



BSI Standards Publication

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

Part 2: Performance

National foreword

This Published Document is the UK implementation of IEC/TR 62001-2:2016. Together with PD IEC/TR 62001-1:2016, PD IEC/TR 62001-3 and PD IEC/TR 62001-4:2016, it supersedes PD IEC/TR 62001:2009 which will be withdrawn on publication of all parts of this series.

The UK participation in its preparation was entrusted to Technical Committee PEL/22, Power electronics.

A list of organizations represented on this committee can be obtained on request to its secretary.

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Published by BSI Standards Limited 2016

ISBN 978 0 580 91367 9

ICS 29.200

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This Published Document was published under the authority of the Standards Policy and Strategy Committee on 31 August 2016.

Amendments/corrigenda issued since publication

Date	Text affected
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TECHNICAL REPORT



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

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.200

ISBN 978-2-8322-3540-9

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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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:

$$V_{g_n} = \sum_{j=1}^k (I_{jn} \times Z_{mjn}) \quad (1)$$

where

n is the harmonic number;

j is the conductor number;

k is the number of conductors on the transmission line;

V_{g_n} is the longitudinal voltage at harmonic n ;

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

Z_{mjn} 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, CDEGS². 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:

$$V_m = \sqrt{\sum_{n=1}^{n=m} \left(\sum_{j=1}^{j=k} I_{jn} \times Z_{mjn} \right) K_n \times B_n \times C_n}^2 \quad (2)$$

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.

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 μ V, and is expressed in dB above this level.

$$N_m \text{ (dBrnC)} = 20 \log (V_m / (24,5 \times 10^{-6})) \quad (3)$$

where

N_m is the metallic (transverse) noise expressed in dB above 24,5 μ V.

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:

$$N_m \text{ (dBrnC)} = N_g \text{ (dBrnC)} - B_{al} \text{ (dB)} \quad (4)$$

where

N_g is the longitudinal noise to ground expressed in dB above 24,5 μ V;

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.

Table 1 – Performance thresholds for metallic noise

Metallic noise thresholds dBrnC	Noise level performance category
≤ 20	recommended
$> 20 \leq 30$	acceptable
> 30	not recommended

Table 2 – Performance thresholds for longitudinal noise

Longitudinal noise thresholds dBrnC	Noise level performance category
≤ 80	recommended
$> 80 \leq 90$	acceptable
> 90	not recommended

Table 3 – Performance thresholds for balance

Balance thresholds dB	Noise level performance category
≥ 60	recommended
$\geq 50 < 60$	acceptable
< 50	not recommended

The "recommended" levels should be treated as both the overall design requirements and objective maintenance levels. The "acceptable" category is acceptable as a temporary situation only until improvement can be reasonably achieved or until telephone customer complaints have been received. Even "not recommended" levels of longitudinal noise or balance could be tolerated if there was low impact on the metallic noise performance. Noise levels above 20 dBrnC are not believed to uniformly result in customer complaint but levels above 30 dBrnC most probably will. On this basis, many communication companies consider an upper limit of 5 % of the network lines exceeding 20 dBrnC, with none above 30 dBrnC, to be an objective. For the particular case of a new HVDC project, the power company would have to control the longitudinal noise due to the power influence of the transmission lines affected by the harmonic generation of the converters to the recommended limit of 80 dBrnC.

3.3.4 Influence of power transmission lines

3.3.4.1 Definitions

The influence of power transmission lines depends on each conductor current at each harmonic, usually from 1 to 49, according to Equation (2). In order to ease the specification of a limit on power influence by the transmission system owner and the calculation of AC harmonic filter performance by the HVDC contractor, these different phase and harmonic components should be combined in a unique value which represents their global effect on the telephone interference level. The definition of power influence limit is discussed below.

It is convenient to convert the transmission line harmonic currents from phase quantities to symmetrical components. The harmonic currents generated by a HVDC converter are either of positive or negative sequence depending on harmonic order. Theoretically, no zero sequence (residual) harmonic currents are generated by the converter station. However, the positive and negative sequence current components flowing in a non-symmetrical electrical

component (i.e. the transmission line) will also partially convert to create some residual harmonic currents that need to be considered due to their high coupling to telephone lines. The harmonic currents flowing in a transmission line are therefore commonly expressed as balanced mode currents (either positive or negative sequence) and residual mode currents. Each is processed independently since it simplifies the specifications and as one mode usually predominates.

