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

Part 3: Modelling

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National foreword

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High-voltage direct current (HVDC) systems – Guidance to the specification and design evaluation of AC filters – Part 3: Modelling

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

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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 62001-3, 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 62001-3, together with IEC TR 62001-1, IEC TR 62001-2 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 6;
b) new Clause 4;
c) new Clause 5;
d) new annexes on the location of worst case network impedance;
e) accuracy of network component modelling at harmonic frequencies;
f) further guidance for the measurement of harmonic voltage distortion;
g) project experience of pre-existing harmonic issues;
h) worked examples showing impact of pre-existing distortion;
i) comparison of calculation methods.

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

Enquiry draft	Report on voting
22F/411/DTR	22F/415/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 dateindicated 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 TR 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, seismic requirements, equipment design and test parameters.

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

Part 3: Modelling

1 Scope

This part of IEC TR 62001, which is a Technical Report, provides guidance on the harmonic interaction across converters, pre-existing harmonics, AC network impedance modelling and simulation of AC filter performance.

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 61000-3-6:2008, *Electromagnetic compatibility (EMC) – Part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems*

IEC 61000-4-30, *Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques – Power quality measurement methods*

3 Harmonic interaction across converters

3.1 General

In order to facilitate the analysis of harmonic generation by an HVDC converter, simplifying assumptions are often made. Typically, the HVDC converter is regarded as a generator of harmonic currents, with an infinite internal impedance. Such an assumption is reasonably valid for practical purposes for most harmonics, and is the basis of the calculation methods described in IEC TR 62001-1.

The customer should be aware, however, that such a simplified approach has limitations, and can lead to incorrect analysis and design in some circumstances. In practice, the converter is a link between the AC and DC side harmonic systems, and the AC side harmonic currents may be strongly influenced by the harmonic impedance and harmonic current flows on the DC side.

This is particularly true for low-order harmonics, and it is strongly recommended that the analysis of third harmonic distortion and filtering requirements should take into account the AC/DC side harmonic interaction. At the 11th and 13th harmonics, the interaction effect can also be significant. At higher frequencies, although interactions occur, their practical impact on filter design and harmonic performance will normally be negligible.

Subclauses 3.2 to 3.15 give an overview of the interaction phenomena, focusing on practical implications for AC filter design. The technical specification should make it clear that such phenomena have to be taken into account, and the customer should be able to address the subject in his evaluation of the bidders' designs.

The terms "harmonic interaction" and "cross-modulation" are used synonymously in this report. "Cross-modulation" is to be understood here as the process of harmonic transfer across one converter, not, as it is sometimes used in a more specific sense, as the transfer of harmonics from one AC system to another via the intervening HVDC link.

CIGRE Technical Brochure 143 [1][1] discusses in detail the technical aspects related to the subject. This is a comprehensive review of the subject and included valuable references to other publications. However, it concentrates on the theoretical aspects of calculation procedures. CIGRE Technical Brochure 533 [2] contains more guidance on the practical requirements for specifying and evaluating the treatment of cross-modulation during a tender and subsequent design process and some aspects not included or only briefly covered in [1]. Some of the fundamental conclusions of [1] [2] and other referenced books and papers have been summarised in this document.

Harmonic interaction across the converters can be a cause of problems, some examples of which are illustrated in 3.2. Proper consideration of cross-modulation during the design process can be of benefit, not only in avoiding such future problems in operation, but also in possibly simplifying designs. There are examples of where 3rd harmonic filtering would have been necessary when using a simplified classic calculation with a stiff current source, but shown to be unnecessary when a full interaction model was applied, taking into account the impedances on both sides of the converter. It should therefore not always be assumed that consideration of cross-modulation will introduce problems or make the design more difficult – it may actually resolve some difficult issues.

This document does not recommend prescribing calculation procedures and conditions in the customer's technical specification. In practice, issues involving harmonic interaction have been treated in very different ways and using different study methods by various HVDC contractors in the past. However, customers need comparable bids and want to be in control of the risks associated with this phenomenon. Clause 3 will therefore pinpoint the important assumptions that need to be defined in a technical specification and it will recommend that contractors should justify their chosen calculation procedure and verify its accuracy.

3.2 Practical experience of problems

There has been considerable experience from operational HVDC schemes of adverse harmonic interactions between AC and DC sides of the converter. Several experiences are described in detail in [1]. A brief summary of some illustrative issues is given below.

One of the earliest incidents of reported interaction is related to the Kingsnorth HVDC link [3]. The particular combination of DC reactors and DC cable capacitance of the Willesden pole resulted in a series resonance condition at the fundamental frequency in the DC circuit. A small 2nd harmonic present on the AC side therefore resulted in high fundamental current on the DC side, which in turn gave cause to unequal firing pulse spacing. This resulted in a further contribution to the fundamental frequency voltage on the DC side and created small direct currents in the converter transformers, which tended to saturate the transformer cores, generating further 2nd harmonic distortions on the AC side. An additional flux control loop in the HVDC control system solved the problem. This was one of the earliest examples of what

1 Numbers in square brackets refer to the Bibliography.

is known as "core saturation instability" which has subsequently been observed on several HVDC schemes.

At the Chateauguay back-to-back converter station, a similar phenomenon occurred. A 2nd harmonic resonance condition was observed at the AC side of the converter [4]. The initially small pre-existing voltage distortion at the 2nd harmonic was transferred to the DC side of the converter. The resulting fundamental current on the DC side transferred back to the AC side as a 2nd harmonic current. Due to a parallel resonance of the AC network impedance at the 2nd harmonic, this converter current gave rise to a corresponding voltage distortion, and the loop was closed. The problem was solved by introducing an auxiliary direct current controller which created an external damping for the fundamental frequency component of the direct current. Shunt filters tuned to the 2nd harmonic have also been installed on the AC side.

During commissioning of the Gezhouba-Shanghai HVDC transmission, non-characteristic DC harmonic currents of orders 2, 6 and 18 were observed which caused an unduly large equivalent disturbing current. It was found that pre-existing voltage distortions of order 3, 5 and 7 on both AC sides caused a number of non-characteristic voltage distortions on the DC side. These met with near-resonant conditions at these frequencies on the DC side resulting in the observed current distortions. The implementation of additional resistive damping in the DC filters, as well as changes to the neutral capacitor, solved the problem.

For the same scheme, it was also reported that the 11th harmonic AC side converter current was significantly higher, and the 13th harmonic significantly lower, when a 12th harmonic current of not negligible value flows in the DC circuit. Possibly, this is the case for most HVDC schemes, but is rarely mentioned.

In the design of the Quebec-New England multi-terminal scheme, a 60 Hz component in the DC circuit caused by induction from nearby AC lines was anticipated due to the planned DC line route. This induced fundamental frequency current would cross the converter and generate direct current in the transformer winding, which could lead to core saturation. The design of the scheme therefore included a series blocking filter tuned to the fundamental frequency inserted in the DC neutral of each converter.

A second issue in the same project was related to the Radisson converter station [5]. The station is located in an area of the far north of Canada where geomagnetic activity is strong and the ground resistivity is high. This combination can create high direct currents in transformer neutrals during geomagnetic storms. During such an event, 5th and 7th harmonic distortion on the AC side due to transformer saturation produced excessive 6th harmonic on the DC side resulting in the failure of a DC filter arrester. It was found that the converter impedance as seen from the AC side, which was heavily determined by 6th harmonic impedance of the DC side, shifted the resonance frequency between the AC network and the complete converter station from below 3rd (i.e. not considering converter impedance) to around 5th harmonic. The problem was mitigated by introducing a 5th harmonic re-tuning circuit to two existing 36/48th harmonic AC filters. This re-tuning circuit consists of a filter reactor in parallel with a resistor, installed at the neutral side of the filter. This circuit, normally short-circuited by a bypassing switch, is activated when high 5th or 7th harmonic distortion is detected, resulting in a re-tuning of the filter to 5th harmonic.

At the Sandy Pond inverter station of the same scheme, increasing levels of pre-existing 5th harmonic in the AC network resulted in overload of the DC side 6th harmonic filter, due to cross-modulation. The problem was resolved by converting the existing shunt capacitors to 5th harmonic filters.

The Blackwater back-to-back HVDC Intertie also suffered from a 2nd harmonic instability related to transformer core saturation. A solution was reported which involved modulation of the converter firing angles.

