PD IEC/TR 62001-2:2016

BSI Standards Publication

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

Part 2: Performance

National foreword

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TECHNICAL REPORT

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

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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

Part 2: Performance

FOREWORD

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The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a Technical Report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

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:

$$V\mathrm{g_n} = \sum_{j=1}^{k} (I_{\mathrm{jn}} \times Zm_{\mathrm{jn}}) \qquad (1)$$

where

n is the harmonic number;

j is the conductor number;

k is the number of conductors on the transmission line;

$V\mathrm{g_n}$ 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:

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

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.

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

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:

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

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.

Table 1 – Performance thresholds for metallic noise

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

Table 2 – Performance thresholds for longitudinal noise

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

Table 3 – Performance thresholds for balance

Balance thresholds dB	Noise level performance category
≥ 60	recommended
≥ 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:

$$V_{\mathrm{mbal}} = \sqrt{\sum_{n=1}^{n=m} \left(I_{\mathrm{bn}} \times Z_{\mathrm{mbn}} \times K_{\mathrm{n}} \times B_{\mathrm{n}} \times C_{\mathrm{n}}\right)^2} \qquad (5)$$

$$V_{\mathrm{mr}} = \sqrt{\sum_{n=1}^{n=m} \left(I_{\mathrm{rn}} \times Z_{\mathrm{mrn}} \times K_{\mathrm{n}} \times B_{\mathrm{n}} \times C_{\mathrm{n}}\right)^2} \qquad (6)$$

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):

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

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):

$$I_{\mathrm{eq}} = \sqrt{\sum_{n=1}^{n=m} (I_{\mathrm{n}} \cdot H_{\mathrm{n}} \cdot C_{\mathrm{n}})^2} \qquad (8)$$

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 dBrnC, 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 Ω·m	1 000 Ω·m	10 000 Ω·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 Ω·m	1 000 Ω·m	10 000 Ω·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 Ω-m. The noise to ground limit of 80 dBrnC 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 ($Z_m > 1$ Ω), 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 Ω-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.

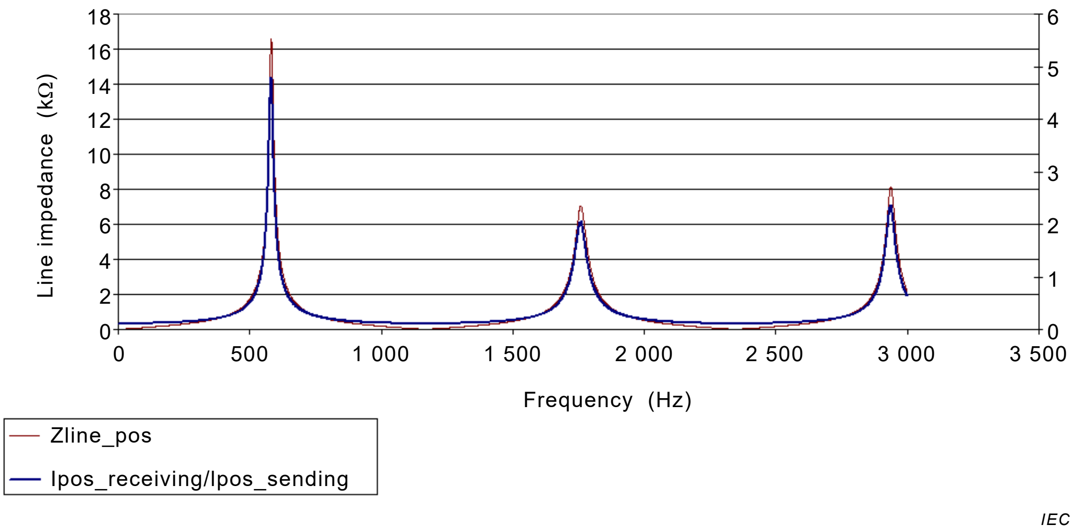


Figure 1 – Conversion factor from positive sequence current at the sending end to positive sequence current at the receiving end, and input impedance of a 230 kV line, 124 km long, 1000 Ω-m

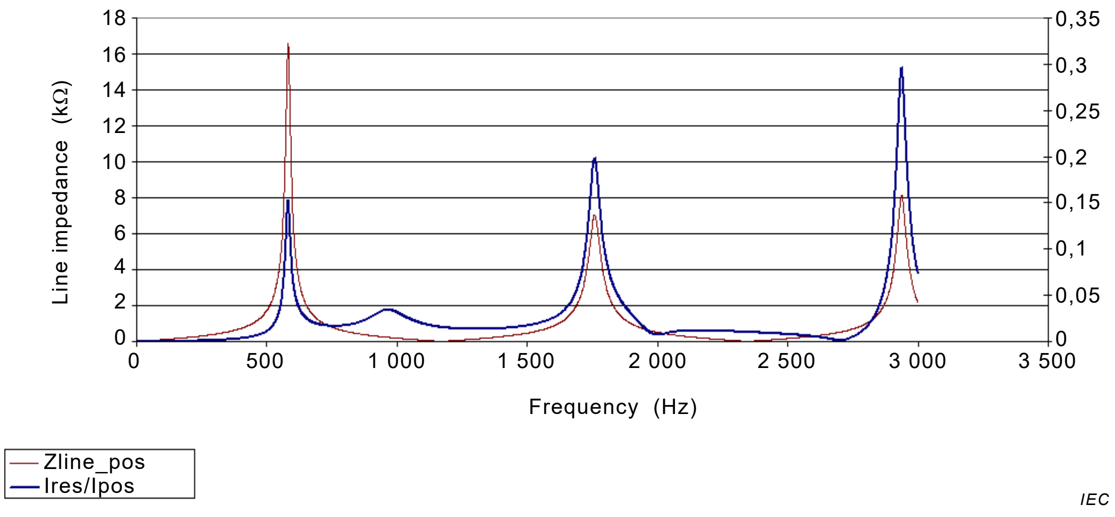


Figure 2 – Conversion factor from positive sequence current to residual current, and input impedance of a 230 kV line, 124 km long, 1 000 Ω-m

The digital simulations should take into account the accuracy of the network component data, the limitations of component impedance models in the frequency domain and the variation of component impedance with ambient and system conditions (see IEC TR 62001-3:2016, Clause 4 [18] and [1], Clause 2. In such studies, this is usually accomplished by considering a range of frequencies around the harmonic of interest. The range of frequency is chosen in accordance with the estimated accuracy of the network model. For instance, the analysis of the harmonic flow at the 11th harmonic would retain the worst result considering that the frequency of the injected current could vary from 627 Hz to 693 Hz (60 Hz times 11 ± 5 %) or 522,5 Hz to 577,5 Hz (50 Hz times 11 ± 5 %).

It has been said at the beginning of 3.3.5.2 that the objective of a harmonic penetration study is to determine the decisive transmission lines, in terms of telephone interference, by calculating transferred harmonic currents in nearby transmission lines. While the telephone interference is proportional to the balanced and residual harmonic currents flowing in parallel to the telephone lines, as shown in 3.3.4.2, the accurate determination of induced voltage in telephone lines requires the derivation of the three sequence components flowing in the transmission line, each being defined by a magnitude and a phase angle. In addition, the definition of the IT assumes a linear variation of the mutual impedance between the transmission line and the telephone line with frequency, which can differ somewhat from the real coupling characteristics.

A more straightforward and accurate method to determine the relative telephone influence of different transmission lines is to use test lines in parallel with the transmission lines to be checked. The voltages induced in such test lines will accurately indicate the level of telephone influence, albeit without the influence of shielding and balance, relative to the injected harmonic current, as long as the parallel separation is similar to the actual telephone lines adjacent to the transmission lines. More than one test line could be used if several separations are required to represent the different telephone lines involved. The reference value used to compare each transmission line influence would then be a C-message weighted voltage corresponding to the longitudinal induced voltage discussed in 3.3.4.2.

Note that at this stage it is only required to identify the transmission lines that need a telephone interference influence limit so the absolute IT or induced voltage levels are not critical. However, correction of severe amplification conditions by modification of the AC system can be considered at this stage, if deemed more economical.

3.3.5.3 Inductive coordination study

The transmission line influence alone is not enough to determine the need for limiting harmonic flow in a specific line; the presence of telephone lines and coupling characteristics are also verified. A meeting with the local telephone company representatives is recommended to ascertain the number of telephone lines involved and the range of exposure length and separation distance to the transmission lines. Valuable information on existing noise levels, shielding and telephone susceptibility can also be obtained on this occasion. A convenient way to proceed is to provide a set of maps showing the local roads and the transmission lines to the telephone company so they can highlight adjacent telephone lines (usually along the roads) in the zone of influence of the line. This zone of influence of a transmission line is a distance either side of the line for which the AC transmission line can cause significant induced noise. The extent of the zone depends on earth resistivity and length of telephone lines and can involve hundreds of telephone exposures.

Given the necessary information on telephone exposures and preliminary values of earth resistivity, it is then possible to calculate IT or I_{eq} limit for each exposure within the zone of influence, either by using Table 4 and Table 5, specialized software or the method described in [7] and [8]. At this stage, only the reference frequency mutual impedance (value at 1 kHz) is required. The results can be conveniently ranked in descending order of telephone influence values. It is then possible to estimate the probable cost of mitigation measures as a function of IT or I_{eq}. At this stage, the H_{n} and K_{b} factors required in the definition of the telephone influence limit should be derived from the most critical exposures.

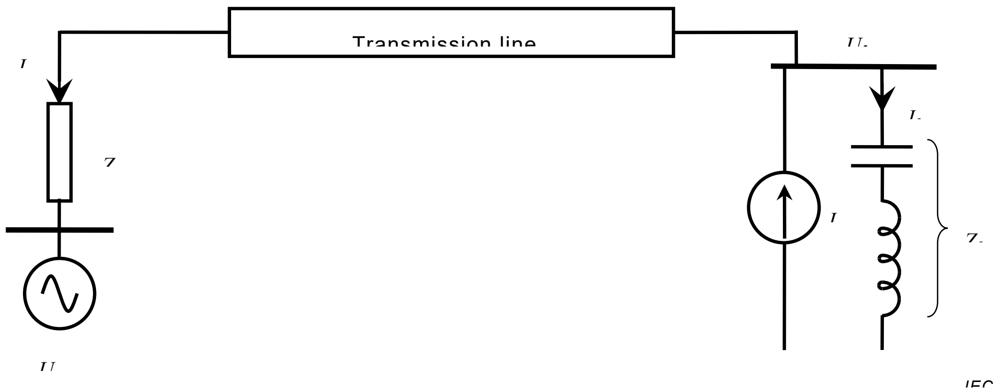
In parallel with this study, the estimate of filtering cost as a function of IT or I_{eq} should be sought from the potential HVDC contractors for normal operating modes. It should be recognized that the level of I_{eq} or IT specified should ideally be that at which the incremental cost of improving the filtering is equal to the incremental saving in mitigation required in the telephone circuits. The whole process of determination of the range of IT or I_{eq} limit appropriate for each line section is described in more detail in [9]. The derivation of appropriate limits should consider that some margin exists in practice since a noise level of three times the recommended limit can be accepted temporarily on telephone lines, until mitigation is applied to achieve the recommended level. This should be discussed with the telephone company taking into consideration the consequence of a risk of excessive noise and the degree of conservatism used in the assumptions and the determination of data.

It is recommended to accompany studies on harmonic penetration and inductive coordination with measurements of existing IT or I_{eq} on the questionable lines. If actual measurements show lower susceptibility levels of the telephone systems than the values estimated with this document, they are considered the more reliable.

3.3.6 Pre-existing harmonics and future growth

The telephone interference limit for a specific project should also consider pre-existing harmonic sources in the network and give allowance for future increase of the harmonic level. Indeed, the addition of a large AC filter installation can increase IT levels on transmission lines because the shunt filters act as a sink for pre-existing harmonics. Simply stated, the addition of a new shunt filter can increase harmonic current flow due to pre-existing harmonic distortion and thereby cause telephone interference.

The effect of pre-existing harmonics on the design of the AC filters has been discussed in depth in clause 3 in relation with the harmonic voltage distortion in the network. The same principles apply to the telephone influence of the transmission lines, except that the harmonic current in specific transmission lines is the parameter to control. Figure 3 shows a simple case to illustrate the application of pre-existing harmonics for telephone interference purposes.



Key

I_{cn} injected harmonic currents from the converter

Z_{fn} filter harmonic impedance

I_{fn} filter harmonic current

Z_{sn} AC network harmonic impedance

I_{sn} AC network harmonic current

U_{fn} filter (or optionally pcc) busbar harmonic voltage

U_{on} specified pre-existing harmonic voltage source

Figure 3 – Simple circuit for calculation of harmonic performance taking into account pre-existing harmonics

The pre-existing sources of harmonic current which are the most likely to influence the design of the new converter AC filters are large harmonic sources at the same voltage level, or in close proximity to the planned installation. In this case, an aggregate type of criterion should be used, as recommended in IEC 62001-3:2016, Clause 5 [18], in order to get realistic assessment of telephone influence in the decisive transmission lines. Where such a pre-existing harmonic source is present, the technical specification should provide all the data required to assess the harmonic generation of this source.

In principle, the pre-existing harmonics from other voltage levels are also considered. However, it requires the determination of an adequate model with consistent sets of harmonic voltages and impedances. Such models cannot be easily produced because of the sparsity of harmonic sources, the knowledge of harmonic levels in the network and the extent of network modelling required. It should also be recognized that the results of a study of telephone influence in an extended network cannot be very accurate because of the limitation in network models at higher frequencies (accurate up to the 20th harmonic according to IEC TR 61000-3-6 [17]) which are prevalent for telephone interference. This is particularly true for cases where the residual mode coupling is higher because it involves data on earth resistivity and surrounding screening circuits that are difficult to assess. Alternatively, a model combining worst case harmonic impedances with harmonic planning levels will likely result in very conservative IT levels, thereby eliminating possibly optimal AC filter solutions. It would be preferable to measure the pre-existing harmonic level at some existing bus of the network, but then consistent source voltage/network impedance sets are required in order to get realistic results. Measurements should cover most expected operating conditions and contingencies.

A rational approach could be to consider only harmonic generation by the HVDC converters (new project plus nearby converters) in the determination of the limit associated to a specific project. Experience from at least one large utility with a lot of high voltage capacitor banks installed at every voltage level shows that there has not been any problem of telephone interference in operation. In theory, any capacitor bank (including its series reactor) installed in a HV network is a sink for high order harmonics. Probably most of the background harmonic sources are located on the distribution level or at remote locations, and they see the HVDC filters through the intermediate transmission line and transformer impedances, which tend to prevent significant amplification because of the damping of loads and transformers.

In practice, other sources of interference like the distribution network (paralleling telephone lines) can also cause some additional level of interference in the telephone lines. A conservative approach would be to limit the contribution of each source to 17 dBrnC, considering RSS summation of the contributions. However, if the contribution of the new project together with the nearby converter installations is set to limit the metallic noise to 20 dBrnC, the maximum contribution from a distribution line to the total metallic noise will not bring it to an unacceptable threshold level. For instance, if the contribution of both sources is 20 dBrnC, the total noise will be 23 dBrnC, well below 30 dBrnC. For one source at 25 dBrnC and the other at 20 dBrnC, the total noise will be 26 dBrnC.

The optimal choice of influence level will likely require mitigation measures to be applied to several telephone lines. Considering that the calculation method is conservative and that higher noise can be tolerated during the time necessary to apply mitigation measures, it is possible to wait for measurements done on the most affected telephone lines during acceptance tests to confirm the need for such mitigation measures. Measurements on telephone lines at an early stage of the project are recommended when telephone interference is a concern, to fix any problematic situation (unacceptable susceptibility level of the telephone system or distribution level influence).

Allowance for future growth of harmonic generation in the system, such as future planned HVDC converter installations, should be accounted for; however, in most situations, it is seldom possible to predict such new installations except for the near future. Other background sources with progressive increase can be controlled through complaints to the telephone companies; a process recognized by the standards. A suitable allowance for future growth should consider the maturity of the network, the foreseen evolution of the telephone system and the consequences of exceeding the recommended levels of metallic noise.

3.3.7 Recommendations for technical specifications

Once the IT or Ieq limit along the critical transmission lines is set, the technical specification should define adequately the network and the line characteristics in order to achieve a correct assessment of the interference influence (IT or I_{eq}) by the HVDC contractor, which will result in an optimal filter design. This information should be provided in the specifications in a convenient way, and it is the responsibility of the utility or its consultant to provide a clearly defined calculation method.