Equation (2) can be split in two components of metallic voltages:

$$V_{\text{mbal}} = \sqrt{\sum_{n=1}^{n=m} (I_{\text{bn}} \times Z_{\text{mbn}} \times K_n \times B_n \times C_n)^2} \quad (5)$$

$$V_{\text{mr}} = \sqrt{\sum_{n=1}^{n=m} (I_{\text{rn}} \times Z_{\text{mrn}} \times K_n \times B_n \times C_n)^2} \quad (6)$$

where

- V_{mbal} is the weighted metallic noise voltage in balanced mode (V);
- Z_{mbn} is the mutual impedance in balanced mode at harmonic n (Ω);
- I_{bn} is the balanced mode current at harmonic n (A);
- V_{mr} is the weighted metallic noise voltage in residual mode (V);
- Z_{mrn} is the mutual impedance in residual mode at harmonic n (Ω);
- I_{rn} is the residual mode current at harmonic n (A).

It is possible to further simplify the preceding equations with the concept of "equivalent disturbing current" [14]. This is a notional single frequency reference current flowing in a notional single conductor located geometrically between the line conductors which produce the same weighted noise in a nearby communication circuit. This representation allows the metallic noise voltage to be calculated with Equation (7):

$$V_{\text{m}} = I_{\text{eq}} \times Z_{\text{m1}} \times K_1 \times B_1 \quad (7)$$

where

- I_{eq} is the C-message weighted equivalent disturbing current (A);
- Z_{m1} is the mutual coupling impedance between the notional conductor and the communication circuit at the reference frequency (1 kHz), including the screening effect of shield wires on the transmission line towers and other grounded conductors (Ω);
- K_1 is the telephone circuit shielding factor at the reference frequency;
- B_1 is the communication circuit unbalance factor at the reference frequency;

The equivalent disturbing current I_{eq} (A) combines the effect of each individual harmonic current with Equation (8):

$$I_{\text{eq}} = \sqrt{\sum_{n=1}^{n=m} (I_n \cdot H_n \cdot C_n)^2} \quad (8)$$

where

- I_n is the the single frequency RMS current at harmonic n (A);
- m is the the maximum harmonic number to be considered;

H_n is the the weighting factor to account for the general nature of frequency dependent coupling between telephone cables and AC transmission line, normalized to 1 kHz.

The term H_n combines the frequency dependent characteristics of $Z_{mn} \cdot K_n \cdot B_n$ over the harmonic range from $n = 1$ to $n = m$, such that:

$$(Z_{mn} \cdot K_n \cdot B_n) = (Z_{m1} \cdot K_1 \cdot B_1 \cdot H_n) \quad (9)$$

The H_n factor for a specific project is based on the assessment of frequency dependencies of mutual impedances, shielding factor and balance for each individual exposure. Since each exposure requires theoretically a different H_n factor, a representative value should be developed for all the exposures involved in a specific project. [9] proposes a method to develop an adequate H_n factor. The combined effect of shielding and balance is practically constant over frequency so this factor reflects the characteristics of mutual impedance versus frequency.

An alternative concept to the "equivalent disturbing current" (A) is the "IT product". The IT product (often abbreviated to simply "IT") is widely used in North America as a measure of transmission line influence and is defined as follows:

$$IT = \sqrt{\sum_{n=1}^{n=m} (I_n W_n)^2} \quad (10)$$

where

I_n is the single frequency RMS current at harmonic n ;

m is the maximum harmonic number to be considered;

W_n is the single frequency TIF weighting at harmonic n ($= C_n 5 n f_o$).

Equation (10) combines the different harmonic contributions into a single value that represents the overall effect of all harmonic currents flowing in a line. The IT can be considered as a special case of I_{eq} which assumes a linear frequency dependence of the coupling. The IT product can be used with the balanced component of harmonic currents or the residual component. The balanced IT can have a large influence on telephone lines in close proximity to the transmission line but its influence decreases very rapidly with increasing separation between the two systems especially with low earth resistivity. The residual IT has a larger zone of influence and is more dependent on earth resistivity.

