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TECHNICAL REPORT

colour inside

High-voltage direct current (HVDC) systems – Guidance to the specification and design evaluation of AC filters – Part 2: Performance

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CONTENTS

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

Part 2: Performance

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IEC TR 62001-2, which is a Technical Report, has been prepared by subcommittee 22F: Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment.

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

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

a) expanded and supplemented Clause 19, and Annex B;
b) new Clause 3 on current-based interference criteria;
c) new annexes on induced noise calculation with Dubanton equations;
d) addition of a TIF requirement in a technical specification,
e) specification of IT limits dependent on network impedance and on the impact of AC network harmonic impedance; and
f) specification of voltage level on the filter design necessary to fulfil an IT criterion.

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

Enquiry draft	Report on voting
22F/410/DTR	22F/414/RVC

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

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

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

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

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- withdrawn,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

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

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

INTRODUCTION

The IEC 62001 series is structured in four parts:

Part 1 – Overview

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

Part 2 – Performance

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

Part 3 – Modelling

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

Part 4 – Equipment

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

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

Part 2: Performance

1 Scope

This part of IEC 62001, which is a Technical Report, provides guidance on the performance aspects and verification of performance of harmonic filters.

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

This document concerns the "conventional" AC filter technology and line-commutated high-voltage direct current (HVDC) converters.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC TR 62001-1:2016, *High-voltage direct current (HVDC) systems – Guidebook to the specification and design evaluation of AC filters – Part 1: Overview*

IEC TR 62001-4:2016, *High-voltage direct current (HVDC) systems – Guidebook to the specification and design evaluation of AC filters – Part 4: Equipment*

3 Current-based interference criteria

3.1 General

Permissible distortion limits and performance measures for limiting telephone interference, such as telephone interference factor (TIF), product of RMS current (A) and TIF (IT), (the definitions of these criteria are shown in 3.3.4.1 and Clause A.4), are discussed in details and summarized in IEC TR 62001-1:2016, Clause 4. Where these measures are applied with strict limits, particularly current-based criteria such as IT, they can be a decisive or limiting factor for filter design. Thus, these measures can directly affect the costs of filters and the concomitant effects of larger filters (extra station space, shunt reactors to compensate excess reactive power produced by the filters, etc.). On the other hand, a few HVDC projects have experienced high levels of telephone interference that caused problems during commissioning and early operation. Reference [1][1] considers basic interference criteria, defines telephone interference limits and discusses consequences of the telephone interference for filter design.

Because these criteria, based on psophometric or C-message weighting of harmonics, are specific to evaluation of noise induced on telephone circuits electromagnetically coupled to AC lines, they should only be specified where significant coupling between AC transmission

1 Numbers in square brackets refer to the Bibliography.

lines and analogue telephone circuits can be reasonably anticipated. This document provides guidance for discriminating those situations where risk of telephone interference exists. However, there are many factors that affect the potential for telephone interference and it is not possible to provide definitive, quantitative guidelines. One of the most elusive factors is the propagation of harmonic currents through the AC system. Experience has shown that significant harmonic HVDC-created current flow can exist in lines that are remote from the converter station and beyond transformations to other transmission voltage levels. A full inductive coordination study, which involves the calculation of harmonic current flow in the system in order to determine the problematic transmission lines and the assessment of their actual coupling with the adjacent telephone lines, is the only mean to assess the interference potential with any certainty.

The specification of telephone interference should also take into account local particularities, as discussed in 3.2.

A valuable paper produced by the Joint Task Force 02 of WG14.03/CC.02 [2] gives a very complete description of the inductive coordination process and the main parameters affecting telephone interference. The IT limits are based on experience from the Finnish telephone system, while making use of some approximations for the network characteristics. This document will focus on North American practice for IT limits, although the principles and calculation methods are applicable worldwide and will indicate the important system parameters that need to be defined in a technical specification.

