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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

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- withdrawn,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

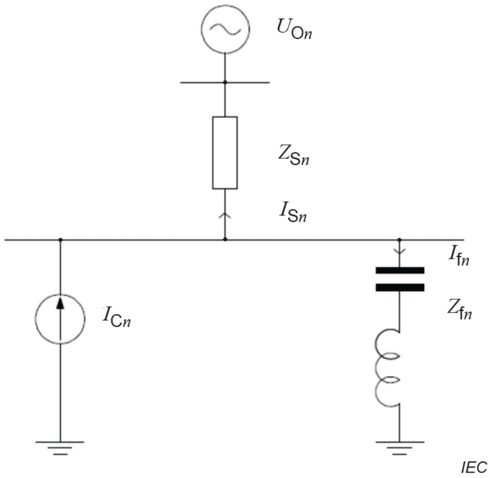
4.1 General

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.

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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 $I^{i}{}_{fn}$ and $I^{ii}{}_{fn}$, one option is that that these individual contributions to filter rating are summated on root sum square (RSS) basis at each harmonic:

$$I_{fn} = \sqrt{I_{fn}^{i\;2} + I_{fn}^{ii\;2}} \tag{3}$$

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

4.2.4.2 Capacitors

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

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

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.

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