Most technical specifications specify a telephone interference limit defined at the point of connection of the converter to the network, either in terms of balanced weighted current or voltage, to be calculated with an impedance locus representing the different network conditions in balanced sequence component. Such a method cannot control amplification at remote locations like the ones described in Annex C. This specification method cannot take into account the distribution of IT flowing into the different transmission lines of a meshed network connected to a converter bus and the generation of ground mode harmonics by the transmission lines. In addition, the generation of residual current by the transmission lines, which in many cases can be the main contributor to telephone interference, is not taken into account.

Consequently, the technical specification should ideally define in detail the electrical characteristic of the transmission line where telephone interference should be limited. Some tolerance on line length is then considered. For a simple case with a radial transmission line connecting the converter to the network, a line model with an impedance locus at the other end can be specified. This type of specification has already been used for one large project. It can be conceivable to extend this concept to two or more radial lines, but this increases significantly the number of possible network impedances for the calculation, as any combination of impedances in both locus should be considered and there can be concerns on the consistency of operating conditions considered for each locus. In addition, the two networks at each line end can be interconnected through other parts of the network, which requires a mutual impedance to correctly model their mutual influence. For specifications requiring a residual harmonic current limitation, additional data is required on the zero sequence harmonic impedance of the network at the load end.

Alternatively, the complete network data can be provided in the technical specification with a list of operating conditions and contingencies to be considered. This method has the merit of using the best model available to represent the harmonic current flow in the network, but it requires a large amount of data, and such a study could be time consuming during the bidding period.

The choice of the appropriate method for specifying the telephone interference limit would depend on several factors such as the complexity of the network to be represented, the number of telephone lines involved and the time schedule of the project. For the bidding stage, the method should be as simple as possible to shorten the bidders' studies, to facilitate the analysis and to ensure that technical proposals from the different bidders are elaborated on the same basis. However, the bidders should have enough information to be able to make a realistic assessment of the resulting filter costs. For the final project design, the method should be detailed enough to allow an optimal filter design.

Where the network is too complex to be represented by an adequate equivalent circuit to be used in a technical specification, or where a simple method is required for bidding purposes, the following method could be used if studies show that some particular conditions are met. It has been observed in Figure 1 and Figure 2 that the amplification of IT along a transmission line is related to the sending end impedance magnitude. In a similar way, it is possible to find the relation between IT in transmission line locations paralleling telephone lines and network impedance magnitude at the point of connection of the converter, while performing the penetration study. If the relation is such that high transferred levels of IT along the decisive transmission lines corresponds to high network impedance values, such a relation can be included in the technical specification for at least the characteristic harmonics. The same method can be applied to the ratio of induced voltage in a representative test line over the injected harmonic current at the converter, with greater accuracy as discussed in 3.3.5. This method will allow a more optimized design than possible with the usual unique IT level at the converter exit combined with an impedance locus. An example of such a study is presented in Annex D.

Once the specification model is set, the technical specification of an HVDC project requiring telephone interference limitation should include

– I_{eq} or IT limits along each transmission line with telephone line exposures,
– the definition of the performance indices, either I_{eq} or IT (Equations (8) or (10)) with the values of H_n if required,
– the values of K_b for each transmission line when residual and balanced mode coupling is considered (Equation (11)),
– normal operating conditions to be considered for the calculation of telephone influence limit with the possibility of defining relaxed limits for degraded conditions,
– transmission line data, and
– harmonic impedance envelopes.

3.4 Consequences for filter design

This subclause considers the possible consequences for AC filter design of imposing a low IT limit.

If the specified IT limit is very low, the filter designer can find that it is not enough to provide tuned shunt filters just for the main characteristic harmonics. It can become necessary to provide sharply tuned branches for higher order characteristics, rather than the more usual high-pass types.

The provision of such a multitude of sharply tuned branches will inevitably result in high-impedance anti-resonances at intermediate frequencies. Non-characteristic harmonics at these frequencies, which were previously negligible, can then be amplified and become significant contributors to the IT. Tuned filters at some of these non-characteristic harmonics can then be required, or a broad-band damped filter provided in addition to the sharply tuned arms, in order to provide some damping at these intermediate anti-resonance points. A proliferation of small filter branches can result, which is costly to build and maintain and can create problems in terms of reactive power balance.

Shunt AC filters by their nature limit the harmonic voltage at their point of connection. However, if the network harmonic impedance as seen from that point is low, then significant harmonic currents can still be driven into the network. Therefore, shunt filters are not necessarily the best solution for limiting IT.

It can be that the addition of series filters in the outgoing circuit(s) is a more effective approach, thereby increasing the relative impedance of the network side compared to that of the shunt filters. Sharply-tuned shunt filters can be used for one or two particularly troublesome frequencies, but it can also be that a low q-factor, broad-band series filter is sufficient to raise the relative impedance sufficiently at a wide range of frequencies, for example, around the range 20th to 30th harmonic. Series filters can be constructed using reactors similar to those already used for PLC filtering, with the addition of small capacitors and resistors which can be mounted on insulated platforms. The losses need not be too significant. Their effect on the reactive power balance should be taken into account. Reliability and availability considerations can prompt the installation of isolators and a bypass switch for the series filter, although such functions could also be fulfilled by simple bus links.

Active filters, which can cancel low magnitudes of outgoing harmonic current over a wide frequency range, can also be an efficient way to limit IT (see IEC TR 62544 [19]).

Customers should therefore be aware that the consequences for filter design of specifying a low IT limit can be severe and costly and should ensure that such limits are not specified unless really proven necessary.

3.5 Telephone infrastructure mitigation options

It is beyond the scope of this document to go into detail on possible mitigation measures to be applied to the telephone system, but the following list of options is offered simply as basic information for power system engineers. These might typically be considered for specific phone lines or areas when a detailed study has been made and vulnerable circuits identified.

Some mitigation measures apply to existing telephone equipment that can have deteriorated since their installation. Both balance and shielding of telephone line can be restored to their initial values or even improved by the following means.

1) Improvement of cable shielding

   To obtain a good shielding from power line induction, both ends of cable shield are grounded and all shield openings bonded. The shield grounding impedance can be further reduced along the exposure.

2) Improvement of customer loop balance

   The switching centre equipment, telephone cable and customer equipment can affect the customer loop balance. Various steps can be taken to improve the circuit balance. Amongst others, modern cables with much better balance are available.

Several devices can be installed on the telephone circuit to mitigate induced noise.

a) Bridged ringers and ringer isolators

   Ringers that are connected to the ground can cause imbalance between the wires of the telephone pair. Bridge ringers and ringer isolators are designed to solve this problem.

b) Longitudinal chokes

   Such chokes add high longitudinal impedance in the circuit avoiding longitudinal to metallic noise conversion.

c) Negative impedance converters

   The negative impedance converter is used as an active transmission gain element. Shield or spare-pair induced current is sensed by the converter and amplified, thereby increasing the shielding effect.

d) Induction neutralizing transformers

   One or more pairs of a telephone cable are grounded beyond the power exposure at each side of the transformer. These pairs are used as the transformer primary exciting winding; the secondary voltage is connected to the remaining pairs applying a 180° out of phase voltage that partly cancels the induced voltage. This device is generally most effective at 50 Hz or 60 Hz and low order harmonics.

   Another option to mitigate telephone interference problems is to use a different transmission system. The following transmission systems use a signal immune to voice frequency interference.

e) Carrier systems

   This system uses a 40 kHz to 100 kHz carrier modulated by the audio-frequency telephone signal. This permits multiplexing and increases the number of subscribers on a telephone pair. It can not be economical for a few subscribers.

f) Fibre optic cables

This system uses optical fibres for telephone communication. While this system is forecast to increase in the future, it can not be yet economical for rural areas.

g) Cell phones

This system uses a radio signal and a network of antennas to transmit the information. Cell phone service can not be available everywhere in some countries.

h) Digital systems

Various digital technologies have now achieved wide penetration and are immune from audio-frequency interference.

However, mitigation of noise on the telephone circuit can not be a satisfactory solution if the unweighted induced voltages are high enough to be a safety concern on the telephone circuits or can exceed the ratings of typical mitigation equipment. More information is available on noise mitigation measure for telephone systems in [9] and particularly in [13]. Rapid advances in digital technology will also tend to immunize telephone systems from audio frequency interference.

3.6 Experience and examples

3.6.1 General

There is little information publicly available on actual telephone interference levels for HVDC schemes in service. If for no other reasons, this is because performance measurements are typically only made as a part of system tests for which conditions can, and should, be expected to be more benign compared to the conditions for which the filter is designed. One particular case of interference, and its solution, is described in 3.6.4 below.

In view of that, a concise review of which design requirements have been used to limit telephone interference is made below, with the underlying idea that if a criterion had been demonstrated to be inadequate, it would have changed (or been replaced) over time. Briefly, the review shows that, with a few exceptions, almost all use of current based criteria is restricted to the American continent. Following the review, experiences from actual HVDC projects are discussed and in addition a simple design example is included in Annex E.

3.6.2 Review of design requirements

A review of performance criteria for HVDC schemes between 1970's up to the time of publication is made. Table 6 gives a summary of performance limits from published references ([20] to [22] and additional CIGRÉ session papers of respective projects). Table 6 indicates the following:

- 12 out of 48 schemes had current based criteria;
- most schemes had TIF (or THFF) requirements;
- schemes with IT (I_p) requirements are almost all located in North or South America;
- only a few schemes did not have criteria related to telephone interference.

If the table were expanded with schemes up to present day, the same picture would remain. With few exceptions, IT (I_p) requirements are restricted to the American continent. Most schemes have requirements on TIF (THFF) but for some, in particular among the more recent schemes, neither TIF nor IT requirements are given, but typically limits on individual distortion in practice imply calculated TIF levels of about 30.

The regional use of IT reflects differences in national guidelines and recommendations which in turn reflect experience, which will be different as both the structure of power transmission and telecom subscriber systems are built up differently in different parts of the world.

Table 6 – Some HVDC schemes – Specified telephone interference criteria

Name of HVDC System	Location	Year	TIF, -	THFF, %	IT, kA	Ip, A	Remark
Volgograd-Donbass	Russia	1962	--	--	--	--	
Konti-Skan 1 And 2	Denmark-Sweden	1965/88/2005	50				
New Zealand Hybrid	New Zealand	1965/92		1		26	EDV, EDI
Sakuma	Japan	1965/1993		2			
Sacoi	Italy-Corsica-Sardinia	1967/85/93	35	0,9			
Vancouver	Canada	1968/77/79	50				
Eel River	Canada	1972	20		25		
Nelson River 1	Canada	1973/93	25		50		
Skagerrak 1-3	Norway-Denmark	1976/77/93	50	1,5			
Square Butte	U.S.A.	1977	--	--	--	--	
Cahora-Bassa	Mocambique-S.A.	1978	--	--	--	--	
Nelson River 2	Canada	1978/85	25		50		
C.U.	U.S.A	1979	30		10		
Hokkaido-Honshu	Japan	1979/80/93	--	--	--	--	
Acaray	Paraguay	1981	28				
Vyborg	Russia-Finland	1981/82/84/02		2			
Gotland II-III	Sweden	1983/87	40				
Chateauguay	Canada	1984	20		25		
Blackwater	U.S.A.	1985	30				
Highgate	U.S.A.	1985	35				
Madawaska	Canada	1985	20				
Miles City	U.S.A.	1985	25				
Cross Channel Bp 1+2	France-U.K	1986	--	--	--	--	
I.P.P.(Intermountain)	U.S.A.	1986	30				
Itaipu 1	Brazil	1986	22/35		106/-		
Quebec-New England	Canada-U.S.A.	1986/90/92	20/35				
Itaipu 2	Brazil	1987	22/35		106/-		
Fenno-Skan	Finland-Sweden	1989	50				
Gesha	China	1989/90		1			
Mcneill	Canada	1989	35		4		
Pacific Intertie	U.S.A.	1989	30		50		
Vindhyachal	India	1989	30				
Rihand-Delhi	India	1992	30				
Etzenricht	Germany-Czech	1993		1			
Wien-Sudost	Austria	1993		1			
Baltic Cable	Sweden-Germany	1994		1			
Haenam-Cheju	South Korea	1998	40				
Garabi 1&2	Argentina-Brazil	2000/02	40		30		
Swepol Link	Sweden-Poland	2000					
Grita	Greece-Italy	2001		0,9			

Name of HVDC System	Location	Year	TIF, -	THFF, %	IT, kA	Ip, A	Remark
Tian-Guang	China	2001		1			
Cross Sound	U.S.A.	2002	35		12		VSC
Murraylink	Australia	2003	40				VSC
Three Gorges Changzhou	China	2003		1			
Gui-Guang	China	2004		1			
Ballia-Bhiwadi	India	2009		1			
Yunnan-Guangdong	China	2010		1			
Sapei	Italy	2010		0,9			
TIF of 40 corresponds to a THFF of about 1 %.							

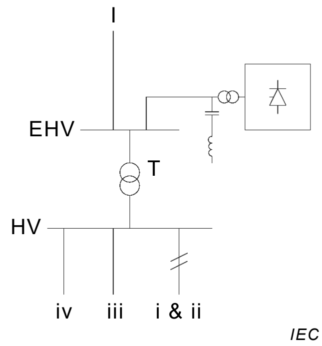
3.6.3 Measured current levels of schemes in service

Table 6 considers the calculated design requirements for HVDC schemes. However, what is measured when the converter(s) are in operation can be rather different. Typically, measured performance can be expected to have a margin below calculated values, as measurements typically will be made for benign conditions compared to design calculations. But this issue can still be of some interest, and so two examples are provided below.

Both examples give 95 % values, i.e. the value which with 95 % probability is not exceeded during the measuring period, which in this case was one week. There is no discrimination made regarding load variation, different filter configurations, etc. nor is there any distinction between converter and pre-existing harmonics, for example in the last example the dominating harmonic current is a 5^{th} harmonic that flows between the EHV and HV lines and therefore not related to the HVDC converter station.

The first example is a 600 MW scheme designed for a THFF of 1 %. Detailed measurements of harmonic voltages and currents were made without and with the converter in operation. The substation connected five incoming lines: one EHV line and four HV lines, 400 kV and 130 kV respectively. Table 7 summarises the results. In addition to the measurements, a detailed model including both the AC system (3-phase) as well as telephone cables were set up and induced noise levels were calculated, based on measured data, both close to and geographically distant to the converter station. In brief, the outcome showed that there was no calculated increase of telephone interference except for one single area out of nine investigated. The area with a calculated increase of noise levels was with a long and close-separation exposure to the 400 kV AC line.

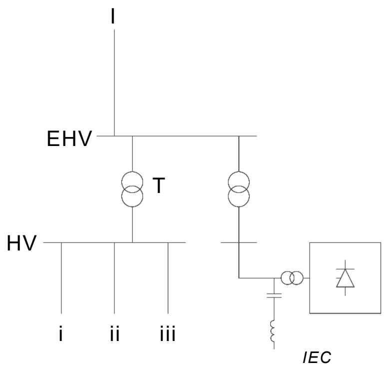
Table 7 – Measured 95 % values of THFF and I_{pe} of a 600 MW scheme (3 phases)

		L1	L2	L3	HVDC	
THFF,%	EHV	0,24	0,23	0,24	No	
	HV	0,21	0,22	0,21	No	
	EHV	0,31	0,29	0,30	Yes	
	HV	0,22	0,21	0,22	Yes	
I_p, A	EHV T	0,59	0,61	0,59	No	
	HV i	0,83	0,77	0,77	No	
	EHV I	4,33	4,80	4,40	Yes	
	EHV T	0,96	1,03	0,93	Yes	
	HV i	1,22	1,35	1,26	Yes	
	HV ii	1,30	1,20	1,23	Yes	
	HV iii	3,38	3,57	3,22	Yes	
	HV iv	0,27	0,30	0,27	Yes	

The second example is taken from measurements made on a 300 MW HVDC scheme designed for a TIF of 50 at the converter bus. Measurements were only made with the converter in operation. As previously, the results presented are 95 % values of psophometric weighted voltages and currents over one week. The results are summarised in Table 8.

The two stations are situated in quite different locations; the first in a more rural area and the other in a more densely populated region. For neither of the two examples were there any reported issues of telephone interference along the route of the AC lines.