In systems where telephone interference potential can be judged to exist, proper specification of harmonic current- and voltage-based performance criteria are of great importance to protect the interests of the HVDC system owner. If not sufficiently addressed by the specifications, and should telephone interference problems arise, the consequences to the HVDC owner can be severe. Resolution of telephone interference after the HVDC system is placed into service can be highly expensive and time consuming. Post-commissioning resolution of telephone interference is complicated by the fact that the interference directly affects parties other than the HVDC owner, i.e. the telephone system operator and its subscriber customers. It is possible that the HVDC system can be forced to cease operation by legal or regulatory action until the HVDC filtering system is redesigned and modified or telephone system mitigation measures are applied. When the whole process of inductive coordination is done correctly, it is much easier to face a problem at the initiation of the project.

If not used with consideration, the requirements, and equally important how to evaluate them, can lead to an unduly complex and costly design. Clause 3 attempts to clarify many aspects of the subject, presenting the theory, assessing practical experience and providing guidelines.

3.2 Determining the necessity for telephone interference limits

While voltage distortion control is a common concern for any electrical network, telephone interference is highly project-dependent. Interference can occur when harmonic currents flow in an AC transmission line which runs parallel to telephone lines. The harmonic currents induce a disturbing voltage in the telephone lines which is proportional to the length of exposure and the per unit mutual impedance between the two circuits. 3.2 specifically deals with harmonic limits related to telephone interference such as IT, TIF, I_{eq} and THFF. These criteria aim to control the interference induced in cable wire telephone lines transmitting signals in the (vocal) audible frequency band, i.e. approximately between 200 Hz and 3 500 Hz.

There is no easy way to give quantitative guidance as to the conditions where telephone interference has the potential to be of significance for a project, or where specific telephone-interference oriented specifications are needed to protect the buyer. Qualitative guidelines are provided below. If there is concern that a project can have susceptibility to one or more of these factors, an inductive coordination study is desirable to guide the development of specifications.

Conditions known to increase the susceptibility to AC-side telephone interference are the following:

- Long sections of exposure between AC lines carrying converter harmonic currents and telephone lines.
- Close proximity of AC transmission lines and parallel telephone lines.
- Even moderate separation distances and longitudinal exposures if combined with very high earth resistivity.
- Open-wire telephone lines. However, shielded twisted-pair telephone circuits provide only a partial reduction of coupling potential, and such circuits are by no means exempt from potential interference issues.
- Radial transmission line(s) to the converter station, where all converter harmonics are forced into the one single-circuit or double-circuit line.
- AC transmission systems having a hybrid overhead/underground design, with overhead lines interspersed with underground cable sections.
- AC transmission systems with a large number of capacitor banks in electrical proximity to the converter station, causing numerous resonances in the AC network. Analysis is complicated in these systems because all combinations and permutations of capacitor bank status can need to be considered.

Converter harmonic currents are not limited to the AC lines terminating at the converter station. Harmonic currents can penetrate several tiers into the transmission network and can cross over transformers to other voltage levels. This can be problematic when lower-voltage transmission lines are more closely coupled to telephone circuits. There is a general tendency for harmonic currents to diminish for tiers remote from the converter station, but this general trend can be offset by resonance conditions to produce greater harmonic current levels at second and higher tier lines than on first-tier lines connected to the converter station.

The following conditions can be assumed to indicate non-existence of telephone interference issues at vocal frequency, and thus no need for psophometric or C-message weighted specifications:

- all exposed telephone circuits are fibre optic cable;
- multiplex systems (time or frequency multiplexing):
- no telephone circuits exposed.

Worldwide experience of HVDC has shown that in some places, telephone interference limits have not been specified, yet no problems have been experienced. Indeed, telephone systems are very similar from country to country but others parameters affecting the potential for interference can be quite different. In North America for instance, telephone interference is a big concern because of the structure of the telephone and transmission systems in rural areas favouring long exposures and close proximity. There is also powerful legal protection for consumers and utilities with a risk of serious economical consequences for an HVDC project causing excessive telephone interference. On the other hand, in China for example, most telephone lines are generally remote from HV transmission lines. Huge HVDC infrastructure projects can have a “national interest” dimension which means that in terms of the overall effect on society it is more important to build them quickly and economically, and to address possible telephone noise problems as a separate issue.