At the Kristiansand converter station on the Norwegian side of the Skagerrak, HVDC Transmission scheme transformer core instabilities and occasional significant harmonic distortions in the low order range have been observed, which led to tripping of AC lines and transformers. Theoretical investigations [6] indicated that the energization of a 400kV shunt reactor in the Tjele converter station in Denmark can cause saturation of the local transformers. The resulting AC side 2nd harmonic voltage distortions cause a significant fundamental current in the DC circuit which is transferred to the Kristiansand converter station in Norway. The Kristiansand converters transform this fundamental current into a DC current on their AC side resulting in unsymmetrical transformer saturation. The zero sequence currents thus generated on the network side can reach values which are able to trigger AC line protection. The effectiveness of a 50 Hz damping control similar to the one developed for the Chateauguay project was proven for the Skagerrak scheme.

A second effect, occasionally observed at Kristiansand, was transformer tripping due to current overload. It was found that high negative phase sequence components of the fundamental frequency voltages in Norway, caused by heavy load flow over not fully transposed AC lines, cause third harmonic current generation by the converters on the AC side, and this feeds into an AC network which can experience occasional resonance at third harmonic. As these network resonances can not be avoided, detuning of the impedance by temporary filter tripping, triggered by a protection related to high harmonic currents, was defined as a general counter measure.

The Sasaram 500MW back-to-back HVDC station interconnects two asynchronous AC systems. During initial commissioning testing, on some occasions the unbalance in one of the AC systems exceeded the specified level of 1 % NPS voltage. This resulted in 2nd harmonic generation on the DC side and consequent 3rd harmonic current generation into the AC system. This resulted in thermal overload of the resistors in the installed 3rd harmonic C-type filters. The problem did not persist, but illustrated the sensitivity of some station equipment to AC-DC harmonic interactions.

During design studies of a large undersea HVDC interconnection in Japan, a vulnerability to core saturation instability was observed. The DC cable system exhibited series resonance near the fundamental frequency, and the AC systems had an impedance resonance near the second harmonic. The AC systems were not particularly weak. For purposes of compaction, the shunt capacitor banks were implemented using dead-tank construction at medium voltage, with transformers connecting these banks to the EHV level. The transformer-capacitor combination yielded a series resonance near the third harmonic, introducing the impedance resonance with the grid at a lower frequency near second harmonic. Small signal analysis techniques, described in [7], were used to screen system conditions for this core saturation instability phenomenon. A modification of the capacitor bank design was implemented, which has avoided this issue during operation.

3.3 Indicators of where harmonic interaction is significant

The practical implications of AC-DC harmonic interaction are mainly related to low order harmonics. Although the theory of cross-modulation is equally valid at all frequencies, the increasing inductive impedance of the converter transformers and DC side smoothing reactors with rising frequency tend to limit higher order DC side harmonic currents and, consequently, their transferred impact on the AC sides is correspondingly smaller.

Harmonic interaction has to be considered for both harmonic performance and filter rating type calculations as well as its impact on protections and the overall dynamic behaviour of the converter station and its controls.

HVDC systems connected to AC nodes with low short circuit ratios, i.e. implying high network impedance at low order harmonic frequencies, and/or nodes which tend to experience significant negative phase sequence components of the fundamental voltage, are more likely to be at risk of harmonic interaction problems.

For back-to-back schemes, interaction should always be investigated, as their DC circuit may not provide effective smoothing or damping of harmonics and as they may interconnect systems with asynchronous or even different nominal frequencies.

As an initial sensitivity check, the AC and DC side impedances should be scanned for possible resonance conditions in the low order range, taking converter impedance into account. Whereas 2nd, 3rd, 5th and 7th harmonic resonances on the AC side are especially significant in supporting harmonic instabilities, the DC side should not be sensitive to fundamental, 2nd and 6th harmonic excitation. Special attention should be paid when the AC and DC side networks are tuned to complementary frequencies, i.e. if the AC side has a parallel resonance at frequency f_1 and the DC is series resonant at a frequency f_2 where $f_1 - f_2 = \pm f_0$ (see 3.9).

In a case where the inductance of a DC smoothing reactor in the DC side is low, 12th harmonic current in the converter on the DC side may also be an issue, with an impact on the relative levels of AC side 11th and 13th harmonics. Even with normal values of smoothing reactors, where a 12th harmonic DC filter is present, the converter current can be high enough to have a significant impact on the 11th and 13th harmonic AC side currents. This will be particularly noticeable in low power operation, where the DC side 12th can be close to its maximum value while the characteristic generation of AC side 11th and 13th harmonics is low, and, therefore, the transferred 11th and 13th currents will have a proportionally greater impact.

Fundamental frequency induction in DC lines from nearby AC lines also introduces a risk of converter transformer saturation due to direct current in the valve windings, and consequent undesirable effects [8]. Detailed study of the level of fundamental frequency induction and of harmonic interaction in such cases is essential (see 3.13).

3.4 Interaction phenomena

The AC voltage and current waveforms can be considered to be composed of positive, negative and zero sequence components of the fundamental frequency along with positive, negative and zero sequence components of other frequencies. The DC side waveforms can similarly be expressed as a DC component plus a broad spectrum of other frequencies. The conversion process involved in the conventional bridge connected converter establishes a well defined relationship between frequencies on the AC side of the converter and frequencies on the DC side.

In general, the relationship is governed by several simplified rules.

- The ungrounded star and delta transformer connections on the valve side of the converter transformers preclude the transfer of zero sequence frequencies from the AC side of the converter transformers to the DC side. Zero sequence coupling is limited to second order capacitive transfer effects.
- Any given positive sequence frequency greater than fundamental on the AC side of the converter is converted to a dominant frequency on the DC side which is lower in frequency than the AC side frequency by an amount precisely equal to the fundamental frequency of the AC side of the converter. For AC side positive sequence frequencies less than fundamental, the resultant DC side frequency is the complement of the AC side frequency.
- Any given negative sequence frequency on the AC side of the converter is converted to a dominant frequency on the DC side which is greater in frequency than the AC side frequency by an amount precisely equal to the fundamental frequency of the AC side of the converter.
- Any given frequency on the DC side of the converter is converted to two dominant frequencies on the AC side. A positive sequence frequency is created which is greater than the DC side frequency by an amount precisely equal to the fundamental frequency of the AC side of the converter. If the DC side frequency is greater than the AC side frequency, a negative sequence frequency is also created which is less than the DC side frequency by an amount precisely equal to the fundamental frequency of the AC system. If the DC side frequency is less than the AC side fundamental frequency, then instead of a negative sequence frequency, a second positive sequence frequency is generated at a value precisely equal to the AC side fundamental frequency less the DC side frequency.

Table 1 provides a summary of the dominant frequencies involved in any interaction:

Table 1 – Dominant frequencies in AC–DC harmonic interaction

DC side frequency	AC side frequencies	
$F_{DC} > f_0$	$F_{DC} + f_0$ (pos. seq.)	$F_{DC} - f_0$ (neg. seq.)
$f_{DC} = f_0$	$2f_0$ (pos. seq.)	0,0 (DC)
$F_{DC} < f_0$	$f_{DC} + f_0$ (pos. seq.)	$F_0 - f_{DC}$ (pos. seq.)
F_{DC} = 0	f_0(pos. seq.)	
f_{DC} is the interaction frequency on the DC side of the converter.		
f_0 is the fundamental frequency of the AC side of the converter.		

The above rules are not limited to just harmonic frequencies but in general can be applied to all frequencies. Other frequencies shifted by multiples of the converter pulse number times fundamental frequency (or their complements) can also be involved in the conversion process but for the most part, their contributions to any given interaction are of second order. The relationships hold for not only steady-state conditions but can also be observed in quasi-steady state conditions as experienced under prolonged unbalance fault conditions, and even transient conditions (any phenomena lasting greater than 1 or 2 cycles).

3.5 Impact on AC filter design

3.5.1 General

Interaction will influence AC filter design only when the resultant harmonics are of a significant magnitude so as to affect either the AC filter performance or the AC filter rating or both.

Several interactions are known to influence the design of AC filters, and are discussed in the following subclauses.

3.5.2 AC side third harmonic

One such set of interaction frequencies includes

- AC side negative sequence fundamental frequency,
- DC side second harmonic, and
- AC side positive sequence third harmonic.

The presence of a substantial component of fundamental frequency negative sequence voltage in the commutating bus voltage (> 1 % to 2 %) will often result in large components of positive sequence third harmonic in the AC side waveforms and large second harmonic components in the DC waveforms. Considering the two AC networks, current flow is limited by the series combination of the negative sequence fundamental frequency impedance and the third harmonic positive sequence impedance. With low values of net effective impedance, and a large negative sequence voltage, the negative sequence current flow and third harmonic current flow could be large. Installing a low impedance shunt connected third harmonic filter to limit the third harmonic flow into the AC system could actually exaggerate the amount of current flow, increasing the third harmonic current in the filter to values above the flow without the AC filter. This could be further compounded by resonances between the AC filter and the AC system.

