm{r} = \sqrt{\sum_{n=1}^{n=N} I_{\mathrm{fr}n}{}^2 \cdot R} \tag{15}$$

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

$$U_\mathrm{r} = \sqrt{\sum_{n=1}^{n=N} \left(I_{\mathrm{fr}n} \cdot R_{\mathrm{fr}n}\right)^2} \tag{16}$$

This figure, U_r, should become the basis for the determination of the creepage distance for resistor internal support insulation (see also 4.2.5). 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 operate with maintenance intervals of up 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 5, the resistors can experience very high stresses. These predicted stress levels need to be included in the equipment specification.

4.2.5 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 5.

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.

4.3 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.

4.4 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 (1^{st} stage), alarm plus impending timed trip (2^{nd} stage) and instantaneous trip (3^{rd} stage). Capacitor bank rating caters for the loading condition when operating under the 2^{nd} stage alarm. In some cases, only a 2-stage scheme will be implemented, and rating needs only consider the 1^{st} 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.

4.5 Network impedance for rating calculations

The representation of the AC network harmonic impedance ($Z_{\mathrm{s}n}$) for the purposes of equipment rating should be different from that used for predicting performance. As discussed in IEC TR 62001-1 [1], 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 3^{rd}, harmonic filters.

4.6 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, the converter control system will typically reduce 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.

5 Transient stresses and rating

5.1 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 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. The studies should aim to determine the protective level in terms of protective equipment voltage rating and arrester energy rating.

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 the ratings of the low voltage filter components, as 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 5 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.

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 5.2, 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 5.3, includes fast fronted waveform studies, such as lightning strikes and bus flashovers which result in rapid discharge of capacitor banks.

5.2 Switching impulse studies

5.2.1 Energization and switching

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

Routine switching of filters, with other banks already in service, will be the most common transient duty on the filter components. The number of switching operations per annum may vary widely between schemes. For example, a long distance HVDC scheme designed for bulk power transmission may require very infrequent filter switching, whereas a back-to-back HVDC scheme with a reactive power control facility may switch filters frequently. An estimate of the number of switching events will be needed to accompany the transient results and should be included by the contractor in the individual equipment specifications. Frequent switching of filters is of particular importance for the capacitor banks as the high level of dielectric stress imposed during the transient event has an impact on the equipment lifetime. Standards on capacitor banks, such as IEC 60871 (all parts) [5] and IEEE Std 18™ [6] 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 Figure 2 and Figure 3:

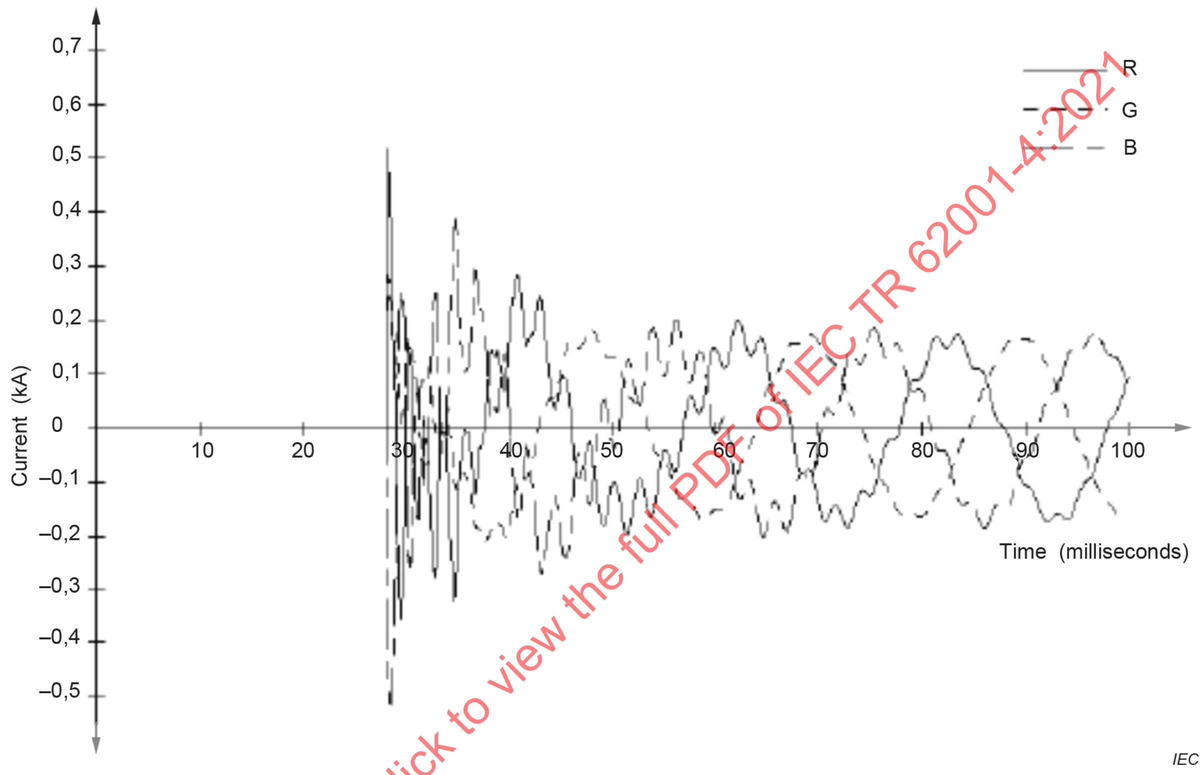


Figure 2 – Inrush current into a 12/24th double-tuned filter

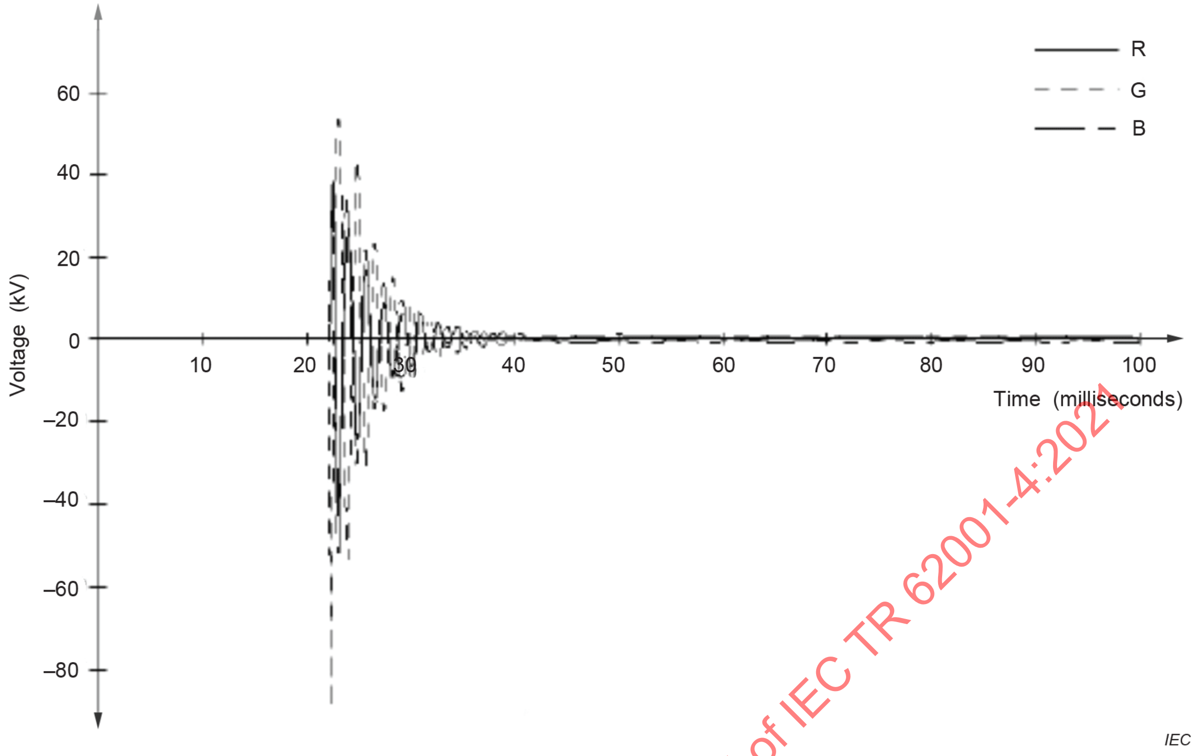


Figure 3 – Voltage across the low voltage capacitor of a 12/24th double-tuned filter at switch-on

5.2.2 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 three-phase bus fault is simulated which is cleared at 100 ms, a reduced period to minimize computation time, resulting in a severe transient overvoltage on the capacitor bank.