Similarly, it is possible to define a residual I_{eq} or a balanced I_{eq} depending on which component of the AC transmission line currents is considered. The I_{eq} criterion has the advantage of defining an H_n factor that better suits the frequency dependent coupling characteristic of a particular exposure, but the IT still should give acceptable results for most cases, taking into consideration the accuracy of the data.

Depending on each specific case, balanced mode coupling or residual mode coupling will prevail but, in most situations, both modes need to be considered. Combination of both coupling modes in one limit is possible by using a correction factor K_b computed from the most critical exposures:

$$K_b = Z_{mb1}/Z_{mr1} \quad (11)$$

where

Z_{mb1} is the balanced mode coupling at reference frequency;

Z_{mr1} is the residual mode coupling at reference frequency.

The K_b factor gives the appropriate weighting to the balanced mode harmonic currents I_n (A).

$$I_n = \sqrt{(I_{rn})^2 + (K_b \cdot I_{bn})^2} \quad (12)$$

where

I_{rn} is the the total residual mode current at harmonic n ;

I_{bn} is the the balanced mode current at harmonic n ;

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

Equation (12) uses RSS summation as a compromise, because the computation of phase angle difference between residual mode and balanced mode induced in each telephone line is too complex. The factor K_b of Equation (12) results in inaccuracy in assessing the influence of balanced mode since this factor is based on the most critical exposures. Where the inductive coordination study shows that the balanced mode is predominant, the equation can be rearranged so that the correction factor is applied to the residual mode. The resulting current can be used to calculate the equivalent disturbing current or IT (Equations (8) and (10)).

3.3.4.2 Illustrative values

An IT value can be converted to its equivalent 1 000 Hz current to calculate, with Equation (2), the resulting longitudinal noise for a given exposure characteristic. With the above considerations, it is possible to obtain a rough assessment of the risk of telephone interference as a function of IT levels and some readily available data on telephone lines. The calculations below are based on a longitudinal noise of 80 dBnC, a balance of 60 dB and a shielding of 10 dB. In fact, the shielding factor varies with cable type, exposure length, frequency and cable shield end grounds, but 10 dB can be used as a typical value for a significant exposure length. Table 4 and Table 5 respectively give maximum length of parallel exposures for a given balanced IT and residual IT as a function of earth resistivity and separation.

Table 4 – Illustrative maximum telephone line length to achieve the North American recommended longitudinal N_g level, as a function of balanced IT level, earth resistivity and separation distance

Separation m	Maximum exposure length km		
	100 $\Omega \cdot m$	1 000 $\Omega \cdot m$	10 000 $\Omega \cdot m$
40	1,0	0,9	0,9
130	3,7	2,9	2,5
500	44	12,2	7,0
1 000	240	29,7	12
3 000	2 880	350	39
NOTE Balanced IT level is 10 000 A.			

Tables 4 and 5 are based on a typical 230 kV transmission line with a horizontal configuration and two steel overhead shield wires. In practice, the coupling in balanced mode increases somewhat with the distance between phases (proportional to the transmission line nominal voltage), but the coupling in residual mode shows a rather low dependency on this parameter. Furthermore, any transmission line configuration which tends to minimize the difference in separation between the phases and the telephone line (vertical configuration) presents much lower coupling to balanced IT. A ratio of 10 to 1 between the balanced IT and residual IT basic levels is chosen because it is considered typical for HV transmission lines [15]. These figures are based on negligible grounding resistance at each end of the exposure; in practice, grounding resistance can have some effect on the induced voltage by

reducing the shielding effect of shield wires. These figures also assume that the current is constant along the transmission line, which can be true for a perfectly balanced line terminated by its characteristic impedance, but it is generally not the case.

Annex B shows an example which illustrates the different steps required to calculate the maximum length of a transmission line taking into account the particular characteristics of the exposure, the main characteristics of the telephone system and the recommended values of N_g . Using the same procedure, a user can recalculate such tables for his own situation, for example with a different line, or different assumptions about acceptable limits, shielding.

The maximum exposure length is inversely proportional to the IT level, and so the results of these tables can be proportionally adjusted to apply to alternative IT limits.

The results show that for this particular transmission line configuration

- short exposures and low IT are required when the separation distance is low,
- when the earth resistivity is high, the separation distance should be much larger, for the same exposure length, and
- for line configuration with low balanced coupling, residual IT becomes prevalent even at low earth resistivity.