The second harmonic impedance of the DC network could also influence the design of the AC side third harmonic filter.

3.5.3 Direct current on the AC side

A second set of interaction frequencies affecting the design of filters includes

- AC side second harmonic positive sequence,
- DC side fundamental frequency, and
- AC side valve winding DC currents.

Fundamental frequency currents on the DC side of the converters can be converted into positive sequence second harmonic and DC currents on the AC side of the converter. The second harmonic currents are transformed and hence appear in the AC network. Although DC currents are initially coupled into the AC network, with time, the AC side currents decay to zero and the DC current flow eventually ends up flowing through the magnetizing path of the equivalent circuit of the converter transformer shifting the transformer saturation characteristics. Depending on the magnitude of the shift, one-sided transformer saturation could occur resulting in the generation of second harmonic positive sequence currents due to transformer saturation. These currents could add to the second harmonics coupled by the interaction network exaggerating the current flows in the three networks.

Fundamental frequency blocking filters on the DC side and second harmonic shunt connected filters on the AC side have been used to limit the interaction effects. The design of the second harmonic filter should take into account not only the direct interaction effects but also the possible amplification resulting from interaction with transformer magnetization.

3.5.4 Characteristic harmonics

Interaction can occur at characteristic frequencies as well as low order non-characteristic frequencies.

Filtering is normally provided for the 11^{th} and 13^{th} harmonics creating a low impedance path in the 13^{th} harmonic positive sequence network as well as the 11^{th} harmonic negative sequence network. If the DC side impedance at the 12^{th} harmonic is also small (as can occur on back-to-back schemes with small or no smoothing reactors), coupling can occur between the 11^{th} and 13^{th} networks of both AC systems. As a result of the coupling, 11^{th} and 13^{th} harmonics of both AC system frequencies could be evident in the respective filter waveforms.

The AC filters limit the impact of the interaction to the converters themselves and as a result the interaction is not normally evident in the AC system voltage and current waveforms. The design of the AC filters however should recognize the potential for interaction with suitable allowance in the filter performance and rating.

3.6 General overview of modelling techniques

3.6.1 General

A theoretically comprehensive investigation into the harmonic behaviour of an HVDC system is only fully possible if a complete AC-DC-AC interaction model is used. This is feasible once all the AC and DC filter design is complete and the filter component parameters are known. Also, full AC-DC-AC interaction models but using approximate representations of the filters, perhaps simply as AC capacitors of the estimated Mvar capacity or DC filters with the predicted capacitor size, can be used to investigate low order resonance conditions during an early design stage when smoothing reactors and transformer impedances are selected, as well as the possible need for low order filtering on either or both sides.

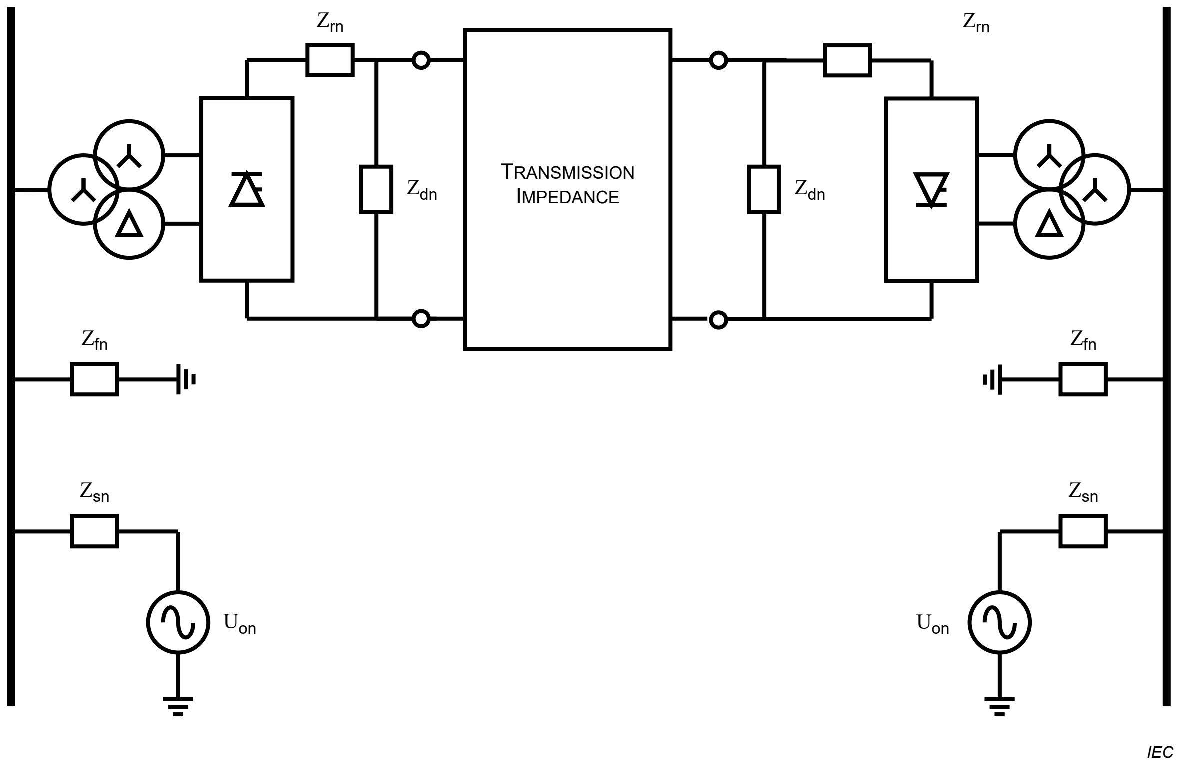
However, it is generally not practicable to use a complete AC-DC-AC interaction model for the detailed filter design itself, as it implies that the design of the individual filter schemes on both AC sides and the DC side would have to be done simultaneously. All such filter design calculations require variation of an extensive number of system parameters and factors affecting detuning, and to do this for all filters in the complete HVDC system simultaneously would be an extremely complicated iterative process. This practical difficulty has led to the use of reduced models which attempt to de-couple the various elements and allow the design of the various groups of filters to be made independently.

One of the most common approaches is to perform the filter design at one converter station with a relatively simple frequency domain model in which converters are modelled as a harmonic current source. Current source values for this equivalent are derived from simplified calculations. The DC filter design calculations can also be performed using a similar model with the converters as harmonic voltage sources. However, there are significant inherent inaccuracies in any such reduced model.

If it can be shown that there is very little harmonic coupling between the two converter stations, for example due to a long HVDC cable, then it may be possible to treat the two stations independently. It may also be useful to treat the two stations separately in a partial analysis to investigate some aspect of the harmonic transfer at one station alone.

Various full and reduced modelling techniques are discussed in the subsequent subclauses. All refer to some or all of the system components represented in Figure 1.

More details, particularly on the mathematical background, are given in [1] and [9].



Key

U_{on} AC system voltage

Z_{sn} AC network harmonic impedance

Z_{fn} AC harmonic filters

Z_{rn} DC smoothing reactor

Z_{dn} DC filter

Figure 1 – Key elements of a complete AC-DC-AC harmonic interaction model

The circuit shown in Figure 1 shows the key elements of any model used to study AC-DC-AC harmonic interactions. The details of these elements are as follows.

- AC system voltage (U_{on}): Represents the positive and negative sequence fundamental frequency system voltage, plus any pre-existing harmonic distortion, including its phase sequence.
- AC network harmonic impedance (Z_{sn}): This models the range of possible harmonic impedances ($R_{sn} \pm \mathrm{j}\, X_{sn}$) of the AC network.
- AC harmonic filters (Z_{fn}): Includes the number of connected filters and the type of filter, for example tuned, high pass, double frequency. Detuning due to various reasons has to be represented if it affects the particular harmonic(s) under study. Shunt capacitors are also represented as their presence affects the overall impedance at low harmonic orders.
- Converter transformer: This represents the impedance of the transformer, also considering any imbalance between star/star and star/delta connections and imbalances between phases and turns ratios. The transformer saturation characteristics may also be represented, using a model which responds to direct current in the valve-side windings. The range of the tap-changer should be considered, as this has a significant effect on the transferred impedances.
- HVDC converter: Models the firing controls of the converter, including any tolerance effects, plus the higher level control system functions such as constant current control and any special functions which affect harmonic interaction.
- DC smoothing reactor (Z_{rn}): This is the series inductance and resistance of the reactor.
- DC filter (Z_{dn}): Considers the number of connected DC filters and the type of filter, for example tuned, high pass, double tuned. Filter outages and de-tunings due to various reasons have to be taken into account. The neutral bus capacitors (not shown) are also represented.
- Transmission impedance: This includes the impedance of the DC system (overhead wire or submarine/underground cable) represented by the exact transmission line equations. In the case of a back-to-back station, this impedance is zero. In case of overhead lines, it might be necessary to consider additional voltages/currents induced by parallel AC overhead lines. Long electrode lines or neutral conductors should also be explicitly modelled.