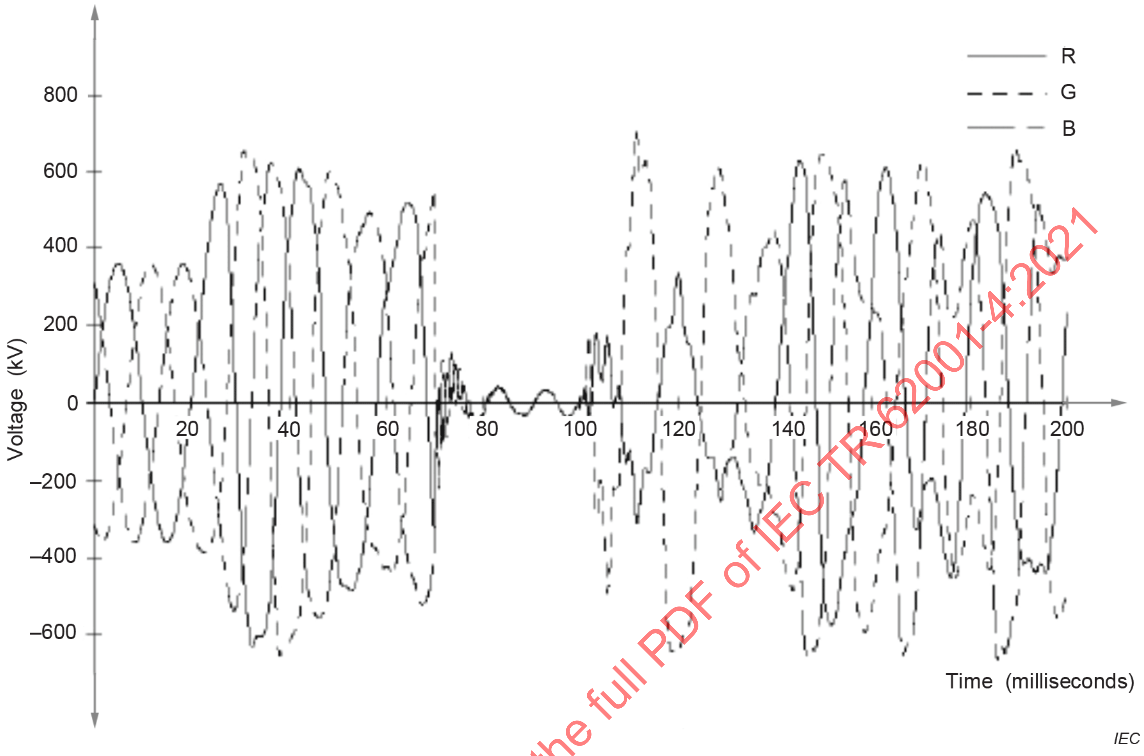


Figure 4 – Voltage across the HV capacitor bank of a 12/24th double-tuned filter under fault conditions

5.2.3 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 5.3.1. 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 5.2.2 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.

5.2.4 Transformer inrush currents

Energization of the converter transformer, or adjacent conventional transformers, can result in significant levels of inrush current that can be sustained for considerable periods of time. Such inrush currents can, however, be minimized by the application of pre-insertion resistors or point-on-wave switching which takes account of remnant flux, in which case the harmonic issues described below should be negligible. As unmitigated 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.

5.3 Fast fronted waveform studies

5.3.1 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.

5.3.2 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.

5.3.3 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.

5.4 Insulation co-ordination

From the results of the studies described in 5.2 and 5.3, 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.

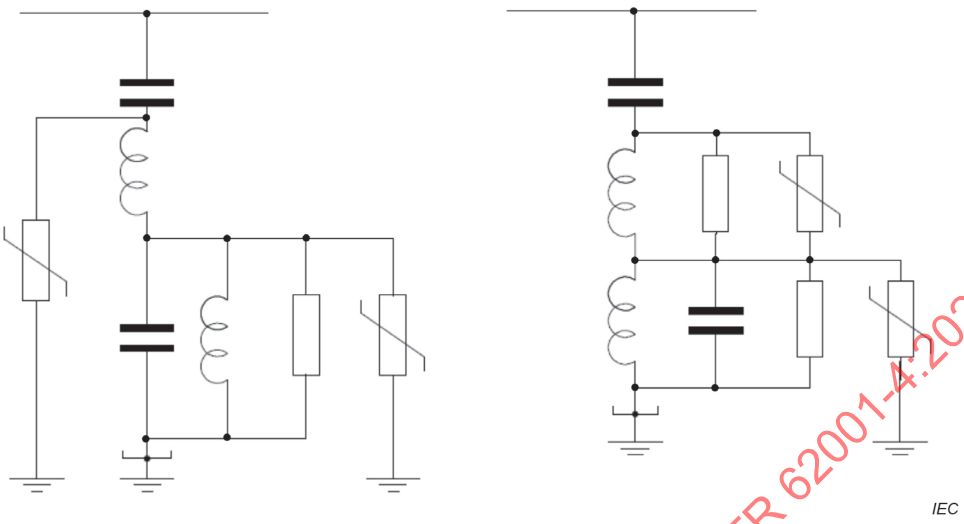


Figure 5 – Typical arrangements of surge arresters

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 [7] or the customer's specification, are achieved. Note that margins in excess of those normally specified by IEC 60099-4 [7] 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 5.2.

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 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.

6 Losses

6.1 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 IEC 61803 [8].

Harmonic filters associated with the AC side of LCC 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 [8], which proposes calculation of losses under essentially nominal conditions, which is a fair basis for most HVDC plants.

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.

Customers should therefore be aware that, by following the guidance of IEC 61803 [8], they may not obtain a realistic estimate of probable AC filter losses. Furthermore, as the losses pertaining to different AC filter designs vary substantially, they will also not be able to make a fair comparison of the designs offered by different bidders.

The information in Clause 6 therefore offers 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 [8], and under the suggested alternative conditions described in 6.4 below, in order to provide all the information needed by the customer.

6.2 AC filter component losses

6.2.1 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. IEC TR 62001-1:2021 [1], 7.4, 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 [9].

6.2.2 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 losses in Table 1 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:

$$P_{\mathrm{c}} = \tan(\delta) \cdot \sum_{n=1}^{n=N} I_{\mathrm{c}n}{}^{2} \cdot X_{\mathrm{c}n} \tag{17}$$

where

P_{c} is the filter capacitor loss;

n is the harmonic number;

N is the maximum harmonic order (typically 49 for LCC, may be higher for VSC);

$I_{\mathrm{c}n}$ is the calculated current in the capacitor at harmonic order n;

$X_{\mathrm{c}n}$ 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.

6.3 Reactor and resistor losses

6.3.1 General

Filter reactors (and where provided, resistors) are a major 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

$$P_{\text{l}} = \sum_{n=1}^{n=N} \frac{{I_{\text{l}n}}^2 \cdot X_{\text{l}n}}{Q_n} \tag{18}$$

where

P_{l} is the filter reactor loss;

n is the harmonic number;

N is the maximum harmonic order (typically 49 for LCC, may be higher for VSC);

$I_{\text{l}n}$ is the calculated current in the reactor at harmonic order n;

$X_{\text{l}n}$ is the reactor reactance at harmonic order n;

Q_n is the reactor Q factor at harmonic order n.

6.3.2 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

$$P_{\mathrm{r}} = \sum_{n=1}^{n=N} I_{\mathrm{r}n}^{\ 2} \cdot R_n \tag{19}$$

where

P_{r} is the filter resistor loss;

n is the harmonic number;

N is the maximum harmonic order (typically 49 for LCC, may be higher for VSC);

R_n is the resistance in ohms at harmonic order n;

$I_{\mathrm{r}n}$ is the calculated current in the resistor at harmonic order n.

6.3.3 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.

6.4 Criteria for loss evaluation

6.4.1 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 [8] 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 in 6.4.7.

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 6.4.2 to 6.4.7.

6.4.2 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.

6.4.3 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.

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

This should be in addition to the calculation method using nominal frequency and an ambient temperature of 20 °C (IEC 61803 [8]), which is of use in comparison of losses for the overall converter station.

6.4.4 AC system harmonic impedance

The choice of an appropriate system harmonic impedance for the calculation of losses is also a sensitive issue. HVDC project specifications have tended to indicate (and IEC 61803:2020, 5.3.1, [8] requires) that for loss assessment the AC system should be assumed to be open circuited "so that all [the converter] harmonic currents are considered to flow into the AC filters".

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

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

This calculation could be done instead of, or in addition to, the calculation with open circuited AC system.

6.4.5 Harmonic currents generated by the converter

IEC 61803 [8] and some HVDC project specifications recommend that the determination of AC filter losses should be based only on the characteristic harmonic currents generated by the converter and imply that non-characteristic harmonics should be neglected.

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

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

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

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

6.4.6 Pre-existing harmonic distortion

Whether the effects of pre-existing harmonic distortion should be included in the loss assessment or not largely depends on the requirements of the performance specification. If, in the assessment of performance, the effects of pre-existing harmonic distortion are to be neglected (see also IEC TR 62001-1 [1]), then it is also appropriate to neglect them in loss assessment. On the other hand, where the performance requirements state that pre-existing harmonic distortion should be included, losses should also be based on their consideration.

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

6.4.7 Anticipated load profile of the converter station

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

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

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

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

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

7 Design issues and special applications

7.1 General

Clause 7 provides some guidance regarding a selection of more advanced design issues and some special filter applications, always with reference to conventional passive AC filters. Other technologies, for example active filtering, are described in IEC TR 62001-1 [1].

Experience from numerous HVDC schemes is condensed in 7.2 to 7.6. The subjects discussed include topics which have arisen in a number of projects, as well as some more unusual applications.

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

7.2 Performance aspects

7.2.1 Low order harmonic filtering and resonance conditions with AC system

The mechanism of generating non-characteristic low-order harmonics is well known and described in IEC TR 62001-1 [1]. The particular influence of negative sequence voltage on the generation of 3rd harmonic is treated in IEC TR 62001-1 [1].

Harmonic AC filters tuned for the characteristic 12-pulse harmonics behave as a capacitive impedance at lower frequencies. By nature, the AC system harmonic impedance, which is in parallel with the filter impedance, creates parallel resonance phenomena at converter busbars. In some HVDC schemes, therefore, low-order harmonic filters have been installed to damp such resonance (reported in [10] and [11]) and to limit the distortion generated by some non-characteristic harmonics from the converters.

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

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

The accurate modelling of the harmonic AC system impedances at the second and third harmonics is important in order not to overdesign such low order filters. For harmonics below the 11th order, a detailed and accurate representation is recommended to ensure that magnification of harmonics is damped out to the optimum. If this is not possible during the planning stage, some flexibility and allowance for risk should be given to the contractors to study this phenomenon during project execution and to mitigate any problem under their own responsibility at a later stage of the project. In some cases, converter control with special features could be used as a solution for low order harmonics problems instead of expensive harmonic filters [12].

It is also vital to model accurately the harmonic interaction between the AC and DC sides of the converter, and the influence of the converter control system, when determining the need for, or the design of, such low-order filters (see IEC TR 62001-3 [3]). Ignoring these factors can result in completely misleading conclusions, and possibly the unnecessary specification for a low-order filter to be installed.