Table 8 – Measured 95 % values of THFF and I_{pe} of a 300 MW scheme (3 phases)

		L1	L2	L3	
THFF,%	EHV	0,37	0,35	0,37	
	HV	0,50	0,51	0,49	
I_p, A	EHV I	1,81	1,74	1,69	
	HV T	3,28	3,35	3,27	
	HV i	2,05	1,99	1,92	
	HV ii	1,63	1,87	1,72	
	HV iii	2,32	2,32	2,23	

3.6.4 Example of actual telephone interference problems

3.1 highlights the need for the customer to base his performance requirements on inductive coordination studies, where it is perceived that there is a risk of telephone interference and also not to specify performance indices based simply on typical values and/or past practice. To amplify this point, following the commissioning of a recent HVDC project, telephone interference was experienced by many users in the near vicinity of the converter station, the pattern of interference being consistent with operation of the converter station. The following points were noteworthy with respect to this issue.

1) The performance criteria in respect of the converter station AC busbar were that over the entire DC power load range the harmonic voltage distortion (incremental) should not exceed 1 % individual or 1,5 % RSS total (n = 2 to 49) and, for telephone interference limits, the criteria was that the value of TIF should not rise by greater than 50. In that respect, the performance criteria could be viewed as not being unduly onerous.
2) The network harmonic impedance characteristics (as seen from the converter station AC busbar) were defined by the simplified approach given in IEC TR 62001-1:2016, 7.3.1.
3) No inductive co-ordination studies were performed prior to the compilation of the enquiry document, neither were there discussions with the relevant telephone operators to determine the likelihood of potential interference. Furthermore, no detailed studies were performed to identify harmonic transfer impedances between the AC harmonic filter busbar and remote busbars within the network to determine potential high levels of amplification of harmonic voltage and/or current from the converter station.
4) On commissioning and during initial operation, there were many complaints (approximately 200) regarding audible noise on customer telephone circuits, and it was apparent that the noise being experienced was due to the presence of an 1 150 Hz component on the circuits with levels of –60 dBm[3] being measured with the HVDC link in service; such levels were deemed unacceptable on communication circuits. The affected customers were connected to exchanges in the vicinity (approximately 5 km) of a substation, some 35 km distant from the converter station AC busbar. In this area, there are several overhead lines all at the same network voltage level as the converter bus with relatively high mutual coupling to adjacent open wire telephone circuits.
5) Measurements of harmonic voltage distortion at the converter station AC busbar with the interconnector in service indicated that the RSS total distortion was less than 1 % with 23rd harmonic (1 150 Hz) being approximately 0,1 %. The calculated value of TIF was also significantly below 50, implying that the performance criteria as specified had been achieved by the AC harmonic filter design.
6) However, at the remote substation referred to in IEC 62001-3:2016, Clause 4 [18], whilst the level of 23rd harmonic voltage distortion showed an attenuation (to approximately 0,02 %, i.e. barely measurable) compared with the converter station busbar, there was a significant amplification of 23rd harmonic current from the converter station to this remote busbar. Calculated values of IT (from harmonic current measurements) for overhead line feeders into this substation were in the order of 30 000 to 40 000 with a significant 23rd harmonic contribution. Such levels of IT would be consistent with potential telephone customer complaints.
7) The above phenomena at the remote substation were indicative of a significant series resonance (transfer impedance) between the converter station busbar and the particular remote substation, which was later confirmed by detailed modelling of the network characteristics.
8) To reduce the telephone interference to acceptable levels, one of the AC harmonic filters was temporarily reconfigured as a 22nd harmonic single frequency tuned filter. As a permanent solution, a 23rd harmonic series "blocking" filter circuit was installed in one of the outgoing circuits from the converter station (no further permanent shunt connected AC filters could be connected because of reactive power exchange limits).

To conclude, the above example highlights both the need to determine whether there is a likelihood of high mutual coupling between overhead transmission and telephone open wire circuits, even at locations remote to the converter station itself, and also to perform studies to determine the self-impedance and, more importantly, harmonic transfer impedance characteristics to such busbars.

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3 This is expressed as dBm, that is, referred to 1 mW base, rather than the dBrnC used in the rest of this document, which is referred to 1 pW. There is therefore a 90 dB difference between the two units of measurement, -60 dBm corresponding to +30 dBrnC (if the C weighting term in dBrnC is neglected).

3.6.5 Experience in China, showing no interference problems

In China, long distance communication is now essentially through optical fibre cable, even including the communication between communication hub stations in urban area. Only the final 1 km to 2 km to customers uses ordinary cable or overhead wires in urban areas, although in the countryside, such ordinary communication wires can be longer. The HV and EHV transmission lines above 110 kV use special towers, with no communication cables being attached on the same tower. However, for the 35 kV utility system, the distribution towers can also be used to carry some communication cables, or communication conductors can be routed in parallel with or cross the route of power distribution lines.

500 kV transmission lines normally pass through agricultural fields, mountains etc. due to environmental pressures. In such excessively wild areas, there is less communication cable in parallel with the transmission line and therefore little possibility of interference. In developing areas, there can be some communication cables in parallel with 500 kV lines, but no complaints have yet been received from communication companies regarding interference due to power transmission.

3.7 Conclusions

In brief, the overall conclusions are the following.

1) If there is no significant potential for telephone interference, then there is no technical justification for either weighted voltage (TIF, THFF) or current (IT, I_{eq}) AC harmonic limits.
2) The impact of such requirements on HVDC filtering cost and complexity can be significant, so such requirements should not be introduced if not necessary.
3) Telephone interference is a magnetic phenomenon and thus inherently tied to the magnitude of harmonic currents. IT is a measure of harmonic current and TIF is a measure of harmonic voltage. Harmonic voltage is only indirectly related to harmonic current, and this relationship is specific for a particular condition and set of system impedances. Conditions maximizing harmonic voltage, and thus TIF, are often not the cases maximizing harmonic currents and thus telephone interference potential.
4) The specification of only TIF has shown, with few exceptions, to have resulted in AC filter designs that have not been associated with objectionable telephone interference. Many of these systems with TIF-only specifications, however, do not have system conditions making them prone to telephone interference issues.
5) Under certain conditions, experience shows that an HVDC plant can cause interference in both adjacent and more remote lines.
6) The degree of interference is not only dependent on the AC and DC system characteristics but also on the quality of the subscriber or signalling circuit.
7) If it is suspected that there is a risk of telephone interference, then both customer and contractor benefit if requirements are made following an inductive coordination study, rather than taking typical values provided by standards and/or design codes.
8) The execution of such a study is complex and specific to the nature of the AC system and the telephone system, and can be lengthy. This is often outside the normal skill set of HVDC engineers, and can be best conducted by the customer prior to issuing the technical specification.
9) The AC network impedance should be very carefully defined, in particular if impedances are given as sectors or polygons. Most probably, a model with detailed primary level modelling and with secondary level aggregate modelling is preferable.

4 Field measurements and verification

4.1 Overview

Clause 4 considers the tests which will be made during and after commissioning, to verify that the AC filter equipment and systems are functioning as required. Suitable specification of the technical and contractual aspects of such testing is important to safeguard the interests of the customer, and a clear definition of what is required is to the benefit of both customer and contractor.

The field tests can be divided into

- equipment and subsystem tests which are performed before full voltage energization, and
- system tests which cover all tests done after full voltage energization.

Another test of interest in the context of AC filters is the measurement of pre-existing harmonic levels for the purpose of design and later for verification of performance.

4.2 Equipment and subsystem tests

4.2.1 General

The subsystem tests are performed without high voltage energization, and are usually carried out by the contractor.

The components of the filters are first verified for integrity: their nominal values of capacitance, inductance and resistance are measured and checked against their nameplate values. After final connections of the components, the overall behavior of the assembly is evaluated at low voltage operation.

4.2.2 Fundamental frequency impedance and unbalance measurement

A single-phase low voltage supply (< 1 kV) is applied in turn to each phase of the AC filters. The fundamental frequency voltage and current measurements permit the evaluation of the fundamental frequency impedance of the filter. Additionally, provided that the filter yard is not influenced by any other voltage source, the unbalance current can also generally be measured down to the microampere range. These results can be extrapolated to the rated voltage of the filter and compared to the contractor's calculations.

4.2.3 Frequency response curve

The purpose of this test is to obtain the impedance of the filter in the frequency range starting with the fundamental frequency up to usually the 50th harmonic. It will also permit selection of the final tap setting of the reactors in accordance with the desired tuning frequencies corrected for the conditions of the test, namely the ambient temperature.

The frequency curve can be obtained by applying the output of a signal generator to the filter through an amplifier. Filter voltage and current measurements taken across the complete frequency range give the impedance curve. However, this exercise is time consuming considering also that the voltage applied to the filter has to be monitored to ensure that it is reasonably free of distortion.

More sophisticated instruments will automatically control the injection signal and take the readings with probes tuned to the injection frequency in order to be more sensitive and less influenced by distortion.

Finally, this evaluation can be done by using a spectrum analyzer: its output noise signal is fed to the filter through the amplifier, and the instrument, by means of fast Fourier transform (FFT) calculations, performs the transfer function directly on the voltage and current measurements. The instrument also provides a coherence function which can be regarded as a confidence criterion in the transfer function obtained.

4.3 System tests

The system tests complete the commissioning of an HVDC project and consist of the tests done at full voltage. The subject of system tests has been well documented by IEC 61975 [23]. For each test, the guide gives the objectives, the preconditions, the procedures and the acceptance criteria.

The tests regarding the AC filter equipment and performance are treated in [21]. The following paragraphs only summarize this information, adding more details on certain aspects concerning the measurements.

4.4 Measuring equipment

4.4.1 Overview

4.4.1.1 General

For the system tests, results are required in both time and frequency domains. The time domain measurements are usually provided by the transient fault recorder (TFR) and the sequence-of-events recorder (SER) while the frequency domain measurements are obtained from a harmonic analyzer.

4.4.1.2 Transient fault recorder and sequence-of-events recorder

The specification will often ask that these recorders be part of the equipment supplied by the contractor. The TFR is now based on digital technology and is used to analyze transients, which implies that the selected input scales are usually much greater than the nominal values. Since there are many variables to monitor around the converter, the limited number of TFR channels will normally not permit recording more than one phase of each filter branch. Connection of the TFR might have to be reconfigured depending on the commissioning test being performed.

The SER gives a precise time-stamping and is therefore very useful to verify protective sequences and to co-ordinate measurement results with the prevailing equipment or system configuration.

4.4.1.3 Harmonic analyzer

Although the digital nature of the TFR would permit harmonic analysis, it cannot generally be used for filter performance evaluation: it is not sensitive enough because high input scales should be selected for transient purposes.

Harmonic performance evaluation of HVDC converters requires an instrumentation that is equipped with very good quality signal conditioners and analog-to-digital converters and which contains the necessary filters to prevent any aliasing. Very good harmonic analyzers incorporating all these features are now easily available or can be assembled from the various components. The whole measuring chain should have a very good signal-to-noise ratio (SNR). For example, a SNR of at least 80 dB is required in order to evaluate a TIF of 10 with the necessary precision.

The input channels of the analyzer should be synchronously sampled to allow evaluation of symmetrical components. Besides the integer harmonics, the harmonic analyzer should also provide the interharmonics (intermediate frequencies) which are useful to ascertain that the analyzer is functioning properly and that the measurements have been taken in steady state.

A personal computer (PC) should be used in conjunction with the harmonic analyzer in order to store the results of the analyzer, to calculate the various indices (TIF, THD, etc.) for which limits have been set in the specification and to help in the preparation of curves and reports.

IEC 61000-4-7:2002/AMD 1:2008 [24] describe the general requirements for harmonic analyzers depending on the application. Harmonics generated by HVDC converters will usually not fluctuate in steady state operation, especially if the interconnected AC systems are synchronous or if the DC line is very long. Therefore, when referring to IEC 61000-4-7, one should look for the requirements applicable to the measurements of quasi-stationary harmonics.

4.4.1.4 Current and voltage transformers

Conventional current and voltage transformers are suitable for the time domain measurements. Conventional current transformers are also suitable for harmonic performance evaluation since their first resonance frequency is usually above the range of interest. However, capacitive voltage transformers cannot be used because of their non-linear response at harmonic frequencies. Inductive voltage transformers are usually better but their frequency response should be verified prior to their utilization, and suitable corrections made if necessary. The possibility of measurement errors due to magnetic coupling from nearby components to inductive voltage transformers is also considered, as there is evidence that this can introduce significant discrepancies at some harmonic frequencies.

If the permanently installed voltage transformers are found to be not suitable for harmonic measurements, the following alternatives can be considered.

- Install special capacitive voltage dividers (dividers with a flat response for a large frequency bandwidth). An accuracy of 1 % is normally attainable with such devices.
- Derive the harmonic voltages from the current flowing in an apparatus having a stable impedance. A good example is the capacitance of the PLC filters. A calibration test should be carried out before the actual harmonic measurements. Unless otherwise stated in the specification, an accuracy of 5 % to 10 % in the 0 kHz to 3 kHz frequency band should be sufficient.

4.4.2 AC filter energization

These tests are part of the converter tests. AC filters are energized one at a time and are soaked (left energized) for about 2 h. Using the TFR, the three-phase current and voltage waveforms should be recorded upon energization. The records should be analyzed to evaluate the effectiveness of the means of controlling transients. The steady state filter currents should be balanced. The steady state voltage variation can be used to evaluate the short circuit level.

4.4.3 Verification of the reactive power controller

The reactive power controller should be verified in all its operating modes, and this will therefore be done at various stages of the commissioning tests. It will be mostly verified using the operator's interface, although the TFR and SER might be useful to analyze certain situations.

4.4.4 Verification of the specified reactive power interchange

This verification should be done for the operating conditions given in the specifications, for example: transmitted power level, mode of operation (rectifier or inverter), AC and DC voltage levels and maximum firing angles. As there is usually a penalty attached to this requirement, the most precise current and voltage transformers (usually the billing ones) should be used. The harmonic analyzer might be accurate enough for this measurement at fundamental frequency. If not, a power analyzer is the best instrument for the application.

4.4.5 Verification of the harmonic performance

4.4.5.1 General

These tests are part of the steady state performance and interference tests. The objective is to establish the various harmonic levels for various operating conditions defined in the technical specification in order to verify that the specified levels are not exceeded during such conditions and that the levels remain acceptable under contingency modes. It should be understood that the measurement conditions will probably never correspond to the worst case conditions for which the filter design has been made.

4.4.5.2 Signals to be analyzed

To verify the AC side harmonic performance, the signals showed in Figure 4 should be brought to the harmonic analyzer. Suitable transducers, giving accurate reproduction of harmonics should be used (see 4.4.1.4):

- the three phase-to-earth bus voltages;
- the three AC system currents (or currents in separate AC lines if needed for IT evaluation);
- the three converter currents;
- the three filter currents;
- the converter firing angle;
- the DC side voltage and current signals.

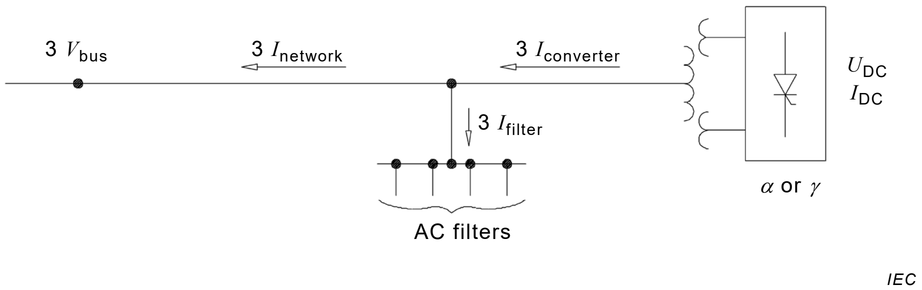


Figure 4 – Converter variables for harmonic performance tests

The DC side harmonic performance will usually be evaluated at the same time. The related signals will be added to the above list and this will dictate the required number of input channels for the analyzer.

Harmonic analysis will be performed on all the signals brought to the analyzer. This analysis is required for the AC signals in order to evaluate the harmonic factors (TIF, THD, etc.) and for the study of any abnormal condition. Harmonic analysis of the DC side voltage and current will be very useful to study any AC/DC harmonic interaction. Although it is the average value of the converter firing angle which is usually of interest, harmonic evaluation should also be performed on this signal as the presence of a low order harmonic variation of firing angle could affect AC and DC side harmonics.