For a full, closed-loop model, all the above AC and DC side systems and converters need to be represented.

3.6.2 Time domain AC-DC-AC interaction model

The most comprehensive model is a full representation in the time domain of the AC and DC side circuits and the converters, as this includes all aspects of "real life" interaction. The studies can be performed using electromagnetic transient programs, including full representation of the converters and their control systems, such as PSCAD/EMTDC or EMTP-RV. A full three-phase detailed switching model of the converter is included, including its control system. Careful attention should be given to choosing an appropriate time step to accurately represent harmonic generation (some programs use time-step interpolation to relieve some of these issues). When coupled to models of the AC side and DC side systems, this gives a powerful tool to analyse the AC-DC-AC interactions across the converters. The model can be used to calculate the voltage and current waveform at any location of interest. A Fourier analysis of the waveform will determine the harmonic components and the phase sequence of these components. Experience with Fourier analysis tools is vital and care should be taken to avoid misleading results.

Although a powerful technique, such time domain studies require a considerable expertise and effort to perform, especially considering the long run time for such complex models and the many cases which need to be considered for filter design. Hence, a complete investigation of all relevant filter design cases (including variation of AC network impedance and component tolerances as well as all load and configuration cases) is not feasible with this model. Moreover, specific AC network models are used, which effectively removes the capability to independently model network impedances at the various harmonic frequencies, such as should be done when the AC network impedances are defined by envelopes in the R-X plane. Hence, this technique is normally used as a validation of the frequency domain studies for certain specific comparison cases, especially for low order harmonic results.

Another possible use for time-domain models is to determine linearised harmonic coupling parameters, to represent the converters in a subsequent full closed-loop frequency domain analysis (see 3.6.3). Effectively, this approach makes the closed loop frequency domain analysis actually a hybrid between frequency- and time-domain approaches.

3.6.3 Frequency domain AC-DC-AC interaction model

A model of similar extent, but implemented in the frequency domain, can also include all key elements to calculate interaction. The benefit of this model is that a very large number of design cases can be calculated very efficiently. Modelling of AC network impedance envelope in the R-X plane as well as variation of tolerances can be easily realised.

One of the most important features of a frequency domain model is the way it considers the converter impedance on the AC and DC sides respectively. Whereas simpler models often only use the commutating reactance of the converter transformers, more sophisticated models use impedance transformation functions to account for all impedances. An example of such functions has been given in [10]. The apparent converter impedance at a given frequency on the DC side is influenced by AC side impedances at various other frequencies – and vice versa. A common approach is to limit the number of considered frequencies to the most significant ones.

However, the determination of the case sensitive converter transformation functions (i.e. voltage, current and impedance) is difficult. A function taking into account the effects of closed-loop controls can be determined by calculations using a corresponding time domain model. This matter has been elaborated in [10]. Interactions can also be studied using an appropriate small-signal modelling tool, such as described in [9]. In either case, final verification of analytic results requires use of time-domain simulations.

In a less sophisticated open-loop frequency-domain modelling of AC-DC-AC harmonic interaction, the impact of converter controls is neglected (i.e. constant firing angles according to the selected operating point are used). Under this prerequisite, the transfer functions of voltages, currents and impedances can be calculated analytically.

More details on this subject can be found in [1].

3.6.4 Frequency domain AC-DC interaction model

This is a reduced frequency domain model which neglects the impact of harmonics generated at the remote station and the transferred impedance of that station. The DC circuit within such a model is simply modelled by a passive impedance. Obviously, the benefit of this simplification is that calculations can be performed separately for each converter station and the number of design cases is reduced significantly. This model might be applicable if 2nd harmonic shunt DC filter were installed at the remote station, thus effectively short-circuiting the converter and remote AC system as seen from the DC side.

The disadvantage of doing so is that the DC impedance used is less accurate as it does not take into account the AC network and AC filter impedance of the remote station. Moreover, the cross-modulated harmonic contributions of the remote station, which can be significant, will not be modelled.

3.6.5 Frequency domain current source model

In this simple frequency domain modelling, it is assumed that at all harmonics the converter behaves on the AC side as a source of harmonic current. This model provides a very efficient way to investigate the AC filter design for one converter station and has been used in [11] when discussing other issues of AC filter design. Harmonic current source values have to be determined using an AC-DC interaction model as described above, but with only generic or even no consideration of AC network and AC filter impedance.

However, this assumption may introduce significant errors for low order harmonics. For example, in cases where there may be a natural resonance between the AC filters and the AC network close to 3rd harmonic, the converter may behave more like a harmonic voltage source than a harmonic current source. In such cases, the said resonance will result in a high impedance for the 3rd harmonic as seen from the converter. This high impedance will be transferred to the DC side and seen mainly as a 2nd and 4th harmonic impedance. Hence 2nd harmonic currents on the DC side will be heavily influenced by the 3rd harmonic AC side impedance. Finally, as 2nd harmonic DC side currents will cause the converter to produce 3rd harmonic currents on the AC side, these currents would therefore be dependent upon the network and filter impedance, rather than behaving as a constant current source.

This means that a time consuming iterative design process should be used which re-calculates current source values using the anticipated AC filter design and the AC network impedance. Following this, the AC filter design has to be re-confirmed (or changed) using the new source values. Nevertheless, such a procedure may be quicker than the use of a complete AC-DC-AC interaction model.

3.7 Interaction modelling

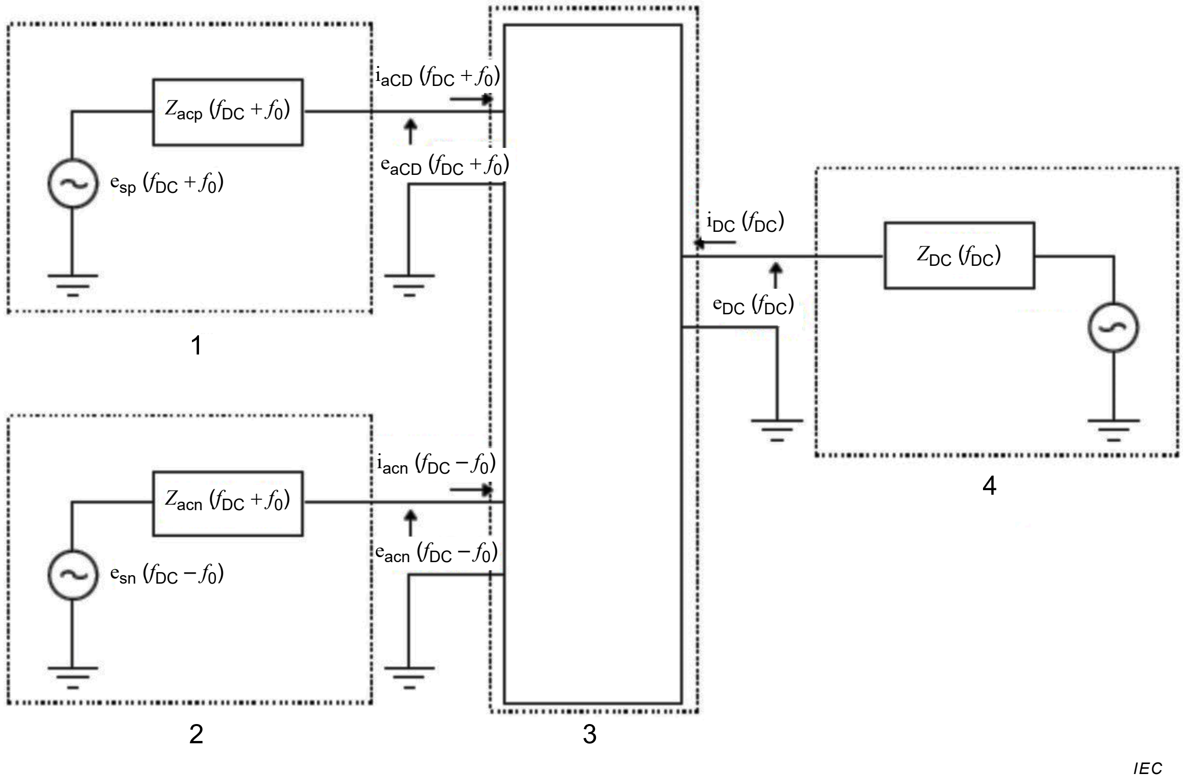
3.7.1 General

For any given set of AC and DC side operating conditions (AC voltage, DC voltage and current and firing angle), the DC converter can essentially be treated as a linear passive device similar to a three winding transformer but which transforms voltages and currents between the three networks (at three different frequencies) involved in any interaction as illustrated in Figure 2. The figure depicts the condition where the DC side interaction frequency is greater than the fundamental frequency of AC system. Representation of the other conditions is similar with the sequence and frequency of each of the networks established from the table of frequencies shown above.