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

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

7.2.2 Definition of interference factors to include harmonics up to 5 kHz

In most technical specifications for LCC HVDC, the maximum harmonic order to be considered for AC filter performance is the 50th. However, a few specifications for LCC HVDC have extended the range to be considered to higher frequencies, such as the 83rd harmonic at 60 Hz, i.e. 5 kHz. The impact on the filter design and costs when considering harmonics higher than the order of 50 can be significant, and careful consideration should be given by the customer before making such a requirement. This requirement is increasingly common with more VSC converters being built and more detail is provided in CIGRE Technical Brochure 754 [2].

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

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

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

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

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

- specify performance requirements only up to the 50th harmonic, but specify in addition that the AC filters should have a damped characteristic above the 50th (possibly also defining the maximum permitted filter impedance phase angle permitted at harmonics above the 50th); or
- specify performance requirements up to the 83rd order, but increase the maximum limits for TIF, telephone harmonic form factor (THFF) or the product of RMS current I and TIF (IT product) accordingly, in order to avoid an unnecessarily expensive filter design.

7.2.3 Triple-tuned filter circuits

Double-tuned filter circuits have been established for many years as a standard design for passive AC filters, as the savings in the high voltage capacitor banks and AC switchgear justify a filter design with more than one tuning frequency. In certain circumstances, further optimization may be possible if more than two tuning frequencies can be achieved. In a number of projects, manufacturers have identified a cost saving advantage if triple-tuned filters could be provided (see also IEC TR 62001-1 [1]).

Tuning for triple-tuned filter circuits is more complicated than for single- or double-tuned filters, but is quite feasible. Moreover, if the filter is designed so that sharp tuning is only required at one of the frequencies, with broad-band damped characteristics at the other two frequencies, then sufficiently accurate tuning can be readily achieved.

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

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

- operational requirements for reactive power control within narrow limits;
- combination of stringent THFF or TIF voltage distortion combined simultaneously with low IT product limits;
- minimizing filter reactive power installation close to generators;
- low order filtering combined with a 12/24th harmonic filter;
- saving in AC switchgear and space;

- lower reactive power of a 3/12/24th harmonic filter at light load conditions compared to a 3rd harmonic + 12/24th harmonic circuit, thus reducing the need for shunt reactors;
- higher redundancy for all types of filter used.

Possible disadvantages to be considered (see also IEC TR 62001-1:2021 [1], 6.4.3), apart from the more complicated on-site tuning, are as follows:

– sensitivity of the tuning to blown capacitor fuses;

– number of current transformers (CTs) required to ensure protection of all components, or possible overrating of unprotected low voltage components.

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

7.2.4 Harmonic AC filters on tertiary winding of converter transformers

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

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

Consideration should be given to filter outages. Any spare or redundant filtering has to be provided on a per-transformer rather than a per-station basis, and this can significantly reduce any cost advantage. Filters may be shared by the use of off-load disconnectors to allow sharing without increasing fault levels.

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

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

- The additional tertiary winding has to be designed for the short-circuit duty and has a relatively low leakage impedance from tertiary to the HV bus winding.
- The transformer reliability will be lower.
- The four-winding converter transformer is not a standardized item of equipment and for system studies a detailed transformer model needs to be developed by the contractor to prove all the assumptions and ratings.
- The converter transformer impedance selection has to reflect the requirement to limit the short-circuit currents to acceptable limits; but on the other hand the choice of the transformer impedances has an impact on the overall harmonic performance of the AC filters and needs to be chosen in such a way that resonances between the filter circuits and the AC system are damped out to a minimum.

- The voltage profile at the tertiary filter busbars has to be considered when calculating the reactive power compensation, and in general a larger reactive compensation will be required than if filters were installed on the high voltage bus.

7.3 Rating aspects

7.3.1 Limiting high harmonic currents in parallel-resonant filter circuits

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

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

7.3.2 Transient ratings of parallel circuits in multiple tuned filters

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

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

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

7.3.3 Overload protection of high-pass harmonic filter resistors

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

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

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

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

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

If tuned filters are used, the tuning reactors are sufficient to limit these inrush currents. If one or more shunt capacitors in parallel are included in the design, it is recommended to provide additional current limiting reactors in the shunt capacitor banks to damp the discharge between the individual branches. For circuit breaker design aspects, refer to 11.7.

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

7.3.5 Short time overload – reasonable specification of requirements

Subclause 7.3.5 discusses how far inherent short time overloading of the filters due to system emergencies should be reasonably specified. Short time overload for filter components can be caused by one or more of the following system emergency conditions:

- short time overvoltages in the AC system;
- short time AC system frequency deviations;
- short time overload of the HVDC converters.

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

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

Normal system conditions:	10 min to 2 h	duration
Disturbed system conditions:	1 min to 10 min	duration
Emergency system conditions:	1 s to 60 s	duration

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

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

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

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

a) Filter capacitors

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

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

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

b) Filter reactors

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

c) Filter resistors

Filter resistors are the components most sensitive to overload, due to the loss dissipation. The overload stresses depend on all the impacts discussed in 7.3.5. In some recent projects, studies showed that the rating of the resistors is the critical point when considering short time overloads.

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

7.3.6 Low voltage filter capacitors without fuses

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

For operating currents lower than the rated values, the fuses will not be able to clear failed capacitor elements due to the missing dominating fundamental frequency component in the current. Typically the low-voltage capacitor(s) will be of a fuse-less design and with a de-rated voltage rating such that the probability of dielectric element failures at steady-state conditions is negligible. In some cases, these have been designed for extremely high harmonic current ratings (due to detuning and outages of filter banks). For example, in some filters, 11th and 13th harmonic current ratings up to approximately 1 000 A RMS for low voltage components of double-tuned filters have been required.

7.4 Filters for special purposes

7.4.1 Harmonic filters for damping transient overvoltages

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

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

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

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

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

As an alternative approach to that discussed in 7.4.1, a special filter was designed and successfully commissioned in Austria for the Dürnrohr and Vienna South-East HVDC converter station. For one particular AC system configuration, various studies were carried out to detect the worst-case scenario for temporary and transient overvoltages. The damping in the AC system was relatively low, and therefore low order harmonic overvoltages, superimposed on the fundamental frequency overvoltages, were caused by transformer saturation phenomena and amplified by the low damping of the AC system during low short-circuit ratio (SCR) operating conditions of the AC system. These overvoltages occurred almost undamped and the AC breakers seemed to be insufficient to clear against these fault overvoltages. Studies recommended the installation of an SVC combined with low order harmonic filters, to limit the transient and temporary overvoltages including transformer saturation phenomena.

The decision for the Vienna Southeast and Dürnrohr stations was to install a non-linear filter for the 2nd and 3rd harmonic with the filter arrangement as shown in Figure 6. This filter arrangement has practically no losses at fundamental frequency and inserts its filtering capability from a certain trigger level (determined by the arrester arrangement). A group of parallel connected arresters inside the filter configuration controls the steady state and transient impedance of the filter. The arresters have been designed for the worst-case energy dissipation during fault conditions.

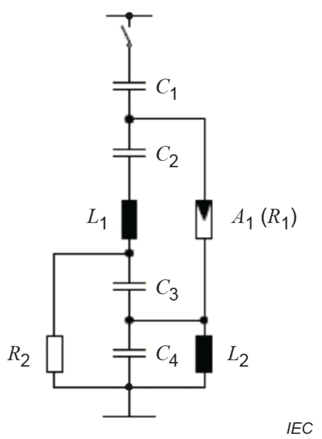


Figure 6 – Non-linear low order filter for Vienna Southeast HVDC station

7.4.3 Series filters for HVDC converter stations

Existing experience in AC harmonic filtering is based almost entirely on the use of shunt type filters. Some detailed investigations have been carried out in the use of a mixed configuration of series and shunt filters for Itaipu and practical applications at Uruguaiana in Brazil and Outaouais in Canada have given good operational experience.

If filtering requirements are such that a series filter is required, the customer should specify whether it should be possible to by-pass the filter in order to continue with the HVDC scheme in service without any degradation except to filter harmonic performance.

A series filter is functionally similar to the wave trap used in power line carrier applications and is built with an inductor (typically in the range of 1 mH to 4 mH) in parallel with a series-connected capacitor plus resistor (Figure 7), tuned to a single resonance frequency. If several resonance frequencies are required, a number of such filter circuits can be cascaded in series, each of them tuned to a particular harmonic frequency. Multiple-tuned series filters (Figure 8) can also be used, presenting two or more impedance peaks (impedance peaks for carrier and/or for radio frequency may also be included if necessary). A damped band-stop characteristic can also be achieved to filter a range of higher order harmonics.

The above mentioned investigations have indicated that, considering the converter as a source of harmonic current, the use of a series filter is efficient only if it is associated with a shunt impedance of relatively low impedance, such as can be obtained with a capacitor bank and/or shunt filter. Therefore the application of a series filter should be done in a mixed configuration of series and shunt filters (Figure 9).