Table 5 – Illustrative maximum telephone line length to achieve the North American recommended longitudinal N_g level as a function of residual IT level, earth resistivity and separation distance

Separation m	Maximum exposure length km		
	100 $\Omega \cdot m$	1 000 $\Omega \cdot m$	10 000 $\Omega \cdot m$
40	2,6	1,9	1,5
130	5,8	3,0	2,1
500	45	8,0	3,7
1 000	180	19,8	5,9
3 000	1 600	192	20
NOTE Residual IT level is 1 000 A.			

A rural telephone line can extend over 25 km or more, but generally only part of the line is close to a transmission line and only that part needs to be considered. For angled exposures, the equivalent horizontal projection length of the telephone line on the power line should be used, as described in [9].

This methodology can be compared to levels that were put forward in a CIGRÉ guide [2] based on the Finnish experience. According to this study, only communication cables with mutual impedance above 1 Ω were considered assuming an earth resistivity of 2 300 $\Omega \cdot m$. The noise to ground limit of 80 dB_{rnC} taking into account a communication cable shielding factor of 10 dB corresponds to a maximum longitudinal noise voltage of 0,775 V weighted (see Appendix 5.1 of [2]). For such communication cables ($Z_m > 1 \Omega$), the equivalent psophometric residual current should be limited to 0,775 A, which corresponds to a residual IT of 3 500 A using a conversion factor of 4 500. Doubling this limit because of the higher metallic voltage permitted by the ITU (European) standards results in a maximum residual IT of 7 000 A for the communication cables that show the lower coupling in the group of communication cables being studied. This figure can be compared to a recommended equivalent psophometric residual current of 2 A or a residual IT of 9 000 A based on Finnish communication cables according to [2], which will result in only 5% of the communication cable in the same group exceeding the recommended noise metallic limit.

It can be concluded that the North American telephone system is more susceptible to the influence of harmonic current flowing in power lines and that care should be exercised when using the limits recommended in [2] for other systems. Furthermore, a statistical approach can not be acceptable for a HVDC project because, in some countries, even a single case of excessive telephone interference can jeopardize the permission to operate the transmission line.

The values of Table 4 and Table 5 can be used to obtain rough estimates of IT limits based on the North American practice with minimal information on exposures between the telephone and transmission lines. These approximate IT limits could be used to specify a range of values to get the cost sensitivity of the filter design. However, many parameters can take a wide range of values that can affect significantly the calculated IT levels (notably cable balance can vary from 50 dB to 70 dB and shielding from 2 dB to 13,5 dB). It is therefore strongly recommended to perform detailed co-ordination studies when there are telephone lines in the proximity of the AC transmission lines, at least for the final selection of AC filter design.

3.3.5 Determination of IT limits for a specific project

3.3.5.1 General

3.3.5 will focus on the detailed studies to be performed in order to produce the technical specification of AC filters for a specific HVDC project. There is very little reference material available on this subject from previous experience, so 3.3.5 will concentrate on the description of the main parameters affecting the penetration of harmonics into the HV network, and the preparation of technical specifications.

It was considered in the past [16] that the calculation of harmonic currents in the conductors of AC transmission lines for the purpose of telephone interference control was too complex because of the extent of the transmission system and the number of network configurations to consider. However, with the computation tools now available and the improvement in transmission element models, it is easier to perform such studies and the accuracy is deemed acceptable. Indeed, an example at the end of 3.3.5.3 shows that it is possible to reproduce a case of severe harmonic amplification on a transmission system by a detailed simulation model. In any case, a telephone interference limit obtained by calculation with the relevant actual characteristics of the network is preferable to an arbitrary limit.

The first step would be to identify the transmission lines that carry a substantial part of, or magnify, the harmonic currents generated by the planned converter station. These transmission lines will likely dictate the telephone interference requirements of the HVDC project. An inductive coordination study should then be performed to determine the telephone interference limit profile along these transmission lines. Finally, all the relevant data should be included in the technical specification so that the HVDC contractor could reproduce the harmonic current flow in these transmission lines and optimize the filter design, ideally with a simple calculation method.

The pre-specification studies can require a large effort to identify all of the harmonic current issues associated with a large AC system, especially where many telephone lines are involved. The presence of a nearby HVDC system will require additional effort to represent its contribution to the telephone influence requirements. Consequently, these studies are started at an early stage of the project in order to not interfere with the project schedule.