It should be noted that, with the availability of the measured three-phase voltage and current harmonic phasors, it is possible to discriminate the direction of harmonic current flow.

System frequency does not have to be explicitly recorded as it can be derived from the processing of the AC bus voltages.

4.4.5.3 Installation of the analyzer

In the past, the analyzer used to be installed for a very short period. It would be set up a few days before the specific harmonic performance tests and removed shortly after.

However, as instrumentation has become easier to obtain (cheap, effective, user friendly), it is advisable to install it at the very beginning of the commissioning tests, i.e. prior to the equipment energization. It should be set up to continuously take samples at regular intervals (every 30 s or so). Plots of the harmonic indices can then be produced and analyzed on a daily basis. Any abnormal harmonic level can be documented along with the converter and AC system operating conditions.

The benefits of this early set-up of the instrumentation are mainly

- a very good evaluation of the pre-existing noise since the converters will not be continuously in operation during the commissioning period,
- an evaluation of the harmonic levels for a large number of converter and AC system conditions,
- a reduction of the duration of the testing period needed for the specific harmonic performance tests, and
- the possibility of establishing statistics related to the harmonic indices.

4.4.5.4 Test conditions

It has been seen in the previous sections that the harmonic performance is influenced by a large number of factors. The harmonic performance tests should cover as many configurations as practically possible. These will usually be

- the whole operating range of the converters including the overload range and operation at reduced HVDC voltage,
- various loadings of the AC system which should also result in various short circuit levels and AC system impedances,
- operation with normal AC filtering, with reduced filtering, and with the whole range of filters (or combinations of different filter banks) which might be connected at a given power level, and
- all DC side configurations (as a DC side resonance can affect AC side distortion).

The other parameters such as system frequency, AC voltage level, voltage unbalance, etc. cannot usually be varied easily and therefore are taken as they occur.

If the instrumentation has been installed at the beginning of the commissioning tests, harmonic performance will be known for many configurations before the specific test period. The test period will be used only to cover the conditions which have not been experienced already or to review some conditions that would have proved troublesome before and would need more documentation.

For the specific harmonic performance measurements, taking samples at regular intervals (e.g. every 30 s) while slowly ramping the converters (around 1 p.u. power in 2 h) has proven more efficient than measuring only at fixed power levels. When using a ramp, it takes less time to cover the whole converter range and it gives much more information. Also, it always remains possible to come back to a specific operating point that would have resulted in abnormal harmonic levels. With such a slow ramp rate, measurements can still be considered to be carried out in steady state. Figure 5 is an example of measurements made during a ramp.

Although the specified harmonic limits will most likely not apply for operation with less than the designed number of AC filters connected, knowing the harmonic levels for these conditions can become very useful to the operating personnel in case of a filter outage.

4.4.6 Verification of audible noise

The audible noise generated by the overall station (the AC filters are only one of many sources of audible noise) should be measured according to the specification, which should give the maximum allowable noise levels as well as the measuring procedures (for more information, refer to IEC TR 62001-4:2016, Clause 8, and IEC TR 62001-1:2016, Clause 9).

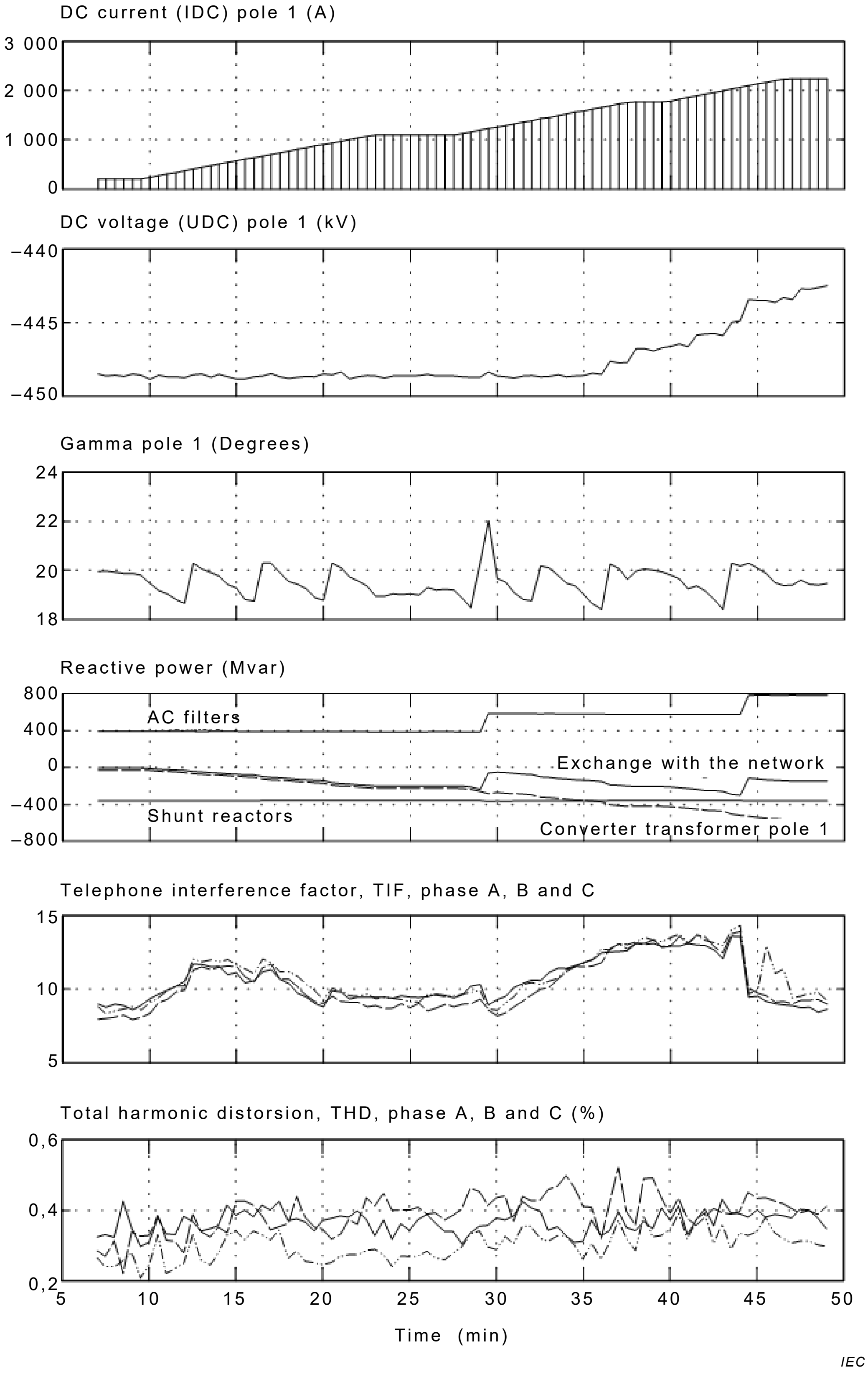


Figure 5 – Example of measurements made during a ramp of the converters

4.5 In-service measurements

4.5.1 General

The customer should consider what filter-related measurements, if any, he wishes to make during the normal in-service operation of the HVDC station. Provision should be made in the technical specification for supply of any equipment, instructions and training related to such measurements.

In most HVDC schemes, no special provision is made for such measurements. If any harmonic investigations are to be made after the completion of the system tests, these will usually employ specialized equipment and personnel provided by the customer.

However, in a few HVDC projects, the following categories of measurement have been considered or implemented, and the customer should consider these in relation to his own operation philosophy and capabilities.

4.5.2 In-service tuning checks

Normally, the only verification of filter tuning after the system tests will be the regular maintenance checks for failed capacitor units and verification of the integrity of other components. However, measurement of the tuned frequency of filters could be made during maintenance periods, using the same equipment and techniques as employed during commissioning tests.

4.5.3 On-line monitoring of tuning

In a very few HVDC schemes, equipment has been permanently installed to permit on-line monitoring of the tuning of AC filters, using measurements of the phase angle between currents and voltages at harmonic frequencies. A cubicle is supplied containing the harmonic analyzer and facilities to switch between signals from different filter branches.

4.5.4 Monitoring of IT performance

If harmonic current in outgoing lines is an important performance issue, the monitoring of the IT criterion (see IEC TR 62001-1:2016, 4.4) could be made on a regular, or permanent, basis by measurement of harmonic current in the lines using the normal line CTs connected to a harmonic analyzer.

4.5.5 Measurements of pre-existing harmonic levels for design purposes

As mentioned in IEC TR 62001-1:2016, Clauses 4, 7, 9 and IEC TR 62001-4:2016, Clause 3, pre-existing harmonic levels have to be addressed in the specification to permit the proper design of the AC filters by the contractor. Therefore, the related measurements to establish these levels will usually have to be carried out at an early stage of the project. These measurements should cover a time span of at least a few weeks in order to obtain statistical figures. A longer period, ideally one year, would be desirable in order to take into account seasonal variations in generation and network topology.

The data obtained will typically only pertain to the amplitude of the bus voltage harmonics as it is difficult to measure the associated harmonic impedance. The final values specified for pre-existing harmonics should take into account the measured pre-existing levels corrected to include future AC system development.

Annex A
(informative)

Voltage and current distortion – Telephone interference

A.1 Voltage distortion limits for HV and EHV networks

A.1.1 General

Utilities control the harmonic voltage levels in their HV and EHV networks in order to keep the disturbance levels below the compatibility levels (defined below) for all their customers, including those in the low-voltage systems.

Each item of plant and equipment should have an emission level lower than, and an immunity level higher than, the defined compatibility level.

To achieve this, planning levels of harmonic distortion are specified by the utility for HV and EHV levels of the system and can be considered as internal quality objectives for the utility. There is also a trend within the utilities to guarantee a certain level of power quality for consumers at any voltage level, and planning levels can be used as power quality criteria for HV and EHV levels.

Harmonic voltages in the system are produced by the combined effect of all harmonic sources at the low voltage as well as the medium and high voltage levels. Figure A.1 shows the harmonic voltage build up in a simple system (taking into account only the inductive reactance of the network). This figure illustrates the need for co-ordination between the different voltage levels.

From the figure, it is clear that the harmonic voltage seen at the low voltage level is the sum of the harmonic voltages over the entire system. The harmonic voltages produced at the HV or EHV level should therefore be limited to a fraction of the compatibility level defined at the LV and MV levels.

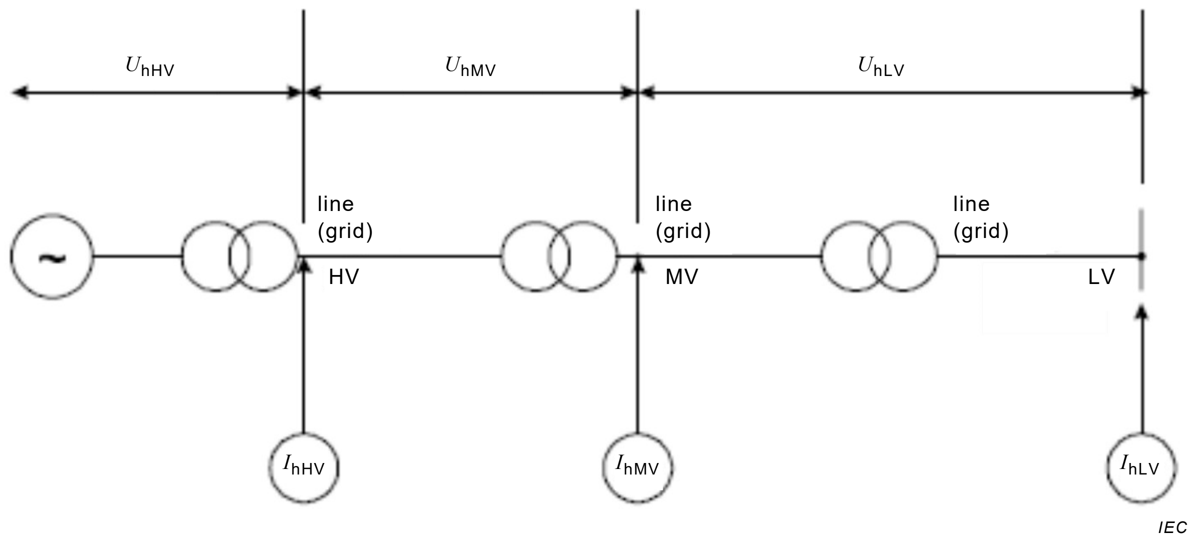


Figure A.1 – Contributions of harmonic voltages at different voltage levels in a simple network

It is also important to note that the harmonic voltages at HV and EHV levels are produced by harmonic sources from every voltage level in the system.

The above is an approximation, as real systems are not purely inductive. Capacitive paths to earth exist at the different voltage levels, and resonant conditions can also occur, which can lead to amplification of harmonic voltages. In addition, the structure of networks is more complex than shown, with usually several MV or LV sub-networks.

A.1.2 Recommended limits for HV or EHV networks

The two main standard organizations, IEC and IEEE, give recommendations on voltage distortion for electrical power systems. They both recommend different distortion limits for distribution and transmission systems recognizing the greater impact of harmonics with increasing transmission system voltage.

As a general observation, recommended limits are lower for IEEE compared to IEC. IEC also proposes different values according to the type of harmonic and the frequency to reflect the results of measurements in power systems and to allow for different effects on sensitive equipment.

The voltage distortion limits recommended by IEEE 519-1992 [4] are shown in Table A.1.

Table A.1 – Voltage distortion limits from IEEE 519-1992

Bus voltage at PCC	Individual voltage distortion %	Total voltage distortion THD %
69 kV and below	3,0	5,0
69 kV to 161 kV	1,5	2,5
161 kV and above	1,0	1,5
NOTE High-voltage systems can have up to 2,0 % THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.		

A considerable amount of work has been completed recently by IEC/IEEE/CIGRE/CIRED/UIE/UNIPEDE committees on the subject of harmonic compatibility levels for AC systems. Based on this work, IEC has issued a technical report (IEC TR 61000-3-6) on assessment of emission limits for distorting loads in MV and HV power systems. This Technical Report outlines principles which are intended to be used as the basis for determining the requirements for connecting large distorting loads to public power systems.

IEC TR 61000-3-6 uses the concept of compatibility levels as a basis for electromagnetic compatibility (EMC) of a system. The electromagnetic compatibility is the ability of a device, equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment. The electromagnetic compatibility level is the specified disturbance level in a system which is expected to be exceeded only with a small probability, this level being such that electromagnetic compatibility should exist for most equipment within the system.

Experimental values for the harmonic voltage normally obtained in the vicinity of disturbing equipment were used within IEC to define the compatibility levels for LV and MV systems [2]. The compatibility levels for harmonic voltages in LV and MV systems are given in Table A.2. These compatibility levels are reference values for co-ordinating the emission and immunity of equipment which is part of, or supplied by, a supply network in order to ensure the EMC in the whole system (including both network and the connected equipment).

IEC TR 61000-3-6 also gives indicative values of planning levels for harmonic voltage in HV and EHV systems, as shown in Table A.3, which reflects harmonic patterns obtained from measurement results on several MV-HV networks [2], note 1. It can be considered typical for AC networks situated in normal load areas. However, the planning levels will be different from case to case depending on network structure and circumstances. These levels should be modified as necessary to reflect the characteristics of the particular network considered.

Note that the original table does not consider explicitly EHV networks, but the general practice is not to differentiate between HV and EHV. Bearing in mind the meaning of "planning levels", such a difference would have little significance. It was proposed not to change the table but to consider HV values as HV-EHV values. However, not enough measurement results are available yet to validate those HV-EHV values, particularly for EHV power systems.

Table A.2 – Compatibility levels for harmonic voltages (in percent of the nominal voltage) in LV and MV power systems [based on Table 1 of IEC TR 61000-3-6:2008]

ODD HARMONICS NON MULTIPLE OF 3		ODD HARMONICS MULTIPLE OF 3		EVEN HARMONICS	
Order *h*	**Harmonic voltage** %	**Order** *h*	**Harmonic voltage** %	**Order** *h*	**Harmonic voltage** %
5	6,3	3	5,0	2	2,0
7	5,0	9	1,5	4	1,0
11	3,5	15	0,3	6	0,5
13	3,0	21	0,2	8	0,5
17	2,0	> 21	0,2	10	0,5
19	1,5			12	0,2
23	1,5			> 12	0,2
25	1,5				
> 25	0,2 + 1,3(25/h)				
NOTE 1 Total harmonic distortion (THD): 8 %.					
NOTE 2 LV refers to U_N ≤ 1 Kv and MV refers to 1 kV < U_N ≤ 35 kV.					