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

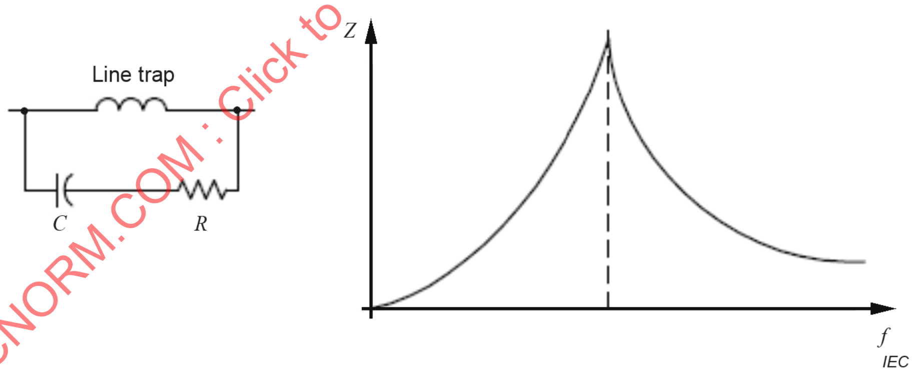


Figure 7 – Single-tuned series filter and impedance plot

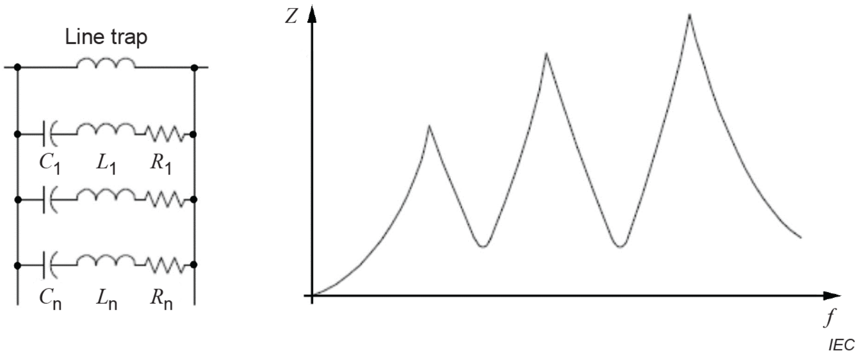


Figure 8 – Triple-tuned series filter and impedance plot

Advantages of series filter circuits are:

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

Disadvantages of series filter circuits are:

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

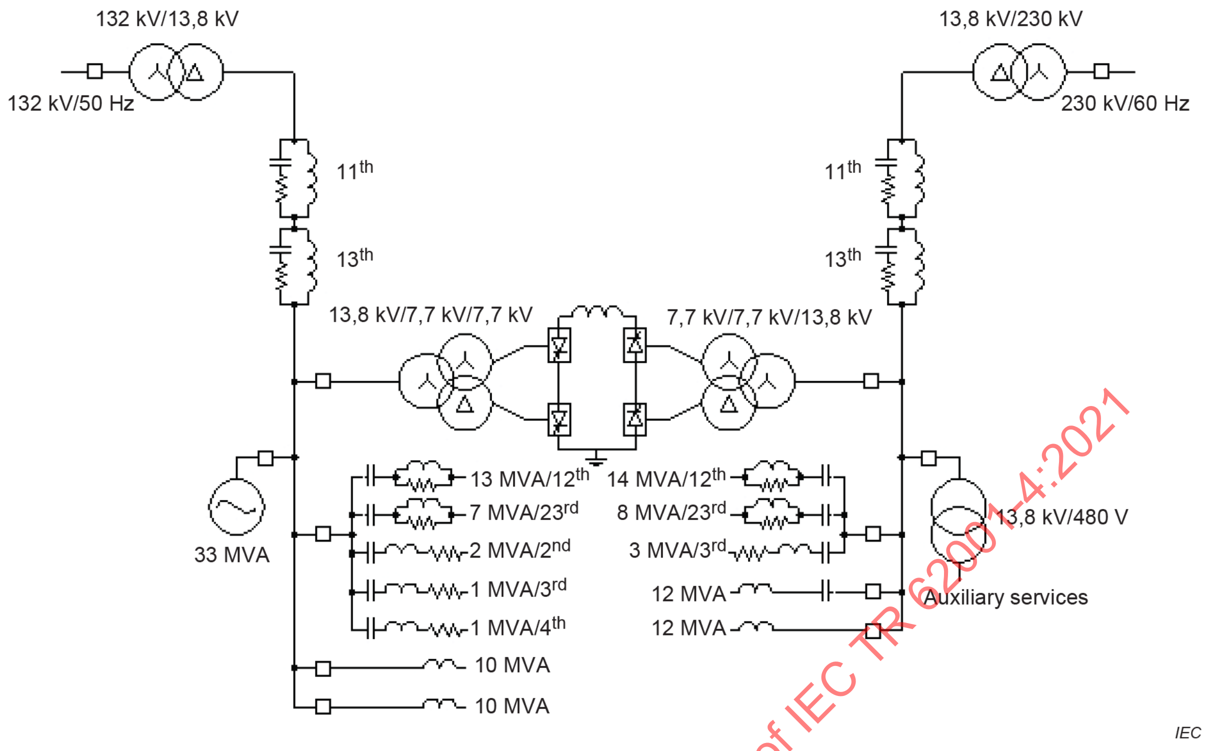


Figure 9 – Mixed series and shunt AC filters at Uruguaiana HVDC station

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

a) The mixed filter configurations with the shunt filters are hard to satisfy if low minimum AC system impedance is combined with requirements for limited emission of harmonic currents into the AC system.

b) For areas of higher soil resistivity (greater than 1 000 W-m), the coupling between power and telecommunication lines is high and potential interference problems may dictate very low limits on harmonic currents in the AC system, thus favouring the use of mixed series and shunt filters.

c) In applications in which the connected AC system includes important shunt capacitor bank and/or underground cables, these capacitors produce low impedance nodes for high order harmonics, draining the major part of the harmonic currents into the AC lines. Series filters could be the most economic means to limit these currents and the resulting interference level.

d) The ability of series filters to limit the harmonic current entering the AC system to desired values, independently of the equivalent harmonic impedance of the AC system viewed from the converter station, may represent an important consideration. This is particularly so in view of the usual difficulty in obtaining realistic equivalents, particularly for the future expansion of the AC system.

e) In those applications in which the steady state voltage control during light load and/or the control of the overvoltage during converter blocking impose limitation on the shunt filter size and/or require the use of shunt reactor, the mixed filter configuration represents an attractive and economical solution, because for the same filtering performance this configuration reduces considerably the size of the shunt bank to be installed.

f) In cases requiring essentially only the control of the harmonic currents fed into the AC system, the mixed solution should be examined because the shunt part of the scheme could be limited to a simple capacitor, determined by the station reactive requirements, and the series part would be a single reactor.

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

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

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

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

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

7.4.4 Re-tunable AC filters

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

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

At Radisson, this solution has been used to avoid interaction between AC side fifth harmonic and DC side sixth harmonic for certain system conditions and in the presence of geomagnetically-induced currents (GIC). When the AC side fifth harmonic becomes greater than a predetermined value, the 36/48th harmonic AC filter is re-tuned to the 5th harmonic (Figure 10) by opening the switch S1. The switch is closed by the operator when the conditions have returned to normal.

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

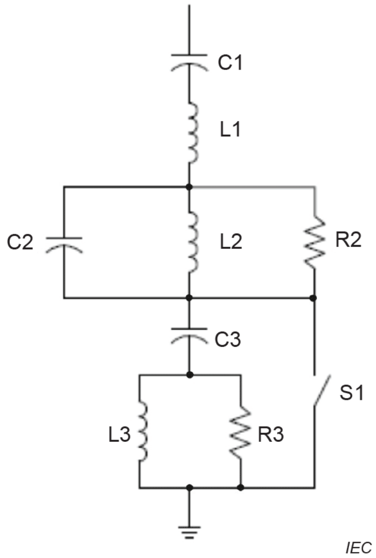


Figure 10 – Re-tunable AC filter branch

7.5 Impact of new HVDC station in vicinity of an existing station

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

CIGRE Technical Brochures 364 [13] and 798 [14] discuss some of the issues to be considered in this case in some depth.

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

a) The performance parameter limits should be specified with due consideration to the effect of the existing converter stations. In doing so, [15] and [12] can be used.
b) Generator harmonic current limits, if applicable, should be such that the total effective injection does not exceed the permitted limits.
c) The effect of resonance between the filters of the existing and the new stations should be taken into account.
d) The AC system harmonic impedance to be used in the design calculations should be defined with due consideration of the existing station and its filters.

The rating aspects to be considered are as follows.

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

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

7.6 Redundancy issues and spares

7.6.1 Redundancy of filters – Savings in ratings and losses

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

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

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

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

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

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

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

   - simple filter arrangement and redundancy (1 out of 2);
   - reduced number of low-voltage (LV) filter components and space requirements.

   The disadvantages are as follows.

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

b) Solution with three identical double-tuned filters

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

   The advantages of this solution are as follows.

   - Higher availability and better harmonic performance (2 out of 3) in case of forced outage of a filter branch. In this case, both harmonic performance and component stresses in the remaining circuits are lower compared to solution a).
   - Component ratings of filter reactors, capacitors and resistors are significantly lower compared to the components for solution a). Therefore, most of the filter components are less expensive. This applies especially for filter damping resistors.

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

The disadvantage is as follows: the increased number of LV filter components in the circuit leads to a more complex circuit arrangement and to enlarged space requirements.

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

7.6.2 Internal filter redundancy

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

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

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

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

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

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

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

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

7.6.3 Spare parts

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

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

One spare of each type of filter reactor needs to be stored. For filter capacitors, a minimum number of capacitor cans of each type should be provided. For this reason, if economically attractive considering all factors, it could be desirable where possible that the filter design uses identical capacitor units for each individual type of AC filter.

8 Protection

8.1 Overview

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

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

The customer should, however, be well aware of the different techniques of AC filter protection, and in the bid evaluation stage be prepared to ensure that the bidder's proposed solutions meet the customer's overall technical requirements. The information given in Clause 8 is mainly concerned with giving the customer the background information needed for this stage of technical discussions with the bidder.

The IEC standards with relevance to the protection of AC filters are the following: IEC 61869-2 [16], IEC 61869-3 [17], IEC 61869-5 [18], IEC 60549 [19], IEC 60871-1 [5], IEC TS 60871-3 [20], IEC 60931-3 [21], IEC 60871-4 [22].

8.2 General

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

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

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

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

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

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

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

- What is the normal standard elsewhere in the AC system?
- Is redundant protection equipment justified for the rated power of the filter or capacitor bank?

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

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

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

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

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

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

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

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

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

1) AC system faults,
2) transformer switching,
3) switching of parallel capacitor banks,
4) commutation failures in the HVDC converters, and
5) DC line faults.