3.3.5.2 Identification of the decisive transmission lines

The obvious lines of interest are those directly connected to the converter station, but harmonic currents can also flow in remote lines due to particular network characteristics, for instance with the presence of cables. A harmonic penetration study is performed to determine which transmission lines should be considered. Such a study can be done with the same digital tool as used to perform the impedance locus study, looking at transmission line harmonic currents when injecting a unitary current at the point of connection of the converter

Transferred currents are determined as a function of frequency, up to about 3 000 Hz, at least for the main harmonic orders generated by HVDC converters.

The converter mainly generates balanced sequence harmonics that will split between the different transmission lines connected to the converter bus according to their relative harmonic impedances, which depend on their electrical characteristics and end impedances. These harmonic currents can be magnified along the lines or at remote locations in the network. Consequently, the harmonic currents should be checked at several locations along their total length with all possible foreseen network configurations and operating conditions.

In addition, the transmission lines will convert positive or negative sequence harmonic currents injected by the converter into ground mode and negative or positive sequence currents, unless the configuration of the conductors is symmetrical with respect to each other and to ground (which is never the case), even when they are transposed for fundamental frequency. Because the coupling between telephone lines and transmission lines is higher in ground mode, this harmonic current ground mode should not be ignored. The sequence opposite (negative versus positive) to that of the current source can also be higher in magnitude than the source sequence at remote locations in the network.

In order to get realistic results, the transmission lines should be represented by an adequate three phase model with the best available assessment of earth resistivity along each transmission line. Note that transmission lines running in the same right of way should be modelled taking into account their mutual impedance because the zero sequence impedance is largely affected by any adjacent transmission line. The impedance at the point of connection should ideally be the same as the future converter installation in order to allow the flow of induced balanced and zero sequence harmonic currents due to mutual impedance between sequences. At the pre-specification study stage, this information is not available, but a low impedance should be assumed at least at characteristic harmonics for which there will probably be tuned AC filter branches. The converter transformers will also create a path to ground through the grounded wye – delta windings for zero sequence currents. At the load end, the different networks conditions are considered with network elements modelled in balanced and zero sequences (transformers, shunt capacitors, etc.) with proper grounding connection.

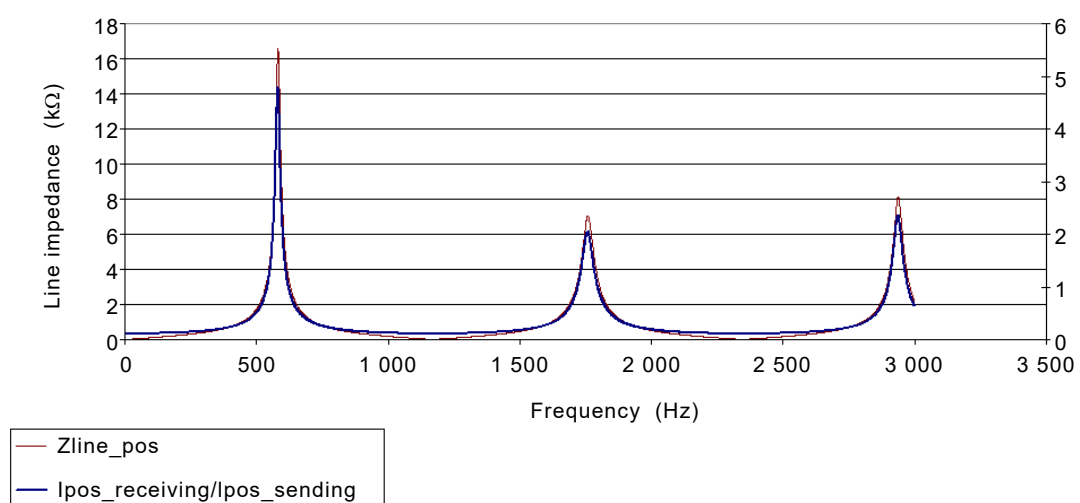
Care should be exercised not to consider unrealistic conditions like cases of parallel resonance seen at the point of connection of the converter which are likely to produce high currents at remote locations for a low current at the injection point. Such parallel resonance conditions generally present high harmonic impedance at the point of connection, which would cause most of the harmonic current to flow in the AC filters instead, especially at characteristic harmonic frequencies where tuned filters are generally provided. The TIF criterion used in many technical specifications has the benefit of avoiding such severe amplifications. Annex C describes a theoretical case.