Table A.3 – Indicative values of planning levels for harmonic voltages in HV and EHV power systems [based on Table 2 of IEC TR 61000-3-6:2008]

ODD HARMONICS NON MULTIPLE OF 3		ODD HARMONICS MULTIPLE OF 3		EVEN HARMONICS	
Order *n*	**Harmonic voltage** %	**Order** *n*	**Harmonic voltage** %	**Order** *n*	**Harmonic voltage** %
5	2,0	3	2,1	2	1,5
7	2,0	9	1,,0	4	1,0
11	1,5	15	0,3	6	0,5
13	1,5	21	0,2	8	0,4
17	1,0	> 21	0,2	10	0,4
19	1,0			12	0,2
23	0,7			> 12	0,2
25	0,7				
> 25	0,2 + 25/2h				
NOTE 1 Total harmonic distortion (THD): 3 %					
NOTE 2 HV refers to 35 kV < U_N ≤ 230 kV and EHV refers to U_N > 230 kV.					

A.2 Harmonic current in generators

One definition of an equivalent negative sequence current I_{2eq} for a six pulse converter is as follows [2]:

$$I_{2eq} = \sqrt{\sum_n \left[\sqrt[4]{\frac{6n}{2}} \cdot \left(I_{6n+1} + I_{6n-1} \right) \right]^2} \tag{A.1}$$

where

n	is an integer;
I_{6n+1} and $I_{6n\text{-}1}$	are harmonic currents flowing into the synchronous machine armature winding.

For twelve pulse converters, only the terms with n equal to an even number will give any significant contribution to the sum in Equation (A.1).

It should be noted that alternative formulae have been developed for use in some HVDC projects, in consultation with the generator manufacturers. It is recommended that the generator manufacturer should be asked to specify a suitable formula to calculate the effective harmonic current flow in the machines. Acceptable limit values for the calculated parameter should be agreed between the customer and the generator manufacturer.

A.3 Causes of telephone interference

Harmonic currents flowing in any conductor of a power transmission line create a magnetic field inducing harmonic voltages and currents in nearby installations. The induced voltage in the telephone lines is related to the harmonic current in the transmission line conductors and the mutual coupling impedance Z_m. The term Z_m is mainly dependent on the frequency, the earth resistivity, the length of exposure and the distance between transmission line and telephone line routes. The mutual impedance should be calculated with the help of computer programs because of the complexity involved in solving Carson’s equations, however the Dubanton equations give satisfactory results over an extensive range of frequencies, separation distances, and earth resistivities. The following equation gives the longitudinal induced voltage on one telephone line conductor:

$$V_{cn} = \sum_{k=i}^{j=k} \left(I_{jn} \cdot Zm_{jn} \right) \tag{A.2}$$

where

V_{cn}	is the longitudinal voltage at harmonic n;
n	is the harmonic order;
j	is the conductor number;
K	is the number of conductors on the transmission line;
I_{jn}	is the phasor current in the conductor j at harmonic n;
Zm_{jn}	is the mutual impedance between conductor j and telephone circuit at harmonic n.

The distance between the transmission line conductors is generally small compared to the distance to the telephone lines, and consequently the mutual impedance is nearly identical for each conductor. In such cases, the induced voltage due to balanced (positive or negative sequence) components of the transmission line currents is comparatively low, compared to the residual component, due to the cancellation of the individual conductor contributions.

Modern telephone systems generally still use cables to transmit the electric signal from the communication centre to the subscribers. Such a cable consists of many twisted metallic conductor pairs protected by a shield. One pair is usually assigned to an individual subscriber. Cables can also be used to transmit information between communication centres. The harmonic voltage is induced on each conductor of a pair along the exposed sectionand is therefore called the longitudinal voltage. For these pairs, the resulting interference voltage, which is applied to the telephone set, is the difference between the longitudinal voltages of each conductor of the pair and is known as the transverse voltage or metallic mode voltage. The ratio between the longitudinal and resulting transverse voltages is called the balance of the circuit.

The two main characteristics of the telephone system which contribute to reduce telephone interference are the shielding and the balance. The mechanical shield also acts as an electromagnetic shield and is very effective at higher frequencies. The balance depends on the earth capacitance unbalances of cables and the terminal equipment unbalances and therefore worsens with increasing frequency. The telephone companies are responsible for maintaining their telephone system in good condition and usually meet certain minimum standards on balance and shielding.

Open-wire communication systems are still in operation in many locations. These systems are very similar to cable systems except that there is no shield and consequently no shielding effect, and their balance is generally lower.

The sensitivity of the human ear varies with frequency, and standard weighting curves have been developed to reflect this frequency dependence of the ear, the response of the telephone receiver and other factors, and so to establish the effective noise level of the individual harmonics. In countries following European practice, psophometric weighting is commonly used, while the C-message weighting curve is more in use in countries following North American practice, the difference between the two being quite slight. Figure A.2 shows the two curves.

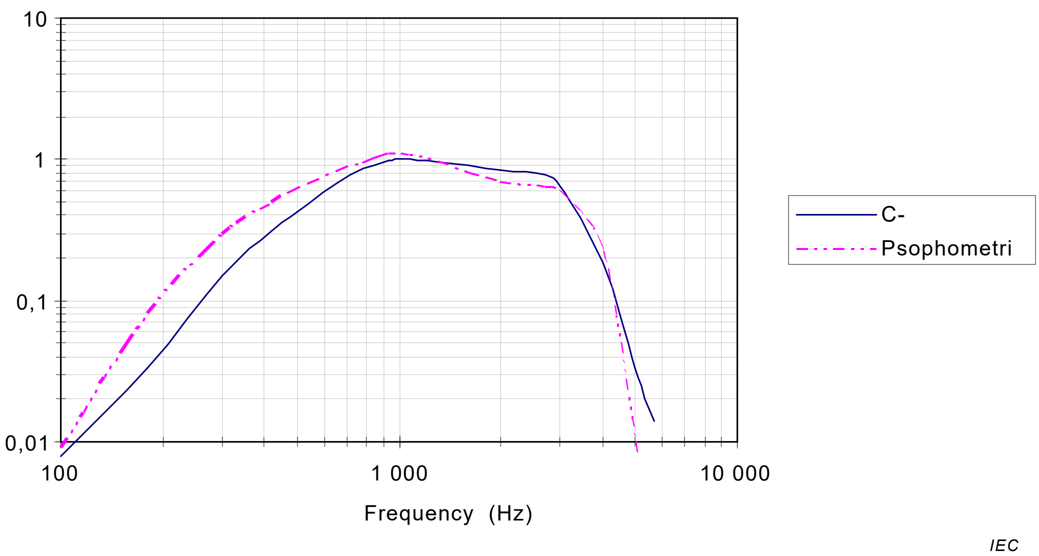


Figure A.2 – C-message and psophometric weighting factors

Using these weighting factors, the total weighted metallic noise level is given by:

$$V_m = \sqrt{\sum_{n=1}^{n=N} (V_{cn} \cdot K_n \cdot B_n \cdot C_n)^2} \quad \text{(A.3)}$$

where

V_m is the metallic mode weighted voltage;

V_{cn} is the longitudinal induced voltage;

N is the maximum order of harmonic to be considered;

C_n is the psophometric or the C-message weighting factor 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 CCITT [25] has specified the acceptable e.m.f. level of the noise at the line terminals of the subscriber's set to be a maximum of 1 mV.

Within ANSI/IEEE, the 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. The communication industry has determined performance thresholds for metallic mode C-message weighted noise on normal business or residential lines. A noise level of 20 dBrnC (0,245 mV) is considered fully acceptable, whereas 30 dBrnC (0,775 mV) is considered unacceptable in most cases. Higher noise levels are generally accepted for open-wire systems.

All the relevant information on the telephone system, including the route of the telephone lines, should be requested from the telephone company at an early stage of the project. Even though some of the references concern the DC transmission lines, the process is the same for both cases. These references also describe the concept of the equivalent disturbing current as a simplified method to calculate the total weighted metallic noise level in telephone lines and to specify telephone interference limits. This method is recommended for the specification of telephone interference limits for HVDC systems. It is therefore possible, for any HVDC project, to calculate the telephone interference level for each exposure with acceptable accuracy and to assess the extent of telephone interference influence related to a particular specified limit.

A.4 Definition of telephone interference parameters

The definitions of the most commonly used telephone interference performance criteria are given below, together with typical values of performance limits. The criteria are presented in two main categories: the ones which are commonly in use in countries following European practice and those which are commonly in use in countries following North American practice.

Criteria according to European practice:

a) Telephone harmonic form factor, THFF

$$\mathrm{THFF} = \sqrt{\sum_{n=1}^{n=N} \left(\frac{U_n}{U} \cdot F_n \right)^2} \tag{A.4}$$

where

U_n is the component at harmonic n of the disturbing voltage;

N is the maximum harmonic number to be considered;

U is the line to neutral total RMS voltage and calculated by $U = \sqrt{\sum_{n=1}^{n=N} U_n^{\ 2}}$.

$$F_n = p_n \, n \, f_o \, / \, 800$$

where

p_n is the psophometric weighting factor;

f_o is the fundamental frequency (50 Hz).

The required limit of THFF for HVDC schemes is typically around 1 %.

b) Equivalent disturbing current I_p is defined, according to CCITT, by:

$$I_p = \frac{1}{P_{800}} \cdot \sqrt{\sum_f \left(h_f \cdot P_f \cdot I_f\right)^2} \quad \text{(A.5)}$$

where

I_f is the component at frequency f of the current causing the disturbance;

p_f is the psophometric weighting factor at frequency f;

h_f is a factor which is function of frequency and which takes into account the type of coupling between the lines concerned. By convention h_{800} = 1.

For practical cases, Equation (A.5) can be expressed as two components, the balanced and the residual equivalent disturbing currents of a three phase line, in the following way:

balanced component:

$$I_{pe} = \frac{1}{16} \cdot \sqrt{\sum_{n=1}^{n=N} \left(n \cdot p_n \cdot I_n\right)^2} \quad \text{(A.6)}$$

where

I_n is the balanced component of the current in the phase conductors at harmonic n;

n is the harmonic order;

N is the maximum harmonic number to be considered;

h_f is set equal to f/800 Hz and is accordingly replaced by n/16 in the above equation. This frequency weighting is suitable for interference caused by earth capacitance unbalance of the telephone cable.

and

residual component:

$$I_{rpe} = \frac{1}{16} \cdot \sqrt{\sum_{n=1}^{n=N} \left(n \cdot p_n \cdot I_{rn}\right)^2} \quad \text{(A.7)}$$

where

I_{rn} is the residual current (sum of the zero phase-sequence components) at harmonic n.

The equivalent disturbing current has been used for few projects but there is no published information on specified limits. However, [5] provides some indicative figures for a typical transmission line, based on the Finnish experience. The figures are:

$$7\ \text{A} < I_{pe} < 20\ \text{A}$$

$$1\ \text{A} < I_{rpe} < 3\ \text{A}$$

Criteria according to North American practice:

a) Telephone interference factor, TIF

$$\mathrm{TIF} = \frac{\sqrt{\sum_{n=1}^{n=N} (U_\mathrm{n} W_\mathrm{n})^2}}{U_1} \tag{A.8}$$

where

U_n is the single frequency RMS voltage at harmonic n;

N is the maximum harmonic number to be considered;

U_1 is the fundamental line to neutral voltage (RMS);

W_n C_n 5 $n f_\mathrm{o}$ is the single frequency TIF weighting at harmonic n;

C_n is the C-message weighting factor;

n is the harmonic order;

f_o is the fundamental frequency.

The strict definition of TIF uses the line to neutral total RMS voltage in the denominator, but the above definition is widely used in the HVDC field for specification of performance requirements for AC filters. The error introduced by using the fundamental voltage in the denominator is very small for typical values of THD in HV and EHV power systems.

Typical requirements of TIF are between 15 and 50.

b) IT product

$$\mathrm{IT} = \sqrt{\sum_{n=1}^{n=N} (I_\mathrm{n} W_\mathrm{n})^2} \tag{A.9}$$

where

I_n is the single frequency RMS current at harmonic n;

N is the maximum harmonic number to be considered;

W_n C_n 5 $n f_\mathrm{o}$ is the single frequency TIF weighting at harmonic n.

Typical requirements of IT are between 15 000 and 50 000 at the HVDC converter station AC bus.

c) Equivalent disturbing current

$$I_\mathrm{eq} = \sqrt{\sum_{n=1}^{N} (H_\mathrm{n} \cdot C_\mathrm{n} \cdot I_\mathrm{n})^2} \tag{A.10}$$

where

I_n is the effective disturbing current at harmonic n (generally corresponding to residual mode current);

N is the maximum harmonic number to be considered;

C_n is the C-message weighting factor;

H_n is the weighting factor normalized to reference frequency (1 000 Hz) that accounts for the frequency dependence of mutual coupling, shielding and communication circuit balance at harmonic n.

Where the balanced mode harmonic currents are expected to contribute significantly to the induced noise, they are included in the calculation of I_{eq}. The effective disturbing current is then specified as:

$$I_n = \sqrt{(I_{rn})^2 + (K_b \cdot I_{bn} \cdot I_{bn})^2} \qquad (A.11)$$

where

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

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

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

The equivalent disturbing current has rarely been used as telephone interference requirement for an AC line feeding an HVDC system. In one instance of its application, limit values in the range 150 mA to 800 mA were specified. The equivalent disturbing current concept has also been used for DC transmission lines for which past experience has indicated that values in the 0,1 A to 1,0 A range are typical for normal operation.

A.5 Discussion

The American and European definitions are very similar. Indeed, the C-message and psophometric weighting factors of Figure A.2 are nearly identical. Except for these factors, the TIF and THFF differ only by a constant ratio of 4 000 (that is, 5 $n f_o$ versus $n f_o$ / 800).

Similarly, the American I_{eq} concept is a variation of the European I_p where the reference frequency and the weighting factor are changed to the American standard. The IT can be considered as a special case of I_{eq} for which the H_n factor is linear with frequency and normalized at 1 000 Hz. For this special case, the ratio between IT and I_{eq} is 5 000.

The linear frequency dependence assumption for H_n is generally considered adequate for standard telephone cable systems and typical exposure characteristics. However, the IT concept is conventionally calculated with balanced mode harmonic currents only. The I_{eq} concept has the advantage of considering both balanced modes and residual mode induction and can be set to fit the needs of a particular project, where the linear frequency dependency assumption is not considered valid (due to high soil resistivity for example), by defining a H_n factor which reflects the particular project characteristics.

The TIF and THFF factors are dimensionless quantities that are indicative of the waveform distortion and not the absolute amplitude.

The definitions of TIF and THFF above use as a reference the total voltage derived as the root-mean-square sum of the fundamental and all harmonics. However, most HVDC technical specifications use instead the nominal fundamental frequency voltage, or the actual fundamental frequency voltage relevant to the operating conditions. Whichever is intended to be used should be stated clearly.

The maximum harmonic order to consider for the calculation should be higher than that for the calculation of harmonic voltage distortion because of the relative weight of the higher harmonic orders and the coupling characteristics. Theoretically, up to 5 000 Hz should be considered but in practice many technical specifications have asked for only up to the 49th harmonic.