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

8.3 Bank and sub-bank overall protection

8.3.1 General

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

8.3.2 Short-circuit protection

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

8.3.3 Overcurrent protection

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

8.3.4 Thermal overload protection

This kind of protection is one of the most important functions, although an overall overload protection can only protect the weakest filter component with the shortest heating time constant that is carrying the main filter current. Therefore, it should be determined, in each case, whether an overall overload protection will be installed and/or if individual protection for reactors and resistors will be installed separately. A simple overload protection for the whole filter cannot protect a damping resistor as the current through the resistor is not proportional to the main filter current. However, protections which use a frequency-dependent calculation of the division of harmonic currents between the resistor and a parallel reactor have been successfully applied. In single-tuned filters, the overall overload protection can be used for both reactor and capacitor. The following remarks should be borne in mind.

- The construction and function of an overload relay can vary from the simple up to the highest complexity.
- A fundamental prerequisite when deciding on the level of complexity is the level of knowledge of the reactor thermal time constants over the frequency range of interest.
- The ambient temperature assumed by the overload protection can be a design input with a fixed setting of the maximum calculated ambient temperature or an actual temperature measurement. A temperature measurement is checked continuously for correct functioning and plausibility.
- If sufficient knowledge of the reactor’s thermal characteristic is not available, a simpler version of overload protection can be selected. This could be a true effective current measurement or with an additional filter function to increase the sensitivity.

- For the ideal function, a true current RMS measurement is not enough. The overload protection should also take into account the frequency dependent thermal loss characteristic of the reactor. The ohmic resistance of a reactor depends on the frequency and so the evaluation of each harmonic current is different.

8.3.5 Differential protection

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

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

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

8.3.6 Earth fault protection

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

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

8.3.7 Overvoltage and undervoltage protection

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

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

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

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

8.3.8 Special protection functions and harmonic measurements

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

The installation of a fast Fourier transform (FFT) analyzer (refer to Clause 9) can be added to enhance such protection.

8.3.9 Busbar and breaker failure protection

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

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

8.4 Protection of individual filter components

8.4.1 Unbalance protection for filter and shunt capacitors

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

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

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

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

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

- detection of neutral voltage,
- different voltages over capacitor phases, and
- different currents through capacitor phases.

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

In unearthed shunt capacitor arrangements, an unbalance current measurement in the neutral is sometimes used. Refer to Figure 11.

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

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

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

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

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

8.4.2 Protection of low voltage tuning capacitors

If the capacitor has a de-rated voltage rating an unbalance protection is not required.

8.4.3 Overload protection and detection of filter detuning

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

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

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

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

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

8.4.4 Temperature measurement for protection

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

8.4.5 Measurement of fundamental frequency components

Low voltage capacitors with series connected reactor (such as in a C-type filter) are often used to minimize the fundamental frequency losses in parallel resistors. By filtering to obtain the fundamental current in the resistor, a sensitive additional protection for the capacitor and reactor can be achieved (refer to the attached high-pass filter protection scheme, Figure 12). The fundamental current in the damping resistor branch should disappear to zero at rated conditions (rated fundamental frequency). If the tuning capacitor in series with the filter reactor changes reactance, caused by a disturbance in a capacitor element, the fundamental current through the resistor can increase, in most cases by a higher amount than by normal frequency deviations.

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

8.4.6 Capacitor fuses

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

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

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

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

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

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

Fuseless capacitors are discussed in 11.2.2.

8.4.7 Protection and rating of instrument transformers

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

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

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

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

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

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

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

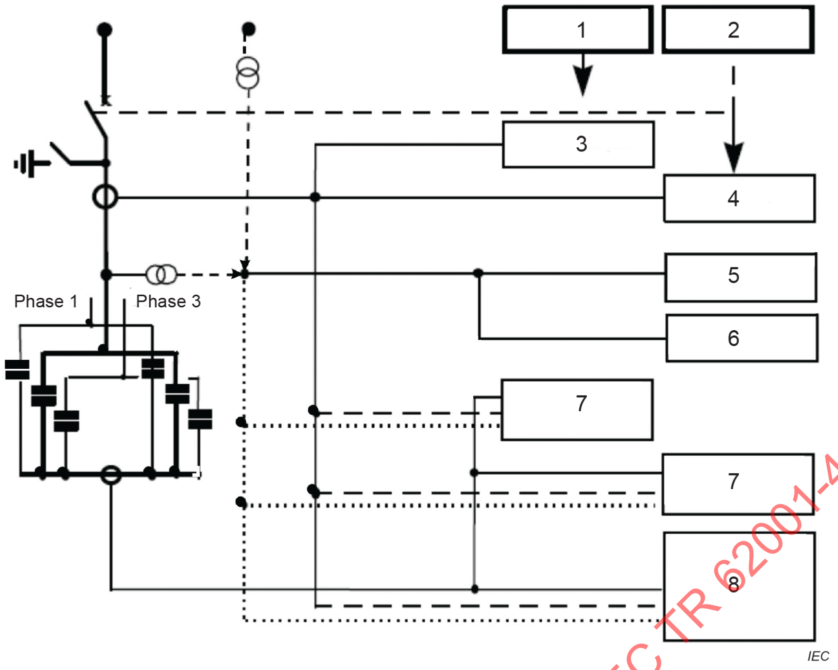
8.4.8 Examples of protection arrangements

An example of a typical protection scheme for a simple shunt capacitor bank is shown in Figure 11 and for a C-type filter in Figure 12. It should be noted that protection schemes may vary considerably depending on the particular features of a given filter design and on the protection philosophy adopted.

8.5 Personnel protection

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

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



Key

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

Figure 11 – Example of a protection scheme for an unearthed shunt capacitor

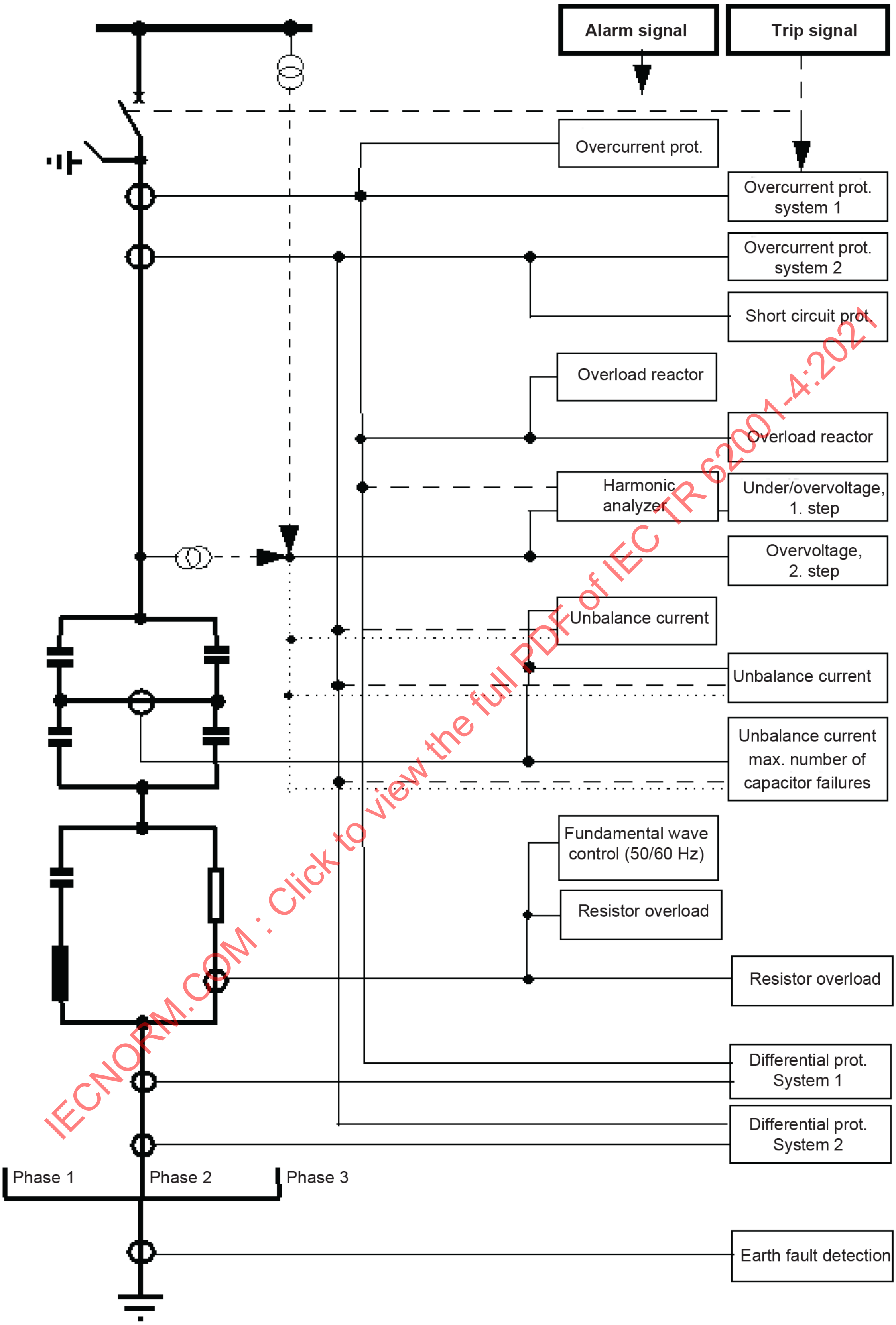


Figure 12 – Example of a protection scheme for a C-type filter

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

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

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

9 Audible noise

9.1 General

An important consideration of converter station design is to prevent potential annoyance of people living nearby due to intrusive audible noise. The intention of Clause 9 is to inform customers of the background to audible noise limitations and the relevance to AC filter design. The treatment of audible noise limitation in the technical specification can be significant, and the issue may also be prominent during bid evaluation discussions and the subsequent project design (see IEC TS 61973 [23]).

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

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

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

Audible noise may be defined as an assembly of acoustic waves in air at frequencies perceived by the human ear. Noise may consist of a monofrequency acoustic signal (tone) or of sounds containing a distribution of frequencies. For definitions of acoustic parameters, see IEC TS 61973 [23].

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

9.2 Sound active components of AC filters

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

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

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

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

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

As an example, Figure 13 shows the current spectrum of a filter reactor. It is assumed that the current consists of a component with fundamental frequency f and one harmonic component with harmonic number n.