Nearly all homes and small businesses in North America and many other parts of the world are still connected to the phone network by the same pair of twisted copper wires that have been in use for decades. Given the continued hurdles to fibre deployment and the increasingly high transmission speeds available over the existing copper network, it is likely that copper will continue to be the industry’s standard for many years to come. This is especially true in rural areas due to the economics of installing fibre optic cabling or coaxial cabling through low density areas. However, in many countries the cellular phone digital technologies are tending to leapfrog analogue landline telephone system. Furthermore, telecom operators’ tariffs in these countries are guiding people to use mobile phones only.

Past experience within the utility and the telephone company with telephone interference from existing facilities would be the best reference since it is likely to reflect the particular situation where the new HVDC project will have to operate.

3.3 Defining telephone interference limits

3.3.1 General

IEC TR 62001-1:2016, Clause 4 gives general recommendations for determination of limits without detailed studies due to possible short time schedule, lack of computational tool, lack of telephone system data or if no serious interference problems are expected because of harmonic distortion. It refers to IEEE Std 368-1977 [3] which gives a table suggesting range of limits applicable to HV and EHV transmission lines, with a clear warning that telephone interference should be carefully studied on a case-by-case basis. The table of values was merely illustrative and its derivation is not given. Successive standards (IEEE Std 519-1992 [4] and CAN/CSA-C22.3 No. 3-98 [5]) have copied this table with no apparent verification of its validity. On the other hand, experience shows that some HVDC schemes with a specified IT emanating from a converter bus of between 25 000 A and 50 000 A function with no problems of telephone interference. Applying these previous limits without any study is therefore not recommended.

If it has been established that there is a significant risk of telephone interference related to a particular HVDC project, a detailed study is required to assess the limits for the AC filter performance specifications. 3.3 gives a general description of the procedure to calculate the influence of a given transmission line on adjacent telephone lines. The method presented is based on the North American practice because interference problems appear to be more acute in that part of the world, and focuses on telephone cable systems, but the same basic principles apply to other systems with different susceptibility levels. Tables of illustrative values of coupling are provided.

It is also necessary to assess the harmonic current flow in transmission lines adjacent to the HVDC project in order to identify the ones that need to be considered for the telephone interference requirement of the HVDC project, and their possible level of interference. Recommendations are given on the required information about the AC system that needs to be included in a specification to achieve an adequate AC filter design.

3.3.2 Mechanisms of interference

Harmonic currents flowing in a transmission line induce harmonic voltages and currents in nearby installations. This voltage can be measured between one end of the telephone conductor and ground, with the remote end grounded, and is called the longitudinal voltage. The longitudinal voltage induced in any parallel conductor can be calculated as follows:

$$Vg_{n} = \sum_{j=1}^{k} (I_{jn} \times Zm_{jn}) \quad (1)$$

where

n is the harmonic number;

j is the conductor number;

k is the number of conductors on the transmission line;

Vg_{n} is the longitudinal voltage at harmonic n;

I_{jn} is the phasor current in conductor j at harmonic n;

Zm_{jn} is the mutual impedance between conductor j and telephone line at harmonic n, including the screening effect of the ground wires and any other nearby grounded conductors.

In Equation (1), the harmonic currents flowing in the transmission line are calculated by the HVDC converter contractor according to the method defined in the technical specifications.

The mutual impedance depends mainly on earth resistivity, separation between transmission and telephone lines, transmission line configuration and frequency. Inductive coordination studies require the calculation of mutual impedances for a large number of exposures between AC transmission lines and telephone lines. The calculation usually includes the effect of screening conductors like shield wires or any other extended conductive installation close by. This calculation is generally done by specialised computer programs such as EMTP, CORRIDOR, MathCAD, CDEGS[2]. However, for simple cases, Dubanton equations [6] can be used with satisfactory results for a typical range of values of exposures. In addition, the calculation of coupling for irregular exposures involves breaking down the exposures into a series of parallel sections and adding these together to obtain the total coupling [7, 8]. Some computer programs have the capacity to calculate mutual impedances for irregular exposures (Crinoline toolbox in EMTP, CDEGS).