The magnitude of voltages and currents which appear in any given interaction are a function of the coupling between the networks, impedances of the AC and DC networks at the respective frequencies as well as the magnitude of the driving force (or forces) which establishes the frequencies in the first place.

3.7.2 Coupling between networks

The amount of coupling from network to network is a direct function of the DC operating conditions and can be quantified in terms of the firing angle and overlap angle. If overlap is not considered in the analysis, the coupling network behaves as an ideal three winding transformer where the "equivalent turns ratios" are dependent on the firing angle. The harmonic current flow into each of the three networks is a function of the "equivalent turns ratio" and as such effectively connects each of the two AC networks and the DC network in series. Inclusion of overlap angle into the analysis is equivalent to adding leakage and magnetizing reactances to the ideal transformer.



Key

1 AC positive sequence network at frequency $f_{DC}+f_0$

2 AC negative sequence network at frequency $f_{DC}-f_0$

3 Transformation matrix transforming voltages and currents at the harmonic frequencies

4 DC network at frequency f_{DC}

Figure 2 – Equivalent circuit for evaluation of harmonic interaction with DC side interaction frequency greater than AC side fundamental frequency

3.7.3 Driving forces

Driving forces could originate in the AC systems. The driving force could be harmonic in nature resulting from the presence of harmonic generating devices such as other DC stations, static var compensators (SVCs), transformer saturation, non-linear loads. Also, the driving force could simply be negative sequence fundamental frequency voltage resulting from unbalanced loads in the vicinity of the DC converter, heavily loaded untransposed transmission lines feeding the converter or asymmetrical faults and/or 2 phase operation during single pole reclosure.

The driving force could originate in the DC converter itself, with harmonic currents and/or voltages driven by firing angle jitter, unbalance in commutating reactances or possibly unbalance in converter transformer turns ratios.

The third source of driving forces includes voltages and currents of the DC transmission network either coupled electromagnetically or electrostatically from nearby AC transmission or directly coupled as a result of some AC/DC interaction phenomena at the remote converter. For the latter, harmonics of the remote AC system frequency would be involved resulting in non-harmonic interaction frequencies at the local station.

3.7.4 System harmonic impedances

The impedance of the three networks at their respective interaction frequencies play an important role in the magnitude of the voltages and currents which can appear at the converters. Series and parallel resonances can occur within each leg of the equivalent network, but also between the three legs. For example an effective series resonance could appear between the positive sequence AC network and the DC network resulting in large current flow at the respective frequencies between the two networks. To the negative sequence network, the resonance condition could appear as a parallel resonance (with a high impedance). In fact, the current flow in the positive sequence and DC networks could be excited by a small voltage in the negative sequence network.

3.8 Study methods

3.8.1 Frequency domain

Both the performance and rating calculations for filters have been carried out traditionally using frequency domain analysis and design tools. A network solution of voltages and currents are calculated for each selected harmonic and the weighted voltages and currents for each frequency are combined mathematically to establish some overall performance or rating index. Study of interaction effects requires the expansion of the single frequency network model into a multi-frequency model. The model could be the simple three frequency model described above or could be expanded to include a broad spectrum of frequencies.

With frequency domain analysis, it is possible to focus on the exact nature of a specific interaction. The AC system and DC side harmonic impedances can be readily varied within a known spread of values to establish if interaction is likely to occur. In the event that interaction can occur, the same procedure can be used to establish limiting conditions for the design including DC control parameters and component ratings. It can also be used to trade off DC design with possible AC and DC system operating restrictions.

Frequency domain analysis is for the most part limited to "small signal" analysis. For harmonic interaction analysis, this is normally valid as harmonic components are typically several orders of magnitude less than the AC side fundamental frequency and DC side DC components of their respective waveforms.

The main challenge involved in frequency domain analysis is the derivation of the coupling coefficients which mathematically couple the AC and DC networks. These can be derived numerically or analytically and can be set-up to include the influence of the DC controls.

In single frequency analysis techniques, HVDC converters are often treated as ideal harmonic current (AC side) and voltage (DC side) sources with magnitudes of non-characteristic harmonics used in the calculations based on experience from measurements on simulators or other DC schemes. When considering harmonic interaction, this treatment may not be completely valid. For example, the third harmonic generated by the converter is for the most part dictated by the magnitude of negative sequence voltage at the converter bus, and hence an ideal third harmonic voltage source would provide a more accurate treatment in the analysis than the conventionally used current source.

3.8.2 Time domain

With the availability of digital simulation techniques approaching (or achieving) real time capability, time domain analysis is an effective tool when coupled with Fourier series or Fourier transform analysis of the voltage and current waveforms. The approach involves the simulation of a set of specific AC and DC operating conditions. Once a steady state condition is achieved, the voltage and current waveforms are recorded and analyzed for their frequency content. The waveform components are then numerically combined to obtain the traditional filter performance and rating indices. This analysis could be carried out on a continuous basis providing "on-line" monitoring of the performance and rating indices.

The major advantage of this method is that the simulation is in fact carrying out the harmonic load flow, hence there is no requirement to compute the coupling coefficients. A significant second benefit is the ability to observe sustained interaction which may be triggered by some disturbance to the network.

The major disadvantage of the time domain solution is the limit imposed on the extent of the AC network which can be practically represented in any given simulation. Without a detailed model, AC system operating conditions, which may result in an interaction, may not be simulated and hence the influence of the potential interaction would not be included in the filter design.

3.9 Composite resonance

This is a term which describes a resonance involving the circuits on both AC and DC sides of a converter, including the harmonic transfers across the converter and the action of the converter control [1] [14]. It is important to recognize that the critical resonance conditions of the system may not be determined by analysis of just the AC side or just the DC side circuits, but should consider the whole interlinked system, as shown in [13]. This reference presents a frequency scan method using a time domain simulation tool to obtain a more accurate frequency characteristic for identifying harmonic instability in HVDC systems. It shows that different impedance characteristics are obtained if AC and DC impedances are determined independently than if the interlinked system is considered.

3.10 Core saturation instability

This phenomenon may be regarded as a special case of composite resonance, with the introduction of an additional "frequency shift" with AC side 2^{nd} harmonic being generated due to one-sided saturation of the converter transformer core by direct current caused by DC side fundamental frequency current [1] [3].

3.11 Particular considerations for back-to-back converters

In a back-to-back HVDC scheme, there is virtually no DC transmission impedance, there are no DC filters, and smoothing reactors may be small or non-existent, due to the absence of DC short-circuits and the lack of interference from DC side harmonics. Due to the close coupling of the rectifier and inverter, there will be a significant harmonic contribution at the rectifier AC side from the inverter and at the inverter AC side from the rectifier. The magnitude of these cross-modulated harmonics can be typically 10 % to 20 % of the local contribution and is dependent upon the impedance within the circuit, which can be seen as the AC side impedances (i.e. transformers, AC filter and AC network), transferred to the DC side by converter operation at both terminals, plus the DC smoothing reactor, if installed.

Although a DC smoothing reactor has an influence on the magnitude of these cross-modulated harmonic components, the presence of such a reactor does not fully eliminate them. In some designs, no DC side smoothing reactors are used, resulting in considerably lower smoothing and hence in higher transferred harmonics. When smoothing reactors are used, they normally have low inductance values, as it is impracticable to manufacture air core reactors with high inductance for very high direct current ratings.

NOTE The smoothing effect of a low inductance reactor in the low voltage, high current circuit can be as high or higher than a much larger inductance reactor in a high voltage line transmission.

If the nominal fundamental frequencies of the two AC systems are different, then due to cross-modulation, harmonics of one fundamental frequency will appear in the AC system of the other side of the back-to-back link as interharmonic frequencies, to which more stringent limits may apply. Beating of the different frequencies will result in sub-harmonic frequencies which may cause light flicker or torsional effects on machines.