A.6 Coupling mechanism from power-line current to telephone disturbance voltage

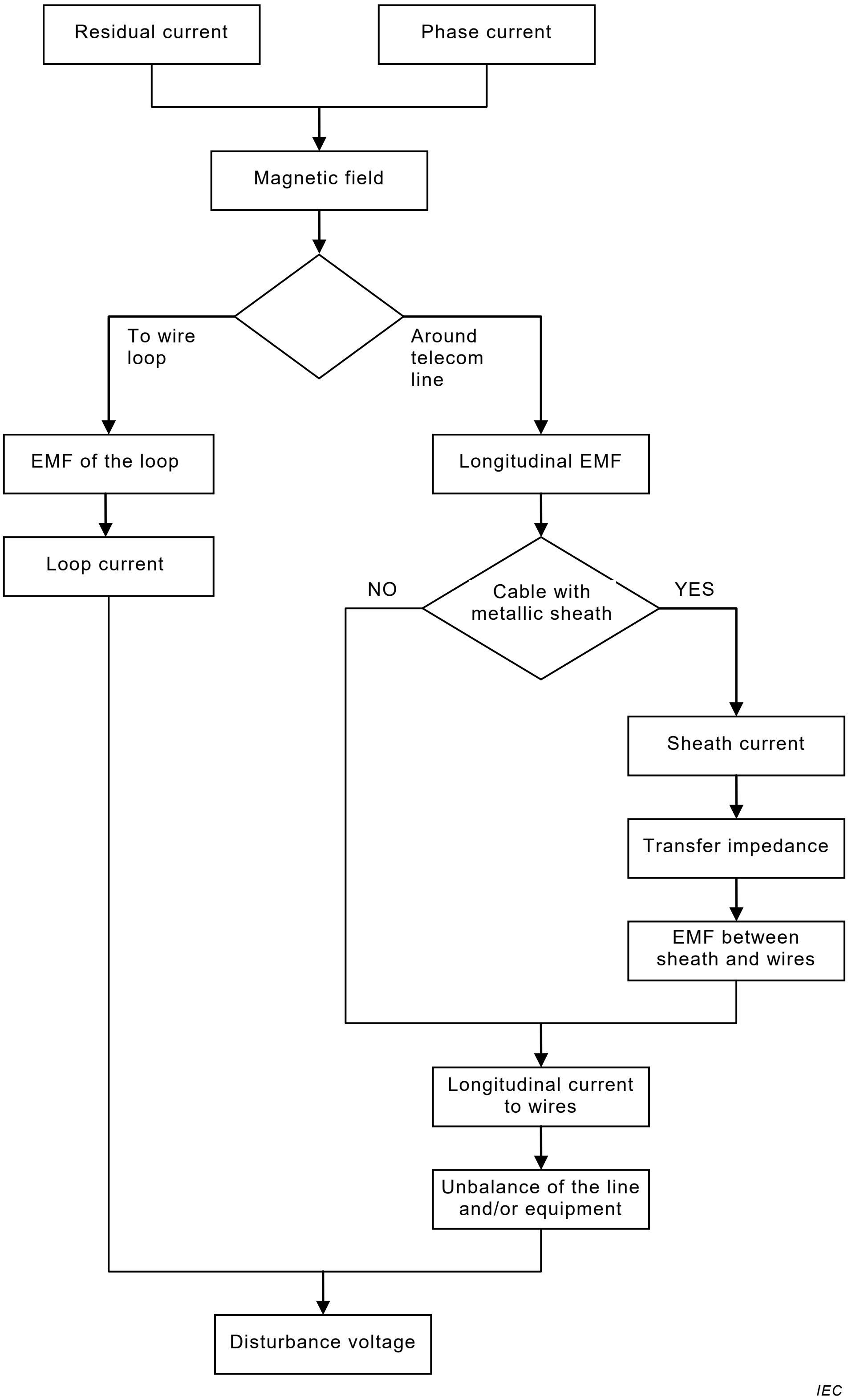


Figure A.3 – Flow-chart describing the basic telephone interference mechanism

Annex B
(informative)

Example of induced noise calculation with Dubanton equations

B.1 General

Annex B shows a simple induced noise calculation based on a transmission line identical to the one used to derive Table 4 and Table 5 and a given value of IT. This example illustrates the different steps required to calculate the maximum length of particular transmission line taking into account the characteristics of the exposure, the main characteristics of the telephone system and the recommended values of longitudinal noise N_g.

Assumptions:

ρ = 1 000 Ω-m

separation = 500 m

single circuit 230 kV line (described in 3.3.4.2)

telephone line shielding factor = 10 dB

telephone line balance factor = 60 dB

residual IT = 1 000 A

balanced IT = 10 000 A

B.2 Residual IT

Calculate Z_m (Ω/m) using the following equations [5]:

$$Z_m = \frac{jw\mu_0}{2\pi} \ln\left[\frac{(h_1 + h_2 + 2p)^2 + D^2}{(h_1 - h_2)^2 + D^2}\right]^{1/2} \qquad \text{(B.1)}$$

where

μ_0 $4\pi\ 10^{-7}$

h_1 10 m (height of transmission line)

h_2 6 m (height of telephone line)

D 500 m (separation)

ω $2\ \pi f$ with f = 1 000 Hz

and

$$p = \frac{1}{\sqrt{\frac{j\omega\mu_0}{\rho}}}\, m \text{ with } \rho = 1\ 000\ \Omega\text{-m} \qquad \text{(B.2)}$$

NOTE 1 $\ln(A+jB) = \ln(A^2 + B^2)^{0,5} + j\ \theta$ where θ = ATAN (B/A) in radians.

Result of calculation is Z_m = 0,87 Ω/km.

NOTE 2 The mutual impedance in residual mode is equal to the mutual impedance between the central phase and the telephone line when the separation distance is large, because each phase has nearly the same mutual impedance to the telephone line.

IT_{res} = 1 000 A then I_{res} = 1 000/(5 × 1 000) = 0,2 A weighted according to Equation (10).

V_g = 0,2 × 0,87 = 0,174 V/km

With a balance of 60 dB and a recommended N_m of 20 dBrnC, N_g should be below 80 dBrnC (Equation (7)). The telephone line shielding being 10 dB, a maximum longitudinal voltage of 90 dBrnC is allowed. A longitudinal voltage of 90 dBrnC corresponds to a V_g of 0,775 V (Equation (6)).

The ratio of the allowable longitudinal voltage to the induced voltage per unit length gives the maximum allowable length (0,775/0,174 = 4,5 km), which is different from the value of Table 5 (8 km) mostly because of the screening effect of the two shield wires. However, part of the difference is due to the accuracy of the calculation method. The shield wires reduce the induced voltage by 4,5/8 or a factor close to 0,56. For one shield wire, the screening effect would be approximately 0,7. This screening effect is relatively constant for a wide range of parameters (separation, frequency, earth resistivity, etc.).

B.3 Balanced IT

For balanced mode with a separation of 500 m, an earth resistivity of 1 000 Ω-m and a horizontal tower configuration with 14,6 m between outer phases:

– using the Equation (B.1) with D_a = 492,7, D_b = 500 and D_c = 507,3 m being the distances between each phase and the telephone line, we get:

  Z_{ma} = 0,889 Ω/km ∟38,3° x 1 A ∟0° = 0,889 V ∟38,3°

  Z_{mb} = 0,874 Ω/km ∟37,8° x 1 A ∟-120° = 0,874 V ∟-82,2°

  Z_{mc} = 0,860 Ω/km ∟37,3° x 1 A ∟120° = 0,860 V ∟157,3°

– summing the three induced voltages = 0,028 ∟35,1° which is equal to Z_{mbal} in Ω/km.

With an IT of 10 000 A, we get 2 A and a maximum length of 13,8 km. Table 4 gives 12,2 km because, in balanced mode, the shield wires have a marginal effect. Moreover, shield wires affect the mutual impedance in balanced mode by making the negative sequence mutual impedance slightly different from the positive sequence.

Annex C
(informative)

Illustration of the benefit of including a TIF requirement in the technical specification

This simulation has been done to illustrate the advantage of a TIF limit in addition to an IT limit for a specification defined at the connection point (without any transmission line in the calculation model). Assuming a 124 km, 230 kV line, the source end is short-circuited for zero sequence, and at the load end there are two grounded shunt capacitor banks with a total of 320 Mvar. The line model has been transposed by appropriate permutations of the phase conductors at one-sixth, a half and five-sixths of the line length because transmission lines feeding HVDC converters are normally highly loaded and the converters are affected by unbalance voltage at fundamental frequency. For this case and for simplicity assuming that all interference is at 1 800 Hz, there is

– 1 A (positive sequence) injected at the source end,
– 15,4 A (positive sequence) at the load end,
– 14,7 A (negative sequence) at the load end,
– 2,7 A (residual current) at the source end, and
– 1,9 A (residual current) at the load end
– 5 800 Ω (positive sequence) seen at the source towards the line.

In terms of telephone interference:

– 7,57 kA (positive sequence IT) injected at the source end;
– 116 kA (positive sequence IT) at the load end;
– 111 kA (negative sequence) at the load end;
– 20,4 A (residual current) at the source end;
– 14,4 kA (residual IT) at the load end;
– TIF of 330 (positive sequence) at the source end;
– TIF of 316 (negative sequence) at the source end.

To limit the TIF level to 40 for 1 800 Hz at the source for instance, the impedance of the transmission line in parallel with the filter should be below 700 Ω. By adding an 800 Ω parallel resistance at the source (to represent a shunt filter), the resulting IT levels in the transmission line become

– 1,49 kA (positive sequence IT) at the source end,
– 14,1 kA (positive sequence IT) at the load end,
– 1,25 kA (negative sequence IT) at the source end,
– 3,32 kA (negative sequence IT) at the load end,
– 1,44 kA (residual IT) at the source end,
– 0,58 kA (residual IT) at the load end,
– TIF of 40 (positive sequence) at the source end, and
– TIF of 7,5 (negative sequence) at the source end.

This shows the benefit of including a TIF requirement even though it has no direct relationship to IT. Of course the TIF limit is selected with consideration to a complete inductive coordination study.

One can also observe that even though the injected harmonic current is of positive sequence only, a non-negligible negative sequence current is also flowing in the line, due to the sequence conversion along the line, as discussed in 3.3.4.

Annex D
(informative)

Specification of IT limits dependent on network impedance

An extensive preliminary study was performed for a planned HVDC project to determine the telephone interference limits to be specified. One converter of this HVDC system would be installed in a 230 kV substation with several connected 735 kV, 230 kV and 120 kV transmission lines as schematized in Figure D.1. A large part of the surrounding network was modelled in detail (in excess of 2 substations away) with EMTP-RV, and more than one thousand combinations of network configuration were simulated. Fictitious 1 km telephone lines were simulated at several separation distances from those 735 kV, 230 kV and 120 kV transmission lines which run adjacent to actual telephone lines to measure the effective telephone influence of each specific transmission line.

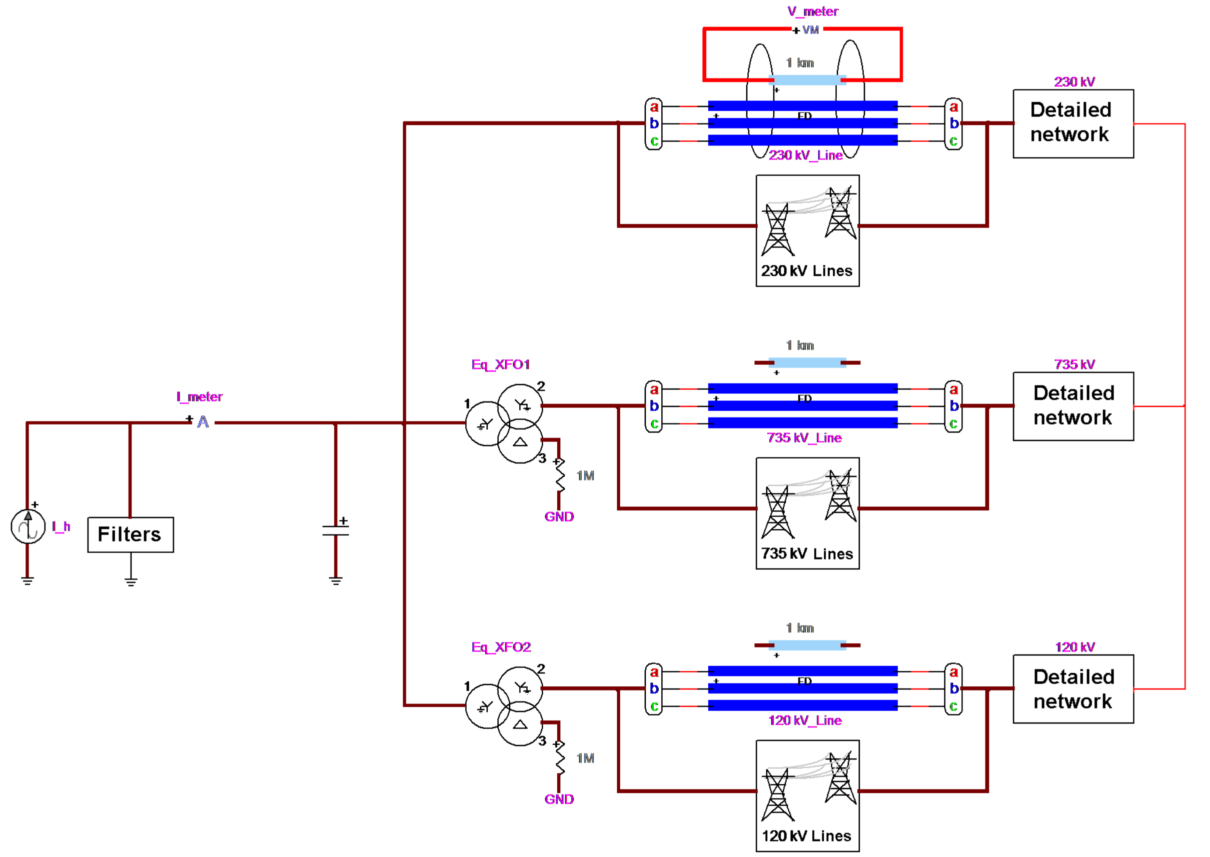


Figure D.1 – Simplification of the detailed network used for telephone interference simulation

Such test lines are preferred over assessment of the IT level in the transmission lines as they accurately combine the interfering effect of the different sequence components of the phase currents. Harmonic currents with the appropriate sequence were injected at the characteristic harmonic orders (11th, 13th, 23th, 25th, 35th, 37th, 47th and 49th) at the point of coupling of the converter to the network. A shunt impedance of low magnitude was used to simulate the effect of the shunt filters at characteristic harmonic frequencies. The filters were represented by low impedances only in order to allow the circulation of sequences other than the injected sequence (e.g. if we inject 11th harmonic which is negative sequence, there will also be zero and positive sequence transformed by the network). The current magnitude of the main sequence is measured by I_meter towards the network (negative sequence for the 11th) and this measurement does not include the current in the filters, as shown on Figure D.1. Since it does not include the filter current, the voltage (negative sequence) that appears at the point of connection divided by the current corresponds to the impedance of the network. Dividing the induced voltage in the telephone test lines by the injected current gives the transfer/mutual impedances required to construct the graph shown in Figure D.2. An existing shunt capacitor bank was also modelled at the 230 kV bus and is therefore included in the network impedance.