Figure 14 depicts the vibration force components acting on the winding of the reactor. The force consists of components with frequencies $2f$, $f_{(n-1)}$, $f_{(n+1)}$ and $2f_n$.

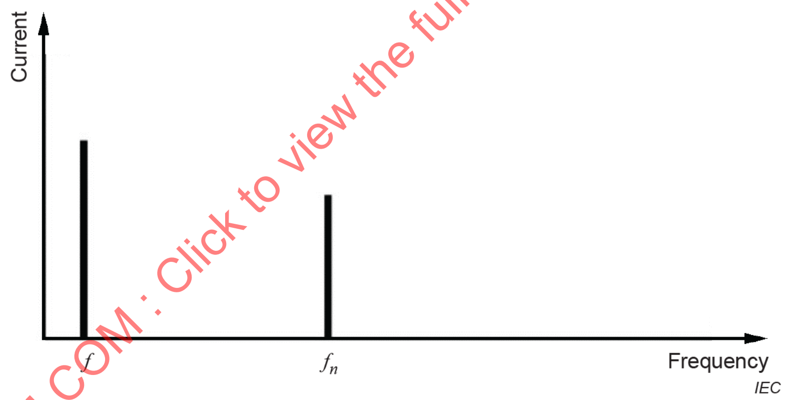


Figure 13 – Electrical spectrum

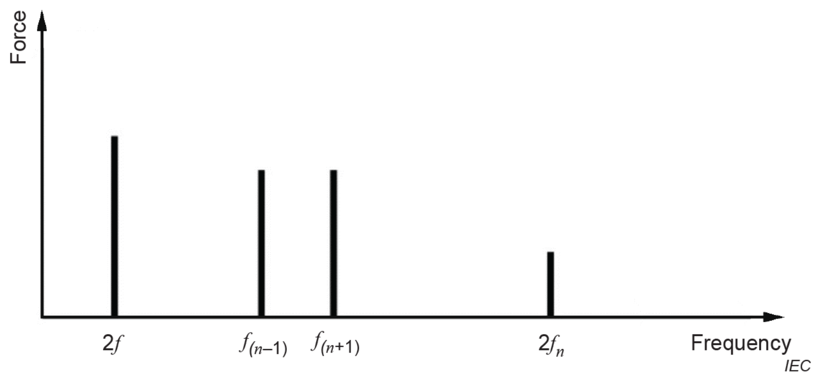


Figure 14 – Force spectrum

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

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

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

9.3 Sound requirements

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

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

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

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

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

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

9.4 Noise reduction

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

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

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

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

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

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

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

10 Seismic requirements

10.1 General

The intention of Clause 10 is to give the customer's engineers dealing with AC filters sufficient background information in order to understand the implications of seismic requirements for AC filter design, and to have a basis on which to discuss aspects of seismic design with bidders. Any seismic requirements for the filters will be defined in the technical specification in the same way as the requirements for the rest of the converter station.

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

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

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

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

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

With respect to the special nature of electrical equipment which contains a large amount of brittle material (porcelain), it is important that realistic loads and reasonable evaluation criteria are defined by the customer. However, the seismic design qualification discussed in Clause 10 is the responsibility of the contractor. Information on the specification of seismic requirements can be found in IEEE Std 693™ [24]. Example of seismic response spectra is shown in Annex A.

10.2 Load specification

10.2.1 Seismic loads

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

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

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

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

If no response spectrum for a specific site is available to the customer then the "required response spectrum" (RRS) of IEEE Std 693 [24] may be used. As an example, the RRS for moderate seismic requirements is shown in Figure A.1. The maximum ground acceleration in this spectrum is 0,25g.

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

10.2.2 Additional loads

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

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

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

10.2.3 Soil quality

In addition to the loads described in 10.2.1 and 10.2.2, the quality of the soil has to be considered. The impact on the ground anchoring depends on the type of soil (rock, clay, sand, etc.). In areas with porous material, the whole filter area, or parts of it, may be anchored to one common foundation. The soil properties should therefore be specified by the customer.

10.3 Method of qualification

10.3.1 General

The qualification may be done by analytical methods or by testing. The customer should specify which kind of qualification the contractor shall apply. If testing is preferred, then the customer may accept a verification of the seismic performance based on results of tests previously performed on structures of similar design and similar seismic requirements. For details on seismic qualification by testing, reference is made to IEEE Std 693 [24].

The usual practice for qualification, however, is by analytical methods.

10.3.2 Qualification by analytical methods

10.3.2.1 General

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

The kind of the analytical method, static or dynamic, mainly depends on the type of equipment. Complex structures with natural mechanical frequencies within the seismic frequency range (0,1 Hz to 33 Hz) usually require a dynamic analysis which is mostly done by the response spectrum method as described further in 10.3.2.2. For simple structures with fewer components, a static analysis may be sufficient. In any case, the numeric calculation is carried out using a generally accepted computer program.

10.3.2.2 Response spectrum analysis

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

The resultant maximum response determined from the individual modal responses is usually done by the SRSS (square root of the sum of squares) method. If not otherwise stated, 2 %

modal damping is assumed for each mode shape. If increased structural damping is employed, measurements are usually required to verify modal frequencies and modal damping ratios.

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

10.3.2.3 Static coefficient method

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

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

10.3.2.4 Static analysis

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

10.3.3 Design criteria

10.3.3.1 General

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

10.3.3.2 Minimum safety factors

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

a) Brittle materials

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

b) Ductile materials

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

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

- 1,2 on the yielding strength,
- 2,0 on the ultimate strength.

10.3.3.3 Buckling requirements

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

10.3.4 Documentation for qualification by analytical methods

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

a) Seismic statement

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

b) Seismic qualification report

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

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

10.4 Examples of improvements in the mechanical design

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

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

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

11 Equipment design and test parameters

11.1 General

11.1.1 Technical information and requirements

Depending on the chosen filter arrangement (see IEC TR 62001-1 [1]), the filter will be made up of a combination of capacitors, reactors and resistors, connected to the AC bus by suitable switching equipment. Additional equipment should be included such as surge arresters for overvoltage protection and instrument transformers as part of the filter protection system.

There are a number of factors which all have significant influence on the design and the ratings of the filter components. Basic information which the customer has to provide in his bid request is described in some detail in Clause 9, Clause 10 and in IEC TR 62001-1 [1].

Clause 11 aims to give the customers some guidance for

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

11.1.2 Technical information to be provided by the customer

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

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

11.1.3 Customer requirements

11.1.3.1 Design, production, installation and maintenance requirements

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

It is recommended that the customers require the contractor to specify the type of support insulators used for the mounting of the filter components and the capacitor bushings. Usually, the insulators and bushings are of porcelain type. Sufficient creepage and clearance should be provided for reliable operation of the equipment. Based on information available to the customers regarding the pollution conditions encountered at the site, the customer should prescribe the minimum creepage distance of the insulators. Typical values for specific creepage are from 25 mm/kV to 45 mm/kV depending on the site pollution level (see IEC TS 60815-1 [25], IEC TS 60815-2 [26] as well as IEC TR 62001-1 [1]). Creepage requirements should be based on the maximum voltage (including harmonics) appearing across the insulators or bushings, evaluated in accordance with 4.2.4 and 4.2.5.

The customers may require the filter to be made up as far as possible by identical interchangeable components so as to simplify maintenance and stocking of spares.

For ease of transportation and installation, the customers may require that each equipment component be equipped with lifting eyes or similar provision for lifting the unit.

The customers may impose a maximum height requirement for any equipment. They may further require a maximum limit on weight of components (capacitor units for example) depending on their location relative to other filter equipment. If the contractors exceed those limits, they should provide appropriate tools for handling during installation and maintenance.

The outline of the filter components should be designed so as to eliminate as far as possible any visible corona at voltage levels typically up to 20 % above rated voltage.

The customers may advise the bidder that the filter components shall be designed to withstand the operational mechanical forces without damage or reduction of life. These are vibrational forces during normal operation, electromagnetic forces during external faults, wind forces, ice loading and seismic forces, if applicable. In case of breakage of one support insulator, the construction should remain stable. The customers may require a static calculation of the filter structures.

The customers may require the contractors to guarantee a maximum annual failure rate for certain filter components such as capacitors, current transformers, etc. on condition that the specified maintenance is provided.

11.1.3.2 Quality system and documentation requirements

It is recommended that the customers specify their minimum requirements on the contractors' quality system to be applied by the contractors to the design, production, testing, installation and maintenance of the AC filter equipment.

Usually, the quality programme is documented by the contractor's quality manual. The customers should review the contractors' manual and they should reserve the right to audit the quality system as described by the manual.

Further to the standard quality programme, the customers may state specific requirements on the kind and quality of materials and workmanship. These should include for example requirements on materials used for terminals and electrical wiring, surface protection by galvanizing or painting, specific requirements on welding.

The customers may specify requirements on the contractors' documentation. Usually, the activities for design and production inspection, testing, installation and commissioning are based on inspection and test plans. The inspection and test plan should define hold points for witnessing inspection or testing by the customers or by an organization representing the customers.

It is recommended that customers request the contractors to submit this documentation for approval during the detailed design stage of the equipment.

11.1.3.3 Test requirements

For general requirements, the customers should refer as far as possible to the applicable IEC standards and recommendations, but ANSI or IEEE standards could be used for comparison. It should be made clear on which standard body, IEC or ANSI/IEEE, the design, rating and testing of the filter equipment is based.

The test program for component specific tests will depend on a number of parameters such as the general technical concept of the filter, overvoltage protection, service experience with specific components gained from other HVDC projects. The test program should ascertain that the specific component will provide the required performance and will withstand all defined electrical and environmental conditions encountered in the field. However, it should be borne in mind that requirements for tests covering unrealistic conditions may considerably increase the cost for the equipment.

The test program should be established in co-operation between the customer, the contractor and his sub-supplier. Usually, it is split into routine tests, type tests and if necessary special or "other" tests. It may be advisable that the customer or his representative plans to witness type and special tests. This is of particular importance in case of difficulties in performing a test, or if there are any doubts about the test result. In this case, the customer's representative may assist in making an immediate decision on how to proceed with testing.