One way to control this would be to consider only conditions for which the calculated harmonic voltages at the point of connection remain under a certain TIF level. In fact, the harmonic voltage distortion requirement will indirectly control the TIF level. For instance, a HVDC project complying with the planning levels of IEC TR 61000-3-6 [17] will limit the individual TIF levels to approximately 50 for odd harmonics which are non-multiple of 3 and to approximately 20 for others. Since the harmonic emission of the converter installation alone should be lower than the planning levels, lower values of TIF can be considered. Even with TIF limitation, it is likely that conditions leading to amplification at remote locations would be offset by the efficiency of filtering at characteristic harmonics, and that unrealistic conditions could be considered.

To further illustrate this concept, Figure 2 shows the ratio of positive sequence current at the receiving end to the positive sequence current at the sending end of a 230 kV line, horizontal configuration, 124 km long and fully transposed at 60 Hz together with its positive sequence impedance, calculated with EMTP with a variable frequency positive sequence unitary current source. A shunt element is connected to the sending end; this element has negligible zero sequence impedance and 800 Ω resistive positive and negative sequence impedance. The

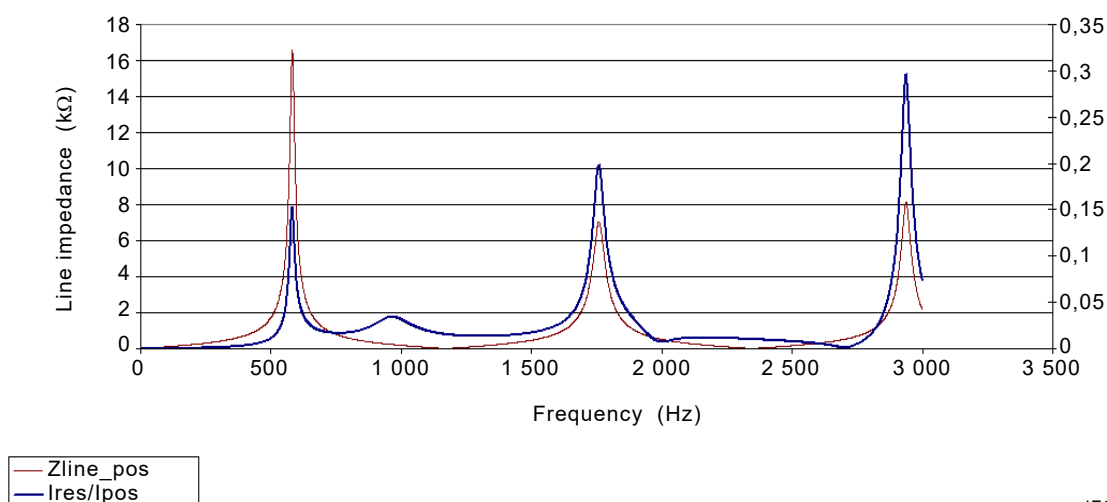
receiving end is grounded and earth resistivity equals $1\,000\ \Omega\cdot\text{m}$. A similar transfer factor can be found if the harmonic current is measured at the middle of the transmission line. High ratios of transfer factor can be found for frequencies close to resonance of the line but values well below 1 are found for low values of line impedance. At characteristic harmonics, where tuned filters should be provided, the filters are very efficient close to line resonance and less so for low values of line impedance. However, if the telephone line is located at the middle or the receiving end of the line, it can be concluded that limitation of IT at the sending end of the line can not be appropriate.

Figure 2 shows the ratio of ground mode current at the receiving end to the positive sequence current at the sending end. The residual harmonic currents in the middle of the line and at the receiving end have approximately the same magnitude and frequency dependence. Figure 2 shows a similar relation between transfer ratio of residual mode and line impedance as Figure 1.



IEC

Figure 1 – Conversion factor from positive sequence current at the sending end to positive sequence current at the receiving end, and input impedance of a 230 kV line, 124 km long, $1000\ \Omega\cdot\text{m}$



IEC

Figure 2 – Conversion factor from positive sequence current to residual current, and input impedance of a 230 kV line, 124 km long, $1\,000\ \Omega\cdot\text{m}$