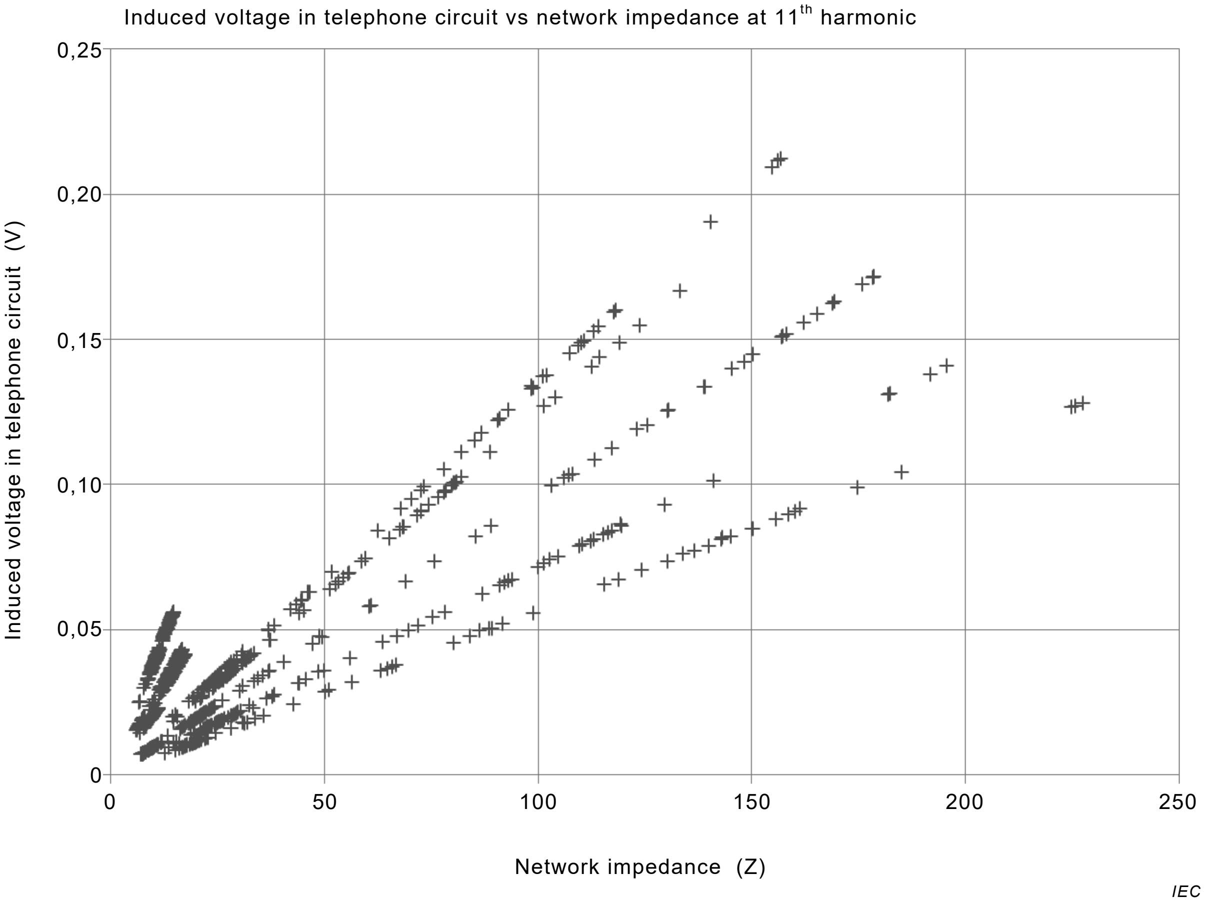


Figure D.2 – Induced voltage in telephone circuit vs. network impedance, for unitary current injected

The induced voltage, for each simulated case, was plotted as a function of the network impedance magnitude for a unitary current injected into the network at the point of connection (I_meter). Figure D.2 represents the tendencies for the 11th harmonic of the transmission line giving the highest induction, which happens to be a 735 kV line. The results showed that there is a relation between the induced voltage in the telephone lines and the network impedance magnitude. The graphic shape is generally the same for all harmonics and lines but the induced voltages and network impedances differ. For a constant injected IT level from the converter station, higher induced voltages on telephone lines correspond to network configurations with higher impedance magnitudes.

The curves show several straight lines that correspond to different contingencies in the 735 kV network. Given that the 735 kV network is in parallel with the 230 kV and 120 kV networks, any change in the 120 kV or 230 kV networks will affect the network impedance seen at the point of connection of the HVDC system, and the voltage applied to the 735 kV network will vary in direct relation. Since the current anywhere in a given 735 kV network is directly proportional to the applied voltage, the induced voltage in telephone lines is directly proportional to the network impedance for changes in the 120 kV and 230 kV networks. For different 735 kV configurations, there should be different lines. In this case, the losses of parallel 735 kV lines had the most influence on the harmonic penetration. Another example of a case where the induced voltage in telephone lines is proportional to the network impedance is shown in Figure 1 and Figure 2 where the current at the receiving end of a transmission line is dependent on the sending end impedance.

Therefore, to maintain the induced voltage at the acceptable level, for higher network impedances the permitted maximum IT is reduced. A limit expressed as a weighted voltage, for example TIF, would tend to reproduce this behaviour, i.e. the higher the impedance, the lower the current. However, for a given induced voltage level in telephone lines, the range of network impedance is rather large so that a limit expressed in TIF would be unnecessarily restrictive for many network configurations.

Considering that it is easier to filter effectively when connected to a network with a high harmonic impedance, a requirement that would be dependent on network impedance magnitude would probably result in a cheaper filter design. For instance, preliminary studies showed that at the 11th harmonic, an IT of 20 000 A would be required for the worst cases that happen for system impedances higher than around 130 Ω. For system impedance higher than 82 Ω, the limit would be 26 000 A. In addition, for an impedance magnitude of 42 Ω and above, the limit would be 40 000 A and finally, for the minimum impedance and above, the limit would be 80 000 A. Figure D.3 shows the different limits associated with their specific impedance locus.

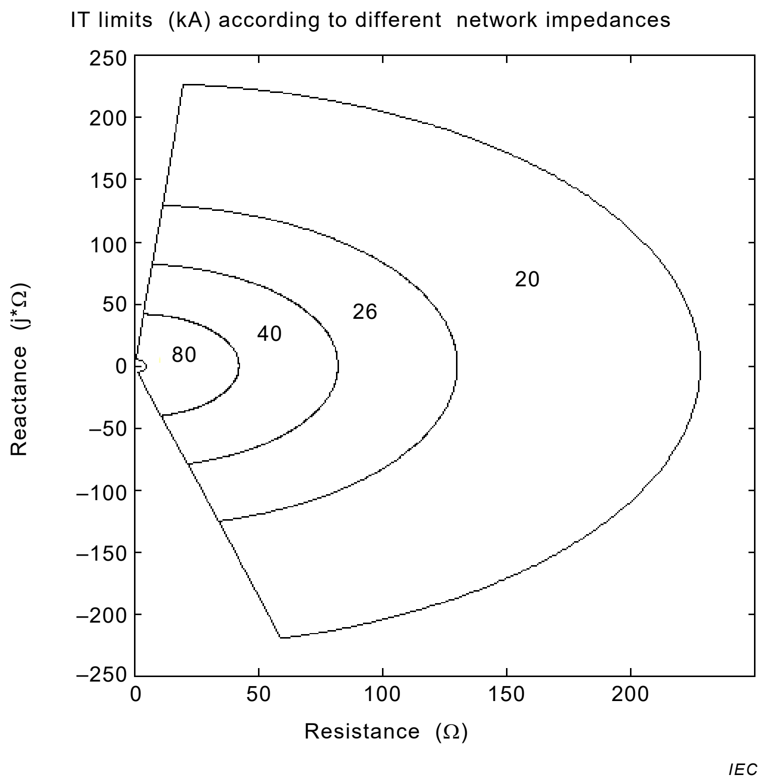


Figure D.3 – IT limits as defined for different network impedances

Knowing for instance that an IT of 20 kA at the 11th produces the same induced voltage as an IT of 80 kA when applied to their specific impedance loci, these values can be normalized to one reference value in order to simplify the calculations by the manufacturer. They can also be normalized between the different characteristic harmonics to combine them in a total IT value representative of the expected induced voltage in the telephone lines.

Such a specification method was considered for the project in question, however the project was delayed and the specification studies postponed. These results are given as information hoping that they can be used in some way to improve the specification of telephone interference. It is anticipated that such a method is not as conservative as a model with transmission line terminated by an large impedance locus, for example, because in the latter case there is a high probability of hitting severe combinations of transmission line and remote network impedances, whereas the proposed method considers only actual network conditions, with some tolerance. This method could be used where preliminary studies show a convenient dependency between induced voltage and network impedance.

Annex E
(informative)

The impact of AC network harmonic impedance and voltage level on the filter design necessary to fulfil an IT criterion

E.1 General

This annex makes an assessment of the amount of filtering (Mvar) required to limit the IT-product to 25 kA for a line commutated converter, as calculated for different system voltages and different ways of representing AC network harmonic impedance. The results are first summarized below in Table E.1, and then a more detailed description of the modelling and filter design is given.

The example is based on a 600 MW converter connected to a system with a short circuit level between 3 to 20 times rated power, system voltage of 240 kV or 500 kV and system frequency of 60 Hz. All designs shown in the table contain shunt filters tuned to all characteristic harmonics, i.e. 11^{th}, 13^{th}, … 36^{th} and 48^{th}. In the calculations, they are represented by single tuned band-pass and high-pass filters, although in an actual scheme they would be implemented as combinations of double or triple tuned branches in order to optimise capacitor bank designs.

The filter Mvar requirements as shown in Table E.1 are very high compared to a design with no IT requirement (but a TIF limit of 40), which would have fewer tuned filter branches and would require an installed Mvar of only about 25 % of rated power. In addition, the Mvar distribution between tuning frequencies is such that an actual design would probably require a shunt reactor to restrict Mvar surplus for almost all designs. In some cases, the degree of installed Mvar would probably justify the use of series filters and possibly self-tuned or active filters.

For a given converter rating, one would typically expect the degree of installed Mvar to be independent of the AC bus voltage. But comparing the 240 kV and 500 kV designs with each other there is a significant difference. The reason for this is that the IT criterion is an absolute measure, in terms of amperes, and not a measure relative to fundamental voltage, such as voltage distortion, TIF etc. (see example at the end of this Annex E).

For the 500 kV filters, the effect of an overhead line, of varying length, between filters and network is also taken into account. In brief, the outcome of this assessment is that more filters are required, but to what degree will depend on the line length. A simplified explanation is that if the line is terminated by a sector impedance, the complete circuit (line + sector) represent a low impedance path, such that even if there is a low degree of residual voltage across the filter, it will cause a high current to flow into the line.

The following harmonic impedance models are used:

1) worst case impedance for individual harmonic selected from a generalised sector impedance such as discussed in IEC TR 62001-1:2016, 7.3.1, and frequently used in design of AC filters for HVDC schemes, though typically with requirements of TIF rather than IT;
2) a resistance in parallel with an inductance, corresponding to the positive sequence surge impedance of the two incoming AC lines and the short circuit impedance of the network. See discussion in IEC TR 62001-1:2016, 7.3.1;
3) the worst case impedance from the sector for the two harmonics that gives the highest IT product and the RL-equivalent for remaining harmonics;
4) worst case impedance from sector impedance for the two harmonics that gives the highest IT-product, plus RL-equivalent for other harmonics, with an explicit modelled transmission line in between PCC and filter bus.

The results are summarized in Table D.1, and the calculations are described in detail in the following sections.

Table E.1 – Required total amount of installed filter Mvars to meet a IT limit of 25 kA for 600 MW transmission

	Required filter Mvar as % of rated power		Remark
	240 kV	500 kV	
1)	73 %	42 %	Worst case impedance
2)	28 %	24 %	RL equivalent , shunt reactor not required
3)	53 %	33 %	Worst case impedance 2 harmonics
4)	--	52 %	Worst case impedance 2 harmonics, 10 km
4)	--	58 %	Worst case impedance 2 harmonics, 20 km
4)	--	45 %	Worst case impedance 2 harmonics, 40 km

The assumptions and preconditions of the example are quite arbitrarily selected (though not unrealistic); however, no detailed optimisation of the designs are made. In other words, the purpose of the examples is not to give any firm absolute guidance in how to design filters nor on how preferred filter designs should look, it is simply to demonstrate that if IT requirements are given they are likely to be decisive and to emphasize that the AC network impedance should be very carefully modelled to avoid unduly costly/complex filter schemes.

E.2 Assumptions and pre-conditions

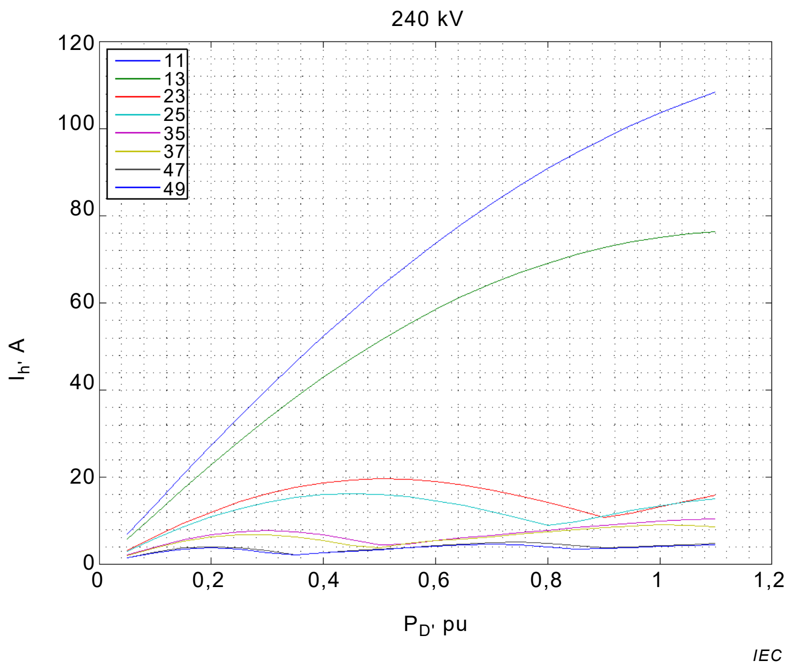
The convertor is a 600 MW monopole, with d_{x} of 6 %, operating with firing angle (α) between 12° and 18°. For simplicity, only characteristic harmonics are considered (11th to 49th), that is effects of any unbalances, asymmetries, etc. are not considered.

The convertor is assumed to be connected to a network with

- a short circuit ratio assumed to be between 3 to 20, (1 800 MVA to 12 000 MVA), and
- AC system voltage of 240 kV or 500 kV (±5 %) and a fundamental frequency of 60 Hz.

For simplicity, filter detuning is considered by applying an equivalent frequency deviation of ± 1% (±0,6 Hz), which is rather small and would correspond to a frequency excursion in the range of ±0,1 Hz or less, thus allowing approximately ±0,5 Hz equivalent to account for filter component tolerances.

The plots in Figure E.1 give the converter harmonic current generation (in amperes) versus load (in pu), both unweighted and also with IT weighting applied, at system voltage of 240 kV. For 500 kV, the currents will be decreased by 240 ÷ 500. Figure E.2 shows a plot giving converter Mvar absorption versus load (in %). Assuming a zero deficit at nominal load, a total of about 300 Mvar in installed filters and shunt banks is a reasonable assumption.



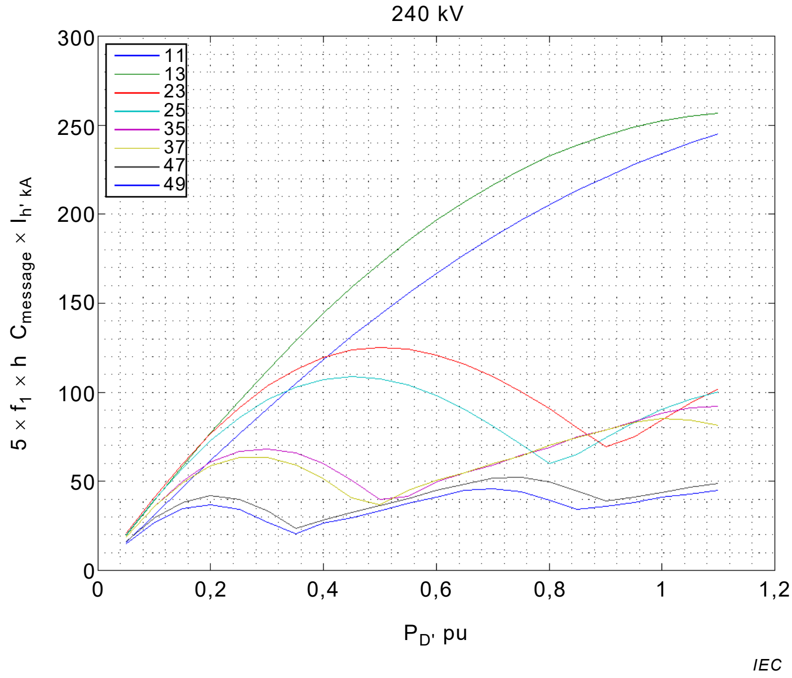


Figure E.1 – Converter harmonics un-weighted (A) and IT weighted (kA) on 240 kV base

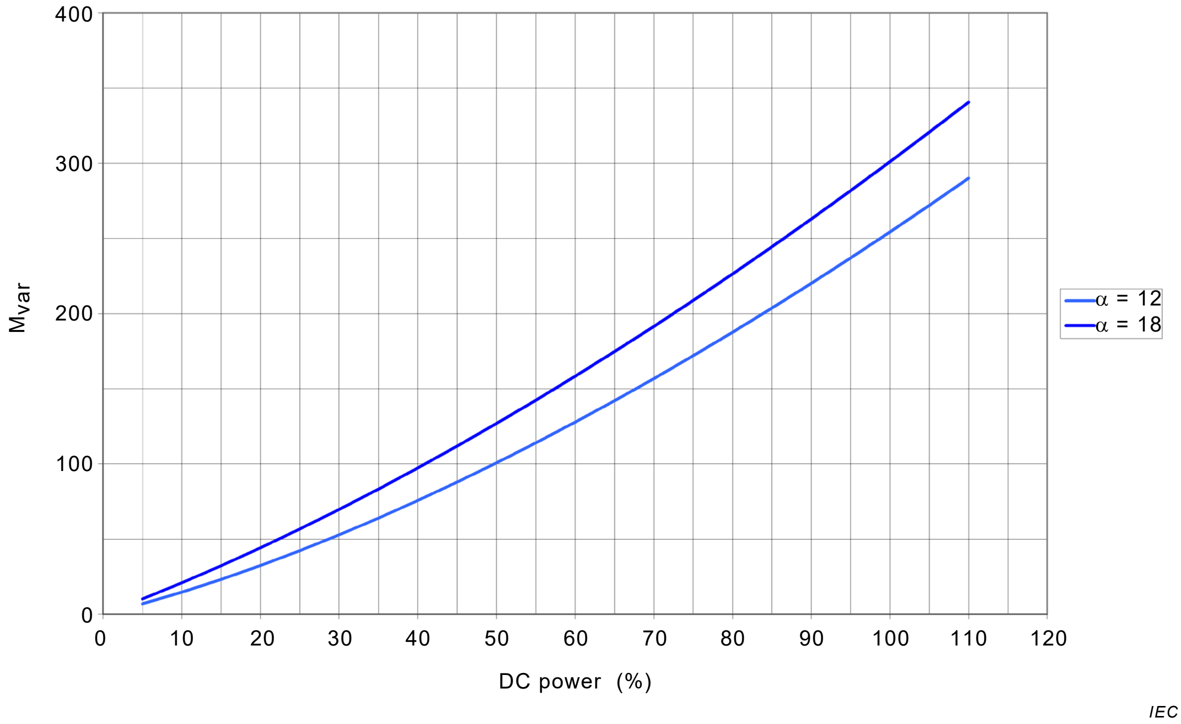


Figure E.2 – Converter Mvar absorption versus load

E.3 Harmonic impedance of AC network

The different assumptions regarding harmonic impedance are briefly discussed below.