Therefore, in the analysis of back-to-back HVDC links, it is not advisable to use reduced interaction models which consider only the impact of one converter station.

3.12 Issues to be considered in the design process

3.12.1 General

As discussed in the preceding subclauses, due to the complex nature of harmonic interaction, complex and time consuming calculations are required to take all aspects into account. For practical reasons, simplifications are therefore needed, especially during the tender stage when only limited time is available. 3.12 discusses assumptions and procedures commonly used.

Firstly, a distinction should be made between the actual design process and evaluation of a design, where the latter is made simply to demonstrate the adequacy of the design. The actual design of the filters is often made with simplified assumptions, for example modelling the converter as a current source, taking harmonic interaction into account through simpler modelling as discussed in previous subclauses, or by simple manual calculations. A major reason for this simplification lies in the nature of designing a HVDC scheme, where typically many aspects of the overall design often have to be made in parallel. That is, main circuit calculation, AC filter design, DC filter design and other studies start more or less simultaneously and run in parallel. This is more the case for a short-duration tender, but to some extent it will still hold true during execution of a project when station layout, civil drawings, etc. await the outcome of technical system studies and subsequent equipment specifications.

Therefore, in many cases filter designs have been completed, and will continue to be in the future, without detailed consideration of harmonic interaction. In such situations it is the designer’s responsibility to ensure that there is an inherent margin in the design such that it could demonstrably meet requirements of rating and performance, if harmonic interaction were to be considered explicitly.

Such a demonstration is often made using time domain tools, such as PSCAD/EMTDC, EMTP or similar, though other methods are used. A restricted number of simulations are usually sufficient in order to demonstrate that a design is acceptable. The contractor needs to be capable of explaining why such restricted cases are governing or sufficient for design.

Which model and software to use is best determined by the contractor according to his capabilities and normal practice. However, the contractor should be prepared to justify and verify the model used, through theoretical and analytical reasoning or any other means acceptable to the customer. Especially for newer converter topologies, for which there is less practical experience, such justification should preferably be verified through practical measurements on an actual converter in service.

Further, if a time domain model is used and harmonics are evaluated using Fourier analysis, some allowance should be made for errors introduced through the limitations of the model. The accuracy will be a trade off between simulation time (how close the simulation comes to steady state conditions) and time-step in simulation (a too large time step can result in unrealistically high calculated harmonic levels).

In the discussion below, the focus of harmonic interaction is on low order harmonics, as theory and practical experience indicate that harmonic interaction is mainly an issue in this range.

3.12.2 Fundamental frequency and load issues

The fundamental frequency aspects that can affect the harmonic interaction are the negative phase sequence component of AC bus voltage, the frequency variation (inasmuch as this affects filter detuning) and, to some extent, the load level of the converter.

It is common practice in filter design to consider a defined operational range for system frequency and positive sequence voltage of the interconnected AC systems. It is also essential to define a maximum value for the negative sequences voltage to be considered. Separate sets of parameters for performance and rating type calculations are often used.

When using such positive sequence values for the driving source U_{on} in a model according to Figure 1 along with a given fundamental AC network impedance, the resulting fundamental frequency voltage occurring at the converter busbar may be unrealistic and exceed normal operational limits. Such a procedure does not take into account the fact that in real AC systems, active and reactive load dispatch will avoid such exceptional busbar conditions. Therefore, the range of fundamental voltage is often considered to be defined at the converter bus rather than behind the network impedance. Alternatively, the magnitude of the source voltage could be adjusted such that fundamental frequency voltage at the converter bus corresponds to the actual operational range. If several different filter configurations are studied, then the source levels may have to be adjusted for different simulations.

The converter load levels should be selected such that the various filter configurations that can affect the result are all considered (see IEEE Std 1124-2003, 5.4.1 [11]).

If harmonic interaction of characteristic harmonics is to be studied, then minimum load should be considered, as the DC side 12$^{\mathrm{th}}$ harmonic and others can be at their highest at this load level.

3.12.3 Negative phase sequence

If the level of negative phase sequence (NPS) voltage to be considered is defined by the technical specification to occur at the converter bus, then when using the model in Figure 1 the negative sequence source voltage is also adjusted such that the desired magnitude at the converter bus is reached. However, the situation for the negative phase sequence fundamental component is slightly different from that for positive sequence. The operation of the converter may in itself generate negative sequence current, which when flowing into the AC network impedance will generate a negative sequence voltage at the converter bus. The angle of this component relative to the original source NPS will depend on the AC and DC system impedances, and may be additive. In that case, the level of NPS at the converter bus will be higher than the specified pre-existing source level. This will not be seen by, or subject to, any system voltage regulation such as applies to positive sequence voltage, and therefore should be taken into account as a real possibility.

Therefore, although it is fairly common practice for technical specifications to define NPS either at the converter bus or in a general way without specifying location, it would be more correct to define it in the same way as a pre-existing harmonic, that is, behind the relevant AC network impedance. Simulations should also take into account the relative phase shift of the negative sequence compared to the positive sequence, as this may interact with converter operation, affecting the DC side second harmonic voltage and consequently both the negative sequence fundamental and positive sequence 3$^{\mathrm{rd}}$ harmonic AC side currents from the converter.

The specification of NPS and the analysis of the impact of NPS fundamental frequency voltages at a back-to-back converter connecting asynchronous systems of the same nominal frequency can be particularly challenging. The fundamental frequency NPS in each system introduces a second harmonic component into the DC current which can beat in magnitude as the phase of the two systems slowly slip against one another due to slight differences in frequency between the two systems. The second harmonic component is then injected into the AC systems on each side as a 3$^{\mathrm{rd}}$ harmonic positive sequence and negative sequence fundamental which tends to modulate the pre-existing NPS voltage. In the extreme case, the amount of 3$^{\mathrm{rd}}$ harmonic current can almost double (and should be considered in the design of any 3$^{\mathrm{rd}}$ harmonic filters) due to the reinforcement of the NPS components from each system. The fundamental frequency NPS in each system will also be modulated by the converter, and the variation in fundamental frequency phase voltage can become large enough to affect tapchanger controls. The effect can be particularly acute when the converter is installed at the end of a single long untransposed AC transmission line which is then loaded to multiple times the surge impedance loading. In this case, any previously measured values of NPS in the AC system would greatly understate the magnitude of NPS voltage that would be experienced at the converter station when operating at full load, and thus the customer should be aware that a "higher than measured" value of NPS is specified as applying at the converter station.

3.12.4 Pre-existing harmonic distortion

Distortion of the AC system voltage at the converter bus also influences the resulting converter harmonics. These voltage distortions are caused by harmonic currents generated by the converters as well as by pre-existing distortion. If an interaction model is used which can consider both effects simultaneously, it is sufficient to use actual values for pre-existing distortion (with an allowance for future growth) as the driving voltage U_{on} in a model according to Figure 1. Separate spectra for performance and rating type calculations may be used.

For the harmonic interaction to be modelled correctly, not only the magnitude but also the phase sequence of the pre-existing harmonics is needed, as this affects the order of harmonic transfer across the converter. In case information is lacking on sequence, then a general assumption of 2$^{\text{nd}}$, 5$^{\text{th}}$ and 8th harmonics being mainly negative sequence, and 4$^{\text{th}}$, 7$^{\text{th}}$ and 10th harmonic being positive sequence may be reasonably valid. Any 3$^{\text{rd}}$, 6$^{\text{th}}$ and 9$^{\text{th}}$ harmonics generated by saturation of transformers and machines will be zero sequence (in which case they can be ignored as they do not cross the converter), but electronic converters (both domestic and industrial) and any other nearby HVDC converters will generate 3$^{\text{rd}}$ harmonic of positive sequence, and so it should not be assumed that all pre-existing 3$^{\text{rd}}$ harmonic is of zero sequence.

Generally, the practical impact on filter design of higher order harmonics is normally negligible.

The relative phase angle (with respect to fundamental frequency voltage) of pre-existing harmonics is also an important parameter in the AC-DC-AC transfer process. Figure 3 illustrates this by showing the DC side 6th harmonic voltage as generated by 5$^{\text{th}}$ and 7$^{\text{th}}$ harmonic on the converter bus, with constant phase angle for 5$^{\text{th}}$ harmonic but varying phase angle for the 7$^{\text{th}}$. In most cases, it is virtually impossible to predict the phase angles, as they are of a random nature. Therefore, in order to assess the probable impact of harmonic interaction with some confidence, a statistical approach would be needed using a large number of simulations with phase angles as stochastic variables. For a worst-case assessment however, such as for rating purposes, then linear addition should be used.