Modern telephone lines use shielded cables to transmit the voice signal to each customer via a twisted conductor pair. The shield supports the same harmonic induced voltages as the conductor pair but allows current flow through its grounded ends which cancels out part of the induced voltage in the conductor pair and is very effective at higher frequencies to reduce the longitudinal voltage. The resulting interference voltage is the difference between both conductor longitudinal voltages, which is called the metallic or transverse voltage, and is the voltage which appears across a telephone receiver.

NOTE The terms "common mode" for longitudinal and "differential mode" for transverse are also used.

The ratio between metallic and longitudinal voltage is called the balance of the circuit and is frequency dependent. The metallic voltage is then weighted to reflect the frequency response of the ear and the telephone system. The C-message weighting is used in North America while psophometric weighting is used in Europe. Other parts of the world adopt one or other of these methods.

The total effective noise will be calculated by the root of the squares of these weighted components for each harmonic to be considered. The total weighted metallic noise voltage is given by:

$$Vm = \sqrt{\sum_{n=1}^{n=m}\left(\left|\sum_{j=1}^{j=k} I_{\mathrm{jn}} \times Zm_{\mathrm{jn}}\right| K_{\mathrm{n}} \times B_{\mathrm{n}} \times C_{\mathrm{n}}\right)^{2}} \tag{2}$$

where

m is the maximum order of harmonic to be considered;

C_{n} is the C-message or psophometric weighting of harmonic n;

K_{n} is the telephone circuit shielding factor at harmonic n;

B_{n} is the telephone circuit balance at harmonic n.

The telephone circuit shielding and balance factors are generally provided by the telephone companies. In practice, the shielding improves with frequency while the balance gets worse as frequency increases. The combined factor is almost constant over the frequency range of interest.

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

IEEE Std 1124-2003 [9] provides a great deal of information about the calculation of mutual impedances and the characteristics of the different parameters relevant to an inductive coordination study. The methodology of inductive coordination for a DC transmission line is basically the same as for an AC line. Useful information on the management of electromagnetic interference by power systems on telecommunication systems can also be found in [10]. Influence of voltage and current distortion on telephone interference level is considered in Annex A.

3.3.3 Noise performance coordination levels

ITU-T EMC-1.6 [11] used in Europe and elsewhere states that the psophometric voltage measured across a resistance of 600 Ω at one end of the line with the remote end terminated with its characteristic impedance should not exceed 0,5 mV.

The North American standards ([12], [13]) recommend limiting the noise contribution on the customer loop to 20 dBrnC. The telephone circuit noise is defined relative to 1 pW in 600 Ω, i.e. relative to an applied voltage of 24,5 μV, and is expressed in dB above this level.

$$N_{\mathrm{m}}\ (\mathrm{dBrnC}) = 20 \log (V_{\mathrm{m}}/(24{,}5 \times 10^{-6})) \quad (3)$$

where

N_{m} is the metallic (transverse) noise expressed in dB above 24,5 μV.

The corresponding metallic noise voltage is 0,245 mV, which is therefore stricter than the ITU counterpart (0,5 mV).

Since the influence of transmission lines on telephone interference is more predominant in North America, the following discussion will focus on the American practice.

The basic quantities in the characterization of interference between HV transmission lines and telephone lines are:

$$N_{\mathrm{m}}\ (\mathrm{dBrnC}) = N_{\mathrm{g}}\ (\mathrm{dBrnC}) - B_{\mathrm{al}}\ (\mathrm{dB}) \quad (4)$$

where

N_{g} is the longitudinal noise to ground expressed in dB above 24,5 μV;

B_{al} is the balance of the telephone circuit in dB (ratio of disturbing longitudinal voltage and the resulting metallic voltage).

Noise to ground is the result of power influence from the HV transmission line and the coupling between this transmission line and a telephone line. This value is related to the level of harmonic current in the transmission line and thus under the network owner's control. The balance measures the susceptibility of the telephone system and as such is the responsibility of the telephone company.

Electrical coordination standards ([5], [13], [19]) define performance thresholds for metallic noise, longitudinal noise and balance on normal business or residential lines which are cable lines as described in Tables 1 to 3.