The impedance sector in Figure E.3 defines the network impedance as having the following.

- Magnitude within $Z_{1\ \mathrm{min}} \times \sqrt{n} \leq Z_\mathrm{n} \leq Z_{1\ \mathrm{max}} \times n$, where Z_1 is the fundamental frequency short circuit impedance. Here, Z_1 varies between 4,8 Ω to 32,0 Ω and 20,8 Ω to 138,9 Ω for 240 kV and 500 kV respectively.
- Phase angle of ±70° (as only characteristic harmonics are studied).

In IEC TR 62001-1:2016, 7.1.6, it is proposed that IT could be calculated with a phase equivalent impedance modelled by a parallel connection of a resistance and a reactance. The reactance can be calculated from the fault level produced by the lines being modelled by this equivalent, and the parallel resistance can be produced by the positive sequence surge impedances of these lines. Here this RL-equivalent is selected to have an inductance of 12,7 mH and 55,3 mH for 240 kV and 500 kV respectively. The feeding line is assumed to be a double circuit, with a surge impedance of 276/2 Ω and 260/2 Ω for 240 kV and 500 kV respectively.

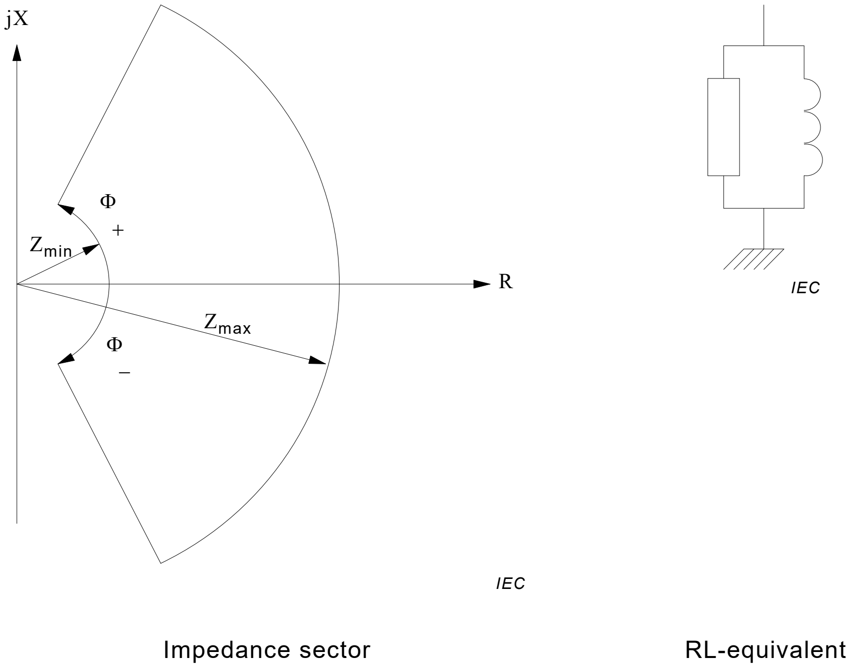


Figure E.3 – Impedance sector diagram and RL-equivalent circuit

For the typical topology of a line commutated converter (see Figure E.4), the worst case impedance of a sector is determined from $I_N = I_C \frac{Z_F}{Z_F + Z_N}$. That is the worst case network impedance (Z_N) of a sector will be that which minimises $Z_F + Z_N$.

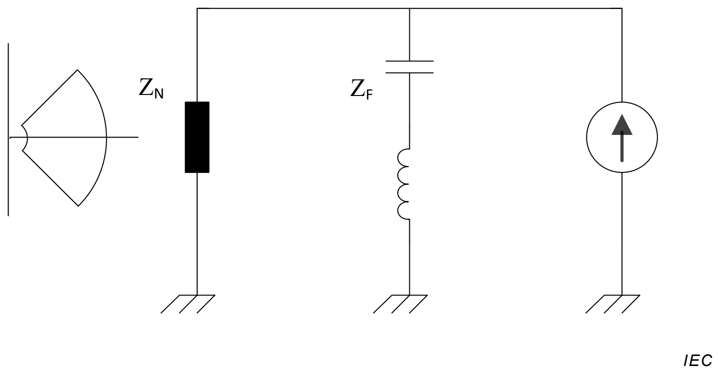


Figure E.4 – Simplified converter/system topology

To select the worst case impedance for each individual harmonic is usually considered to be too pessimistic an assumption. As a compromise between this and an RL-equivalent for all harmonics, design requirements can be limited to use the worst case impedance for the one or two harmonic(s) that give the highest value of IT and using an RL-equivalent for the remaining harmonics.

Which harmonics to select is best demonstrated by an example. Let x_h and y_h be the weighted harmonic components as calculated for the RL-equivalent and for the worst case impedance respectively. Though not necessarily the case, it is reasonable to assume that $x_h \leq y_h$, then the maximum IT product is given by

$$\mathrm{IT}^2 = \sum x_h^2 + \left(y_i^2 - x_i^2\right) + \left(y_j^2 - x_j^2\right) \quad \text{(E.1)}$$

where harmonic i and j are those which give the maximum difference between the squares of individual harmonic components.

If, as in Figure E.5, there is an impedance between the network sector and the filter/converter bus, the network impedance sector, in theory, would need to be mapped across the impedance, in order to maximise the current into the mapped network impedance. However, for practical reasons, the worst case impedance of Z_N is selected instead such that the current into the sector impedance is maximised, i.e. the sum of Z_N and Z' is minimised, Z' being the impedance as seen from the network impedance node towards the converter and filter (by a positive or negative sequence harmonic voltage/current).

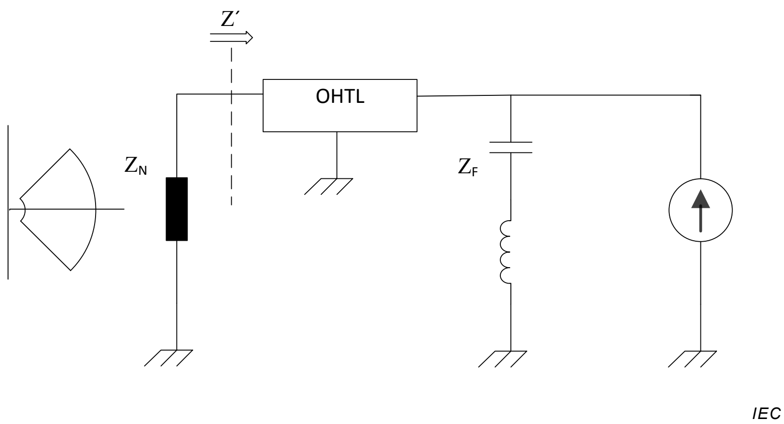


Figure E.5 – Simplified circuit including overhead transmission line

E.4 Filter design

Filter designs for the 500 kV and 240 kV systems are now described under the four different assumptions regarding network representation:

1) Worst case sector impedance for each individual harmonic

The total need for installed filtering Mvar can be assessed by assuming that no individual harmonic should contribute with more than about $\frac{1}{\sqrt{8}}25 \approx 9$ kA to the IT product over the complete load range, the underlying assumption being that the eight characteristic harmonics (up to h48) will be the dominant contributors to IT.

To achieve harmonic performance on a 500 kV system will require about 250 Mvar of filters realised as sharply tuned band pass filters at 11th, 13th, 23rd and 25th harmonic and also tuned high pass filters at 36th and 48th harmonic. Given that the converter-generated individual harmonic current maxima will occur at different load levels, the filters can be optimised and the total Mvar can be brought down to about 210 Mvar. About two thirds of the total is required to manage 11th and 13th harmonic and the rest for the 23rd and higher order harmonics. In other words, the filter scheme would become complex when realised, with either many small different banks or fewer, larger banks plus shunt reactors to restrict Mvar surplus.

For the 240 kV alternative, the harmonic currents will increase with the decrease in voltage and almost 2,1 times more of Mvar would be required, i.e. 440 Mvar, which would be unrealistic for most 600 MW schemes, and a series filter, self-tuned filters or an active filter would most probably be required.

2) RL-Equivalent for each individual harmonic

For the 500 kV system, a design with fewer tuned branches is possible, for example band pass branches at 11th and 13th and high pass branches at 24th and 36th harmonics, but it would still require about 210 Mvar and most likely shunt reactors to limit Mvar surplus at low loads. However, if a design with branches tuned to 11th, 13th, 23rd, 25th, 36th and 48th harmonic is used, a total of about 145 Mvar is sufficient. About 100 Mvar, or two thirds, are required for 11th and 13th harmonic and if a bank size of about 100 Mvar would be acceptable, a design without a shunt reactor should be possible.

For the 240 kV system, a total of about 165 Mvar is required, divided into sharply tuned band pass branches tuned to 11th, 13th, 23rd and 25th harmonic and a high pass branch tuned to 36th harmonic. The 11th and 13th harmonics require about 75 Mvar of the total and, as above, a design without a shunt reactor should be possible.

3) Worst case sector impedance for two harmonics and remaining from RL-equivalent

As discussed previously, to assume that worst case impedance would occur simultaneously for each and every individual harmonic is a pessimistic assumption. To assume a given (fixed) impedance for each and every individual harmonic can be considered to give little room for erroneous assumptions. Measures such as used for TIF and THD consider the worst case impedance for the two harmonic(s) that give the highest value of IT and use an RL-equivalent for remaining harmonics.

At first sight, such a requirement is difficult for a filter designer, given that when the first pair of "worst case" harmonic is filtered out, for example 11th and 13th, the next pair becomes dominant and with that filtered out the following next pair dominant, etc. However, as a first assumption, the limit of each harmonic "worst-case-impedance-value" of about $\frac{1}{\sqrt{2+\kappa}}25$ kA can be used, where the additional harmonic(s) (κ) is added to give a design margin for the additional values. With κ between 1 and 2, the individual harmonic "worst-case-impedance-value" should be below 12 kA to 14 kA.

For the 500 kV system, the required amount of filters is about 200 Mvar, and band pass branches tuned to 11th, 13th, 23rd and 25th harmonic and high-pass branches tuned to 36th and 48th will be required. This relaxation in the requirement for network representation therefore did not give a significant simplification of the design. One advantage is that the design would probably not require a shunt reactor.

For the 240 kV system, the required amount of filters is about 320 Mvar, and branches tuned as for the 500 kV design. To restrict Mvar surplus would require shunt reactors.

4) Worst case sector impedance for two harmonics and remaining from RL-circuit, with intermediate transmission line

For the 500 kV system, the configuration with the HVDC station feeding a transmission line of 10 km, 20 km and 40 km length is evaluated. The line is terminated with worst case sector and RL-equivalent as above.

10 km line: About 315 Mvar will be required with the same topology as (3) above. About two thirds are allocated to 11th and 13th harmonic.

20 km line: With the same filter but with a line length of 20 km, the increase in IT is about 30 % due to 11th and 13th harmonics. About 348 Mvar would be required, of which 78 % is allocated to 11th and 13th harmonics.

40 km line: With increasing line length, the sensitivity to 11th and 13th harmonic moves and instead will occur at 35th harmonic. About 270 Mvar in total is required, of which about 58 % is allocated to 11th and 13th harmonic.

For all three cases, a shunt reactor would be required to limit Mvar surplus.

E.5 Explanation of the difference in impact of relative and absolute performance criteria on required filter Mvar

Here the term "absolute" means based on a physical quantity (amps or volts) whereas "relative" means as a fraction or percentage of the fundamental frequency quantity.

The above examples show a significant difference between the 240 kV and the 500 kV systems in terms of the filtering Mvar required to be installed in order to satisfy an absolute limit such as IT. This is in contrast to what would be expected for a filter design made to satisfy a limit of TIF or other relative measure. The following equations are included to explain why this should be the case.

With reference to Figure D.5, the voltage at, and the current into the AC network can be written as:

$$U_{\mathrm{n}} = I_{\mathrm{C}} \frac{Z_{\mathrm{F}} Z_{\mathrm{N}}}{Z_{\mathrm{F}} + Z_{\mathrm{N}}}\text{, and} \tag{E.2}$$

$$I_{\mathrm{n}} = I_{\mathrm{C}} \frac{Z_{\mathrm{F}}}{Z_{\mathrm{F}} + Z_{\mathrm{N}}} \tag{E.3}$$

For a different voltage level, U' instead of U,

- the converter (source) current will be: $I'_{\mathrm{C}} = I_{\mathrm{C}} \frac{U}{U'}$,
- the filter impedance, with the same Mvar, will be: $Z'_{\mathrm{F}} = Z_{\mathrm{F}} \left(\frac{U'}{U} \right)^2$,
- the network impedance will be $Z'_{\mathrm{N}} = Z_{\mathrm{N}} \left(\frac{U'}{U} \right)^2$, where this is the critical network impedance at each frequency as determined by the network-frequency resonance.
- and the voltage distortion will remain identical:

$$\frac{U'_{\mathrm{n}}}{U'} = \frac{1}{U'} I_{\mathrm{C}}' \frac{Z_{\mathrm{F}}' Z_{\mathrm{N}}'}{Z_{\mathrm{F}}' + Z_{\mathrm{N}}'} = \frac{1}{U'} \left[I_{\mathrm{C}} \frac{U}{U'} \right] \left[\frac{Z_{\mathrm{F}} Z_{\mathrm{N}}}{Z_{\mathrm{F}} + Z_{\mathrm{N}}} \left(\frac{U'}{U} \right)^2 \right] = \frac{1}{U'} U_{\mathrm{n}} \left(\frac{U'}{U} \right) = \frac{U_{\mathrm{n}}}{U} \tag{E.4}$$

- but the current (in amps) into the network will change with the ratio of U to U' as:

$$I_{\mathrm{n}}' = I_{\mathrm{C}}' \frac{Z_{\mathrm{F}}'}{Z_{\mathrm{F}}' + Z_{\mathrm{N}}'} = \left[I_{\mathrm{C}} \frac{U}{U'} \right] \left[\frac{Z_{\mathrm{F}}}{Z_{\mathrm{F}} + Z_{\mathrm{N}}} \right] = I_{\mathrm{n}} \left(\frac{U}{U'} \right) \tag{E.5}$$

That is, for two identical converters under identical conditions but connected to system voltages of 240 kV and 500 kV, filters of the same Mvar (and tuning frequencies, q-factors) will give the same performance in terms of voltage distortion, TIF, THFF; but in order to give the same performance for requirements such as IT and I_{pe}, the filter at 240 kV would need to be approximately twice the size of the filter at 500 kV.

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BSI Group Headquarters

389 Chiswick High Road London W4 4AL UK