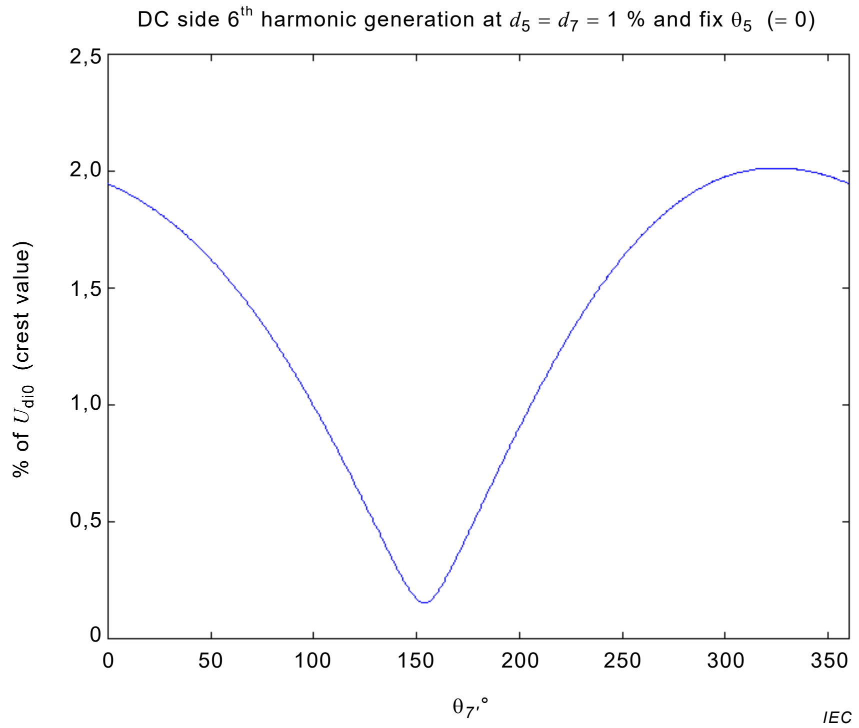


Figure 3 – DC side 6th harmonic voltage due to AC side 5th harmonic (fixed angle) and 7th harmonic (varying angle)

From a practical point of view, the typical situation is that designs are demonstrated to be valid by simulating harmonic interaction for one or a few selected harmonics, for example the harmonic interaction between 5th and 7th AC side harmonics and DC side 6th harmonic. For such case, it is fairly easy to predict response, simply by defining the source voltage behind network impedance in magnitude and letting the phase angle of one harmonic vary.

3.12.5 AC network impedance

Harmonic AC network impedances are normally specified as an area in the complex impedance plane. As there is proof (see Annex A) that worst-case impedances for resonance with the converter station impedance will always be located on the boundaries of such areas, there is no need to scan the complete envelope when considering just local worst-case resonance, but only to scan the boundary to find the decisive impedance for each harmonic.

However, when we consider the doubly-transferred effect of the remote AC network impedance on the local system, it is necessary to consider all possible points within that remote AC network impedance envelope, as what is important is the apparent AC side impedance of the local converter.

Furthermore, as in the complete interaction model, this situation has to be reversed to study the harmonic distortion at the remote terminal, it becomes clear that the full areas of both network impedance envelopes have to be scanned, investigating the effect of every combination of all sampled points within each envelope.

Furthermore, for a single frequency in the DC circuit, the combination of at least four impedance areas (two frequencies at each AC side) have to be scanned. This task therefore requires a considerable computing resource and intelligent selection of the number of sampled points to be studied within each network impedance envelope.

This complexity of calculation would only be justifiable in case there was a strong connection between the respective sides of a DC transmission, for example in a back-to-back scheme with little or no smoothing reactance. For many transmission systems, such as those with long lines or cable transmission, this may not be the case, or only the case for low order harmonics, and the model can be significantly simplified by scanning only the AC impedance boundaries at each converter station individually to maximise the harmonic contribution of that converter and adding contributions according to the methods of superposition as elaborated below.

For studies made using time domain simulations, the network impedance will have to be represented by a circuit equivalent. In many cases, a model as used in dynamic performance studies is adequate, as such an equivalent is often tuned such that it will be reasonably representative for lower order harmonics. In some cases, it can be sufficient to use an even simpler equivalent. In the example below (Figure 4), the aim is to represent the network for 5th and 7th harmonics, with the short circuit reactance tuned to give desired phase angle at the mean of the two, i.e. at the 6th harmonic. The series resistance, RS, is selected to give fundamental frequency X to R ratio and R_p calculated such as to give the desired phase angle at 6th harmonic according to Equation (1). This model would however only be correct for that particular harmonic and may therefore give misleading results for other harmonics in the Fourier analysis of the simulation results.

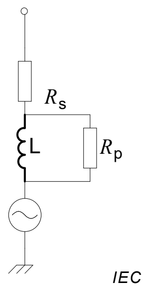


Figure 4 – Simple circuit used to represent AC network impedance at 5th and 7th harmonics

where:

$$R_p = \frac{1}{2}\frac{X_6}{X_6 - R_s \tan\varphi}\left(X_6 \tan\varphi + \sqrt{X_6{}^2 \tan^2\varphi + 4R_s X_6 \tan\varphi - 4R_s{}^2 \tan^2\varphi}\right) \qquad (1)$$

3.12.6 Converter control system

The impact of converter controls on the harmonic transfer through the converter has long been evident in practical situations. Some problems which occurred in very early HVDC schemes due to firing angle modulation were reduced or removed with the introduction of phase locked oscillators and equidistant firing. Other issues have been resolved by the introduction of additional loops within the constant current control, aimed to affect the interaction with the control with one or more low order harmonics. An example of such additional control consists of an alpha balancing circuit, which modulates the final point on wave of firing to achieve balanced (equal) firing angles between the two valves in each limb of each six-pulse converter. It produces a fundamental frequency modulation of valve firing and acts to prevent magnification of second harmonic in the AC system.

When modelling harmonic interaction, it is recommended to include the impact of the current control, if the bandwidth of the control is such as to act on fundamental frequency and low order harmonics and the DC side impedance does not sufficiently attenuate these frequencies. Conversely, if the control bandwidth is such that it does not respond significantly at these frequencies, or the DC side impedance provides strong fundamental frequency and low order harmonic damping, then the impact of the current control may be neglected. An initial DC resonance study could be performed in the time domain at an early stage of the calculations to test this, and thereby possibly allow for simplification of the future harmonic interaction studies.

For most cases, a simplified generic control model is expected to be sufficient to evaluate if there are harmonic interaction issues. The final settings of a control system are in any case generally not usually available until late in the project, after dynamic performance studies have been completed.

3.12.7 Combination with "classic" harmonic generation

Under the simplifying "classic" assumptions for calculation of converter AC side harmonic generation, the direct current is assumed to be completely smooth, with no harmonic content and consequently no consideration of cross-modulation. Under these conditions the characteristic harmonics are generated, plus non-characteristic harmonics due to various factors, among which are the pre-existing distortion and unbalance of the AC voltage source. Therefore, for example, there is a 3rd harmonic current generation caused by a negative phase sequence voltage unbalancing the symmetry of the commutation periods with respect to the different phases. It is important to recognize that this is distinct from the 3rd harmonic current discussed in 3.12.8, also originally due to negative sequence but occurring indirectly due to the generation of 2nd harmonic voltage on the DC side and the consequent flow of 2nd harmonic current in the DC circuit.

These two contributions to 3rd harmonic current are impossible to distinguish in real life or in any time domain simulation, and indeed difficult to treat analytically. In a simplified view, they may be considered as independent sources, with a possible phase angle displacement which depends on the phase angle of the 2nd harmonic current.

It is important to understand that in a full time domain simulation of the harmonic interaction, both effects will be naturally modelled and correctly simulated. In a frequency domain study, however, they will have to be separately calculated and combined, with some uncertainty as to the correct vector relationship to use for summation.

3.12.8 Relative magnitude of pairs of low-order harmonics

Various factors have been observed to have a strong influence on the relative levels of the pairs of low order harmonics transferred across the converter from DC to AC sides. For example, whereas according to modulation theory a 2nd harmonic DC side current should result in equal values of AC side NPS fundamental and 3rd harmonic, time domain simulations of typical HVDC systems tend to show a strong unbalance, with NPS generally (but not always) being higher and 3rd harmonic being lower than predicted. The differences in some cases may be so high that the NPS current is several times the magnitude of the 3rd harmonic current. The average of the two, however, tends to the predicted value.