Certified test reports on previously performed type tests on similar units may be accepted in lieu of performing a type test. Relevant test reports should be submitted to the customer for approval, including a report on deviations in design or technical data. If accepted in lieu of performing a type test, these reports should be included in the inspection and test report as part of the documentation.

If applicable, the contractors should perform a seismic qualification for each equipment component mounted on its support structure. Seismic qualification may be performed either by analytical methods or by testing (see Clause 10).

11.1.4 Technical information to be presented by the bidders

The customers should require the bidder to provide a general description of the filter layout including a schematic diagram clearly identifying the individual filter components. The number of units of filter components including spare units should be indicated by the bidders.

The lists of electrical data presented in 11.2 to 11.7 are intended to be a guideline for the customer on how to specify a particular filter component. Further parameters and further information may be requested by the customers if deemed to be useful. Such required information for example may refer to the thermal time constant of reactors, resistors and of arresters.

The numerical values of the individual parameters for each component are chosen by the bidder depending on his filter design. Since some of the values, in particular for tolerance, may be critical and sometimes difficult to achieve, such values are usually defined in consultation with the component sub-suppliers.

The customers may require the bidders to indicate the amount of manpower for maintenance (in days per annum) necessary for reliable operation of the equipment under defined operating conditions.

11.1.5 Ratings

The following ratings are required to be specified for the various filter components.

- Rated harmonic frequency

  The rated harmonic frequency is that frequency to which the relevant parameters for harmonic filter perfomance are referred. For single-tuned filters, this frequency is equal to the tuning frequency, for double-tuned filters this may be the geometric mean frequency of the two tuning frequencies or may refer to both tuned frequencies.

- Voltage rating

  The rated voltage U_N (RMS) assigned to an AC filter capacitor bank is discussed in 4.2.4.2. The rated voltage of the capacitor units U_r (RMS) should be higher than or equal to the rated voltage U_N of the capacitor bank divided by the number of series connected units.

  It should be noted that there are considerable differences between IEC 60871-1 [5] and IEEE Std 18 [6] in terms of permissible long duration overvoltage capabilities of capacitors.

  It is recommended that the contractor presents oscillograms of the transient oscillatory voltage appearing across the capacitor banks, together with the anticipated number of events per year, in his specification to the capacitor sub-supplier.

  The rated voltage of a reactor or resistor is the arithmetic sum of the voltages at fundamental and harmonic frequencies. The rated voltage across a reactor or resistor is discussed in 4.2.4.3 and 4.2.4.4. The voltage rating to ground depends on the position of the reactor or resistor relative to other filter components and may differ from the voltage rating between the terminals.

- Current rating

  The rated current is the square root of the sum of the squares of the current at fundamental and harmonic frequencies (see 4.2.4).

11.2 Capacitors

11.2.1 General

There are two internationally accepted standards applicable for the capacitors for AC filters: preferably IEC 60871-1 [5] for comparison. It is recommended to refer to one of these two standards for general requirements on capacitors.

For clarification of terminology, the following definitions are used.

- Capacitor element: In practice, normally an individual package (coil, roll) consisting of aluminium foil and insulating paper and/or plastic film.
- Capacitor can or unit: The metallic case including bushing(s), internal discharge and grading resistors, capacitor elements connected in series and parallel, and, if used, element fuses.
- Series group: A set of capacitor units connected in parallel. Several groups are connected in series to meet the voltage requirements.
- Capacitor rack: A metallic framework containing one or several series groups including interconnection buswork and insulators as required.
- Capacitor stack: One or several capacitor racks mounted on a set of base insulators for rack-to-rack insulation, including inter-rack and rack-to-rack connections.
- Capacitor bank: One or several capacitor stacks including inter-stack connections and including the associated monitoring and protective equipment. Often, a capacitor bank consists of sets of two identical stacks connected in parallel so as to provide a bridge arm for measuring unbalance between the two stacks.

In single line diagrams, the capacitor bank is represented by a lumped single-phase capacitor.

11.2.2 Design aspects

11.2.2.1 General

The contractor should illustrate the circuitry of the individual capacitor banks and capacitor units to show how the specified capacitance values are arrived at.

The considerations in 11.2.2.2 and 11.2.2.3 are taken into account.

11.2.2.2 Capacitor unit design

11.2.2.2.1 Capacitor units container and mounting

Depending on the environmental site conditions, it may be advisable to make the cases of the capacitor units from stainless steel. The cases should be designed so as to allow for expansion and contraction due to all ambient and loading conditions expected during the life of the unit including short term and transient conditions. The capacitor manufacturer should provide the criteria for determining when expansion of the case is normal and when it is due to capacitor failure.

Usually, the capacitor units are bolted to the rack. Each capacitor unit should be mounted so that it can be easily removed from the rack and replaced without removing other units or disassembling any portion of the rack. Depending on the weight, if necessary each capacitor unit should be furnished with lifting eyes.

11.2.2.2.2 Dielectric

The dielectric fluid used within the capacitor unit should be environmentally safe and biodegradable. The capacitor unit should not contain PCB type fluid. The capacitor elements should be vacuum dried inside the case prior to impregnation with the dielectric fluid. After impregnation, the capacitor unit should be sealed immediately upon removal of the impregnant reservoir.

11.2.2.2.3 Unit rating

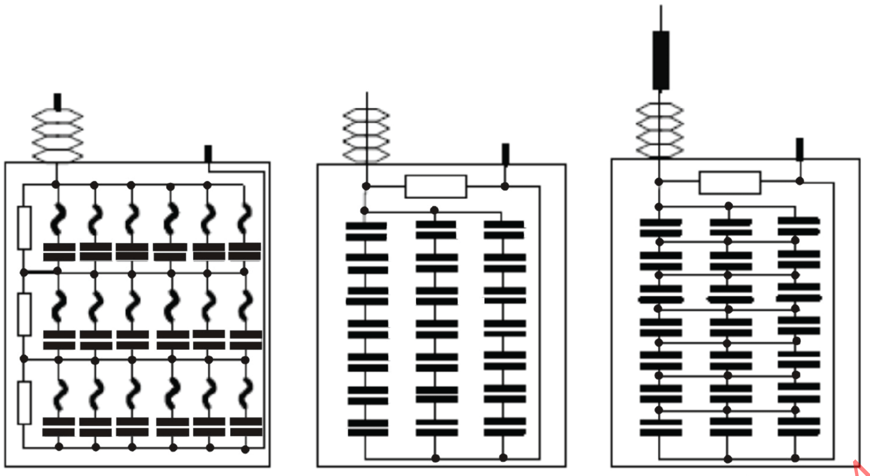
The current, voltage and kVar rating of the capacitor units as well as the measured capacitance or the tolerance class should be given on the capacitor unit nameplate, in accordance with IEC/IEEE standards.

11.2.2.2.4 Unit configuration

The earliest capacitor designs involve the use of external fuses. A capacitor unit failure caused the fuse to operate resulting in the need to replace the fuse and the capacitor unit. The large change in capacitance due to the loss of a capacitor unit has a significant effect on the capacitor bank design.

Subsequently, the internally fused capacitor unit was designed and is widely applied for harmonic filters. These have fuses in series with each element built into the capacitor unit such that an element failure results in a very small loss of capacitance and a modest overvoltage across the remaining parallel elements. After a number of element failures, the increased voltage is excessive and the unit must be replaced.

In recent years, fuseless capacitors have been used for harmonic filters. A commonly used 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 15). 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 15 – Comparison of internal, fuseless and external fused capacitor unit designs

The fuseless design offers a more economical construction of capacitor unit, 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, low capacity filter capacitors. However, it may not be suitable for low voltage, filter banks because one element failure would cause a large voltage stress on the relatively few remaining healthy elements.

The customers' specification should permit the use of capacitors of an appropriate technology for the application of the capacitors. Satisfactory capacitor protection arrangements or significant over-rating in place should be provided.

11.2.2.2.5 Discharge resistors

Each capacitor unit should be provided with internal discharge resistors in accordance with IEC 60871-1 [5]. Longer discharge times (which will reduce losses) may be possible if agreed by the customer.

11.2.2.2.6 Fuses and unit protection

Fuses are intended to protect the case of the capacitor unit from rupture due to capacitor element failures. Internal fuses are intended to safely isolate failed elements during any operational condition.

Customers should indicate which type of fusing – internal, external or non-fusing – is considered acceptable and they should define the criteria for alarm and trip level settings of the unbalance protection. The contractors should show how their proposed fusing/unit arrangement will meet the customers' requirement.

11.2.2.3 Capacitor bank design

11.2.2.3.1 Racks

Usually, the capacitor racks are supplied fully equipped with all capacitor units, insulators, and connections. Lifting eyes should be provided to facilitate assembly of the racks into the stacks. Depending on the environmental site conditions it may be advisable to make the racks of hot dip galvanized structural steel or corrosion resistant structural aluminium. No drilling should be permitted after galvanizing.

The structural members of the racks should not be used as electrical buses. There should be only one single electrical bond between a group of capacitor units and the capacitor rack. All structural members of the rack should be electrically connected together in order to ensure adequate earthing of the rack during maintenance. The rack should be provided with adequate connections for earthing.

Each rack should be clearly labelled with the weight of the fully equipped unit, the phase and bank of which it forms a part, and the maximum and minimum capacitor unit capacitances which may be substituted into the rack as spares. Suitable warning labels should be affixed.

11.2.2.3.2 Capacitor bank

Special attention should be drawn to the capacitor bank design so as to meet acoustic sound power levels as specified in the technical specification (see Clause 7). A sound power calculation should be provided for each bank.

11.2.3 Electrical data

Table 2 is a checklist of data which could be used by the contractor for purchasing the equipment or to inform the customer of the design parameters.

Table 2 – Electrical data for capacitors

Capacitor design parameter	Unit
Rated harmonic frequency	Hz
Rated capacitance per phase (at +20 °C)	µF
Tolerance on rated capacitance	±%
Maximum variation of capacitance versus temperature	%/°C
Maximum total losses at rated voltage and rated temperature	W/kvar
Maximum dielectric losses at rated voltage and rated temperature	W/kvar
Variation of tan (δ) versus frequency	[a]
Rated voltage (U_N) across capacitor bank including harmonics	kV(RMS)
Harmonic voltage spectrum [b], steady state	n/kV(RMS)
Minimum voltage across capacitor bank excluding harmonics	kV(RMS)
Total current (including harmonics)	A(RMS)
Harmonic current spectrum [b], steady state	n/A(RMS)
Continuous voltage across capacitor bank for evaluation of sound power level including harmonics	kV(RMS)
Harmonic voltage spectrum for evaluation of sound power level	n/kV(RMS)
Maximum sound power level	dB(A)
Lightning impulse withstand level (LIWL)	
High voltage terminal to ground	kV
Low voltage terminal to ground	kV
High voltage terminal to low voltage terminal	kV

Capacitor design parameter	Unit
Switching impulse withstand level (SIWL)	
High voltage terminal to ground	kV
Low voltage terminal to ground	kV
High voltage terminal to low voltage terminal	kV
Applied AC test voltage to ground (50 Hz or 60 Hz, 1 min)	kV(RMS)

[a] The variation of tan (δ) with frequency from fundamental to the highest harmonic should be given as a graph or table.

[b] The harmonic voltage or current spectrum is specified in terms of the order number and the RMS value of the individual harmonic voltages or currents.

11.2.4 Tests

Unless otherwise stated, routine tests and type tests should be performed in accordance with the relevant clauses of IEC 60871-1 [5] and/or IEEE Std 18 [6]. Tests on support insulators, where applicable, may be performed in accordance with IEC 60168 [27]. If the customer has additional specific requirements for special or "other" tests and for verification of equipment performance, then these should be stated.

Such requirements may include, for example, the following.

- Discharge test

  A discharge test of the capacitor unit should be performed by charging the capacitor to a DC voltage equal to 1,7 to 2,5 times the rated voltage and discharging it by a short-circuit between the terminals. The DC voltage level to be used in the test should be agreed between customer and contractor.
- Measurement of capacitance dependence on frequency and temperature
- Impregnant test

  The component supplier should propose tests to prove the adequacy of the chemical and electrical characteristics of the applied impregnant.
- Verification of acoustic noise

  The contractor should demonstrate by analytical methods the expected total sound power level in dB(A) for each capacitor bank at fundamental and harmonic voltages as given in the electrical data list.
- Seismic qualification

  To be performed by the contractor or his sub-contractor, if applicable (see Clause 10).

  It is recommended to provide the data of field acoustic noise measurements for the capacitor banks.

11.3 Reactors

11.3.1 General

The standard usually applied for specifying AC filter reactors is IEC 60076-6 [28] which contains a clause dealing with filter reactors..

Since the type of reactor applied in AC filters is usually air-core dry-type, the following information refers to this type of reactor only.

11.3.2 Design aspects

Usually, the reactors are single phase with a winding designed for outdoor installation, for air cooling by natural convection. Therefore, all materials are chosen so as to provide satisfactory withstand to the climatic and environmental conditions encountered at site. For reactors installed in areas of high urban based pollution or oceanic based salt pollution, care should be paid to the protection of the reactor winding against the adverse effects of electrolytic deposition. Under such operating environments, tracking can occur on the surface of AC stressed dry-type air core reactors. It is therefore recommended that if salt type pollution can occur, the reactors should be coated with special coating such as RTV single-component, low temperature curing silicone elastomer, having special hydrophobic properties to prevent water filming on the winding surfaces directly exposed to the environment.

The temperature class of the insulation material usually is either class B (130 °C) or class F (155 °C).

Dry-type air-core reactors do not have an iron core. Therefore, the magnetic field is not constrained and will occupy the space around the reactor winding. Although the magnetic field reduces in strength with increase in distance from the reactor, the presence of this field should be taken into consideration for the installation of dry-type air-core units. The extent to which care has to be taken is largely a function of kVA and is lower for low kVA units.

Usually, the reactors are mounted on support insulators and support structures. The reason for providing support structures may be twofold, firstly to supply safety clearance for substation personnel to the equipment on high potential and secondly to provide sufficient magnetic clearances to the foundations on which the reactors are installed.

The dimensions of the electrical terminals of the reactor and the associated connectors should be kept as small as possible so as to avoid substantial eddy current loss due to the magnetic field of the reactor.

The support structure should be designed so as not to have shorted loops otherwise currents could be induced by the magnetic stray field of the reactor. Grounding of the support structure should be accomplished without creating closed loops in the grounding system.

If necessary, the winding may be designed with intermediate tap positions for inductance variation in steps. Tap position setting is done off-circuit, by hand, without affecting the reactor's main terminal connections.

Usually, the filter circuits would require the use of reactors with Q values at harmonic frequencies much lower than the "natural" reactor Q factor. This may be achieved by connecting a resistor in the circuit with the reactor to damp the filter response. Usually, the resistors are connected in parallel with the reactors. An alternative to the use of a resistor is the addition of a de-Q'ing structure on the reactor, which can reduce its Q factor. The de-Q'ing structure typically consists of several coaxially arranged short-circuited metallic rings which couple with the main field of the reactor. The induced currents in the closed rings dissipate energy and thus lower the Q factor of the reactor.

If the reactors are equipped with lightning arresters, they should be mounted so that the pressure relief valve does not impinge on the reactor.

Special attention should be drawn to the winding design so as to meet acoustic sound power levels as specified in the technical specification. A sound power calculation may be requested for each unit (see Clause 7).

11.3.3 Electrical data

Table 3 is a checklist of data which could be used by the contractors for purchasing the equipment or to inform the customers of the design parameters.

Table 3 – Electrical data for reactors

Reactor design parameter	Unit
Rated harmonic frequency	Hz
Rated inductance	mH
Tolerance on rated inductance (applicable for reactors without tapping range)	±%
Tapping range	±%
Step size	%
Q-value of reactor at fundamental frequency	
Q-value of reactor at rated harmonic frequencies	
Tolerance on Q-value at fundamental frequency	±%
Tolerance on Q-value at rated harmonic frequency [a]	±%
Current ratings:	
Maximum continuous current, including harmonics	A(RMS)
Harmonic current spectrum [b], steady state	n/A(RMS)
Maximum temporary current, including harmonics	A(RMS)
Temporary harmonic current spectrum	n/A(RMS)
Duration	h
Currents for evaluation of sound power level	n/A(RMS)
Maximum sound power level	dB(A)
Transient current	
Amplitude	kA(peak)
Time to crest	μs
Short-circuit current, thermal [c]	kA(RMS)
Short-circuit current, mechanical [c]	kA(peak)
Duration [c]	s
Rated AC voltage (including harmonics)	kV(RMS)
Lightning impulse withstand level (LIWL)	
High voltage terminal to ground	kV
Low voltage terminal to ground	kV
High voltage terminal to low voltage terminal	kV
Switching impulse withstand level (SIWL)	
High voltage terminal to ground	kV
Low voltage terminal to ground	kV
High voltage terminal to low voltage terminal	kV
Applied AC test voltage to ground (50 Hz or 60 Hz, 1 min)	kV(RMS)

[a] Tolerance on Q value at rated harmonic frequency may be of significant importance (Clause 6).

[b] The harmonic current spectrum is specified in terms of the order number and the RMS value of the individual harmonic currents.

[c] If applicable.

11.3.4 Tests

Unless otherwise stated, routine tests and type tests should be performed in accordance with the relevant clauses of IEC 60076-6 [28]. Tests on support insulators, where applicable, may be performed in accordance with IEC 60168 [27]. If the customers have additional specific requirements for special or "other" tests and for verification of equipment performance, then these should be stated.

Such requirements may include, for example, the following.

- Acoustic noise

The contractors should demonstrate by analytical methods the expected total sound power level in dB(A) for each reactor at fundamental and harmonic currents as given in the electrical data list above. As shown in Clause 9, audible noise measurements based on fundamental frequency are of little significance.

- Seismic qualification

To be performed by the contractor or his sub-contractor, if applicable (see Clause 10).

11.4 Resistors

11.4.1 General

IEC TS 63014-1 [29] gives guidance with respect to both rating and testing of resistors Since the type of resistors applied in AC filters is usually dry-type, the following information refers to dry-type resistors with air cooling by natural convection.

11.4.2 Design aspects

The resistors should be designed with negligible inductance and with low dependency of resistance versus harmonic frequencies.

The resistors are made of wires (grid type resistors), deployed metal sheets or cast metal elements. It is preferable to utilize active material with low variation of resistance vs. temperature so as to minimize the variation of the filter characteristic with working temperature at various loading conditions and ambient temperature.

Usually, the resistor elements are mounted in an enclosure for protection against rain to avoid eventual harmful effects of rain water during any mode of operation. The enclosures should be designed so as to prevent the ingress of birds or other animals. Further they should be designed so as to allow simple opening for maintenance. Depending on the environmental site conditions, it may be advisable to make the enclosures of stainless steel, or hot dip galvanized structural steel or corrosion resistant structural aluminium.

The enclosure should be electrically connected to one point of the resistor elements, typically the resistor mid-point.

For the electrical insulation of resistor banks consisting of several series connected modules, consideration should be given to the effects of non-linear transient voltage distribution. See the recommendation for lightning testing (see 11.4.4).

Bearing in mind that the temperature rise of the resistor elements may be considerably high (up to 600 °C), the choice of the insulation within a resistor module requires great care, since the high temperature of air will impact the insulation performance. The breakdown voltage of air at these high temperature levels may be reduced to typically 50 % of the value at ambient temperature. "Chimney effects" of vertically stacked resistors also need to be accounted for.

Care should be taken for the design and the material selection of the electrical terminals to achieve adequate performance at high temperature. Further, the high temperature rise of the resistors requires the internal and external electrical connections of the resistors to be made with sufficient sag so as to avoid undue mechanical stress by thermal expansion.