One factor is the presence of 3rd harmonic due to commutation period unbalance as described in 3.12.7 above. Another is the action of the control system, which can have a strong influence and acts with different characteristics at the rectifier and the inverter. The relative phase angles of the AC side negative sequence voltage and the DC side 2nd harmonic current are also significant.

It is extremely difficult, even with time domain simulations, to separate and explain the different influences of various factors, which in reality have interdependent actions. This behaviour is unlikely to be observed in simplified models which depend on transfer factors calculated according to modulation theory.

For pairs of higher order harmonics, this unbalance effect is less obvious, partly because of the reduced influence of the control system.

The literature has little or no mention of this phenomenon, but it is one which should be observed in any realistic simulation and one which should be taken into account in the design process.

3.12.9 Superposition of contributions

Frequently, harmonic interaction studies may be made by imposing harmonic voltage sources on one side of a HVDC system in steady state conditions and evaluating the outcome in harmonic load flow, then repeating the same procedure for the other side. This is a simplification, but in general it is advantageous as it provides better understanding of the behaviour of the circuit and as the error introduced typically is acceptable. The obvious question is how to add contributions from the different origins.

Where both sides of the HVDC link operate at the same nominal fundamental frequency, the harmonic frequencies can be added up using either an RSS or arithmetic basis. Often, RSS is used for performance evaluation, whereas an arithmetic sum is used when establishing maximum possible equipment stresses, in particular if there is a strong harmonic connection between both sides of the HVDC link.

In the case where both sides operate at different fundamental frequencies, the cross-modulated contributions will be at discrete frequencies and should be evaluated accordingly. That is, performance evaluation should be made considering inter-harmonic performance criteria. In establishing equipment stresses, interharmonic components should be treated as individual frequencies, as this best represents their physical effects on components.

3.13 Parallel AC lines and converter transformer saturation

In some situations, DC transmission lines run in parallel with AC transmission lines over part of their line route. This may occur due to geographical features, wayleave restrictions, desire to keep all transmission in a corridor, or may be physically unavoidable in the approach to a converter station.

Theoretically, both capacitive and inductive coupling between the lines will occur, but for practical purposes at typical line separations the capacitive element is negligible. Inductive coupling can however be of great importance, with fundamental frequency currents being driven in the DC transmission circuit.

In a bipolar transmission, the induced current in the two HVDC conductors will be in the same sense, and therefore be mainly of ground mode with a return path through the neutrals or electrodes of the converter stations. However, due to the different distances between each DC conductor and the AC line, the induction in each will be of different magnitude, and so an unbalanced or pole mode current will also flow.

Typical levels of induced fundamental frequency current are usually not high enough to make any significant impact on either the DC side harmonic performance or the rating of DC side filters and other equipment. Their main significance is in the effect which they can have, through cross-modulation, on saturation of the converter transformers. Fundamental frequency current in the DC circuit is cross-modulated to appear mainly as direct current and positive sequence 2nd harmonic in the valve side transformer windings. The direct current is divided among the three phases of the valve-side winding in proportions depending on the relative phase angle of the induced current to the applied AC source voltage and the firing angle:

$$I_{\mathrm{t}} = \frac{\sqrt{3}}{\pi} I_{\mathrm{d1}} \cos(\varphi_1 + \alpha) + \frac{\sqrt{3}}{\pi} I_{\mathrm{d1}} \cos(2\omega t + \varphi_1 - \alpha) \quad (2)$$

where

I_{t} is the current in one phase of the transformer valve side winding;

I_{d1} is the fundamental frequency current in the DC side;

φ_1 is the angle of fundamental current in DC circuit relative to converter source voltage;

α is the firing angle.

The magnitude of the DC component will therefore be between 0 and $\frac{\sqrt{3}}{\pi} I_{d1}$ depending on φ_1 and α. As the phase angle between the induced fundamental and the converter source AC voltage is an unknown quantity, it is assumed that the direct current in any one phase may reach its maximum possible value, which is $\frac{\sqrt{3}}{\pi} I_{d1}$. The sum of the three phases should be zero as there is no neutral ground path on the valve side windings.

There are other possible sources of direct current in the transformer which should also be taken into account when assessing the risk of saturation. These are: further DC side fundamental frequency current resulting both from AC side 2nd harmonic voltage and from possible firing angle unbalance, stray direct current from nearby electrodes, and, possibly, geo-magnetically induced current [12]. These latter two flow through the line side windings via the neutral point grounding of the Y-winding, and thereby also contribute to core saturation.

The relative magnetizing effect of direct currents in the valve and in the line side windings will depend on the number of turns in each. In order to derive a total effect referred to say the line side winding, a direct current in the valve winding can be approximately represented by a direct current in the line winding, if suitably multiplied by the transformation ratio. Of course, the direct current cannot in reality cross the transformer to the line side windings, and care should be taken when using certain well known time-domain programs whose transformer models do implement such unrealistic transformation of direct currents and voltages. The extent of saturation will also depend on the zero sequence resistance, as shown in [13].

The resultant shift towards single-sided saturation of the core results in the generation of a broad spectrum of harmonics in the magnetizing current on the AC side of the converter transformer. The audible noise produced by the transformer will increase greatly and there is a risk of localized overheating and gassing. Transformer protections may operate with potential tripping of the HVDC link. The additional harmonic generation could result in overload and trip of harmonic filters unless adequately considered in their design and rating. Finally, if the second harmonic current produced by saturation sees a high network/filter impedance, the resulting increased 2nd harmonic voltage may result in further DC side fundamental voltage and current, closing a loop which would result in core saturation instability.

It is therefore clear that induction from parallel AC lines can have extremely serious consequences and should be carefully studied. The AC lines can easily be represented in detail within a typical frequency domain or time domain model of the DC lines and converter stations. Important factors are:

- length of exposure(s) – the induced current is proportional to the exposure length;
- location of exposure(s) – this matters because of the standing wave pattern along the DC line; the fundamental current at the converters will not be the same as that at a remote location of induction;
- geometric layout of the AC and DC lines, including ground wires;
- separation distance – should be clear whether this is centre line to centre line or between nearest conductors;
- ground resistivity – higher resistivity increases the induced current;
- operation mode of the HVDC transmission (bipolar, monopolar ground or metallic return);
- maximum current levels in the AC line, including percentages of negative and, very importantly, the zero sequence components;
- transpositions of the AC line and possibly the DC line.

If calculations show a high risk that induction levels will be such that the converter transformers will be saturated, then there are three possible mitigation measures.

1) Transposition of the AC lines along the length of the exposure. This will cancel the induction due to positive and negative sequence components, whose effects depend on the varying distance to the DC line of the three AC phases. It will however have no impact on induction due to any zero sequence component of AC current.

NOTE 1 Transposition of the DC line conductors instead would be relatively ineffective as it would have no effect on the induction of ground mode current, which is often the dominant component.

2) Implementation of a current control system action which will tend to damp the flow of fundamental frequency current in the DC circuit. This is by far the easiest and least costly solution to implement. The negative consequence of such modulation may however be the generation of a range of harmonics on both the AC and DC sides, which creates different problems.
3) Introduction of either series blocking filters in the neutral side of the converter circuit, or shunt filters, tuned to fundamental frequency. Of these, series filters have always been the preferred option. Shunt filters may act as a bypass for fundamental current induced in the DC line, but they also provide a very low impedance path for fundamental frequency current generated by the converter (for example due to AC side 2^{nd} harmonic), resulting in increased direct current in the transformer.

Series blocking filters have been shown to be a very effective solution and have been used on a number of HVDC projects. However, this solution has a high cost as the filters conduct the full direct current and therefore the reactors are similar to smoothing reactors – in fact sometimes the same design is used.

NOTE 2 However, a reactor of the blocking filter does not contribute to the smoothing effect for direct current, as it is bypassed by a parallel capacitor.

Blocking filters have to be sharply tuned and may become largely ineffective at wide frequency variations due to system disturbances. During such large frequency variations, saturation of the transformers may occur due to the detuning of the blocking filters. The risk of thermal problems and consequent protection actions would have to be carefully evaluated in relation to the anticipated duration of the wide frequency deviation.

3.14 Possible countermeasures

3.14.1 AC (and/or DC) filters

Shunt connected AC filters can be used to limit the impact of interaction on the AC system by providing a low impedance path for interaction current to flow. A low impedance at the interaction frequency results in a small corresponding voltage at the converter bus. In some instances, it may be more advantageous to design the filter to introduce damping into the network. Increased damping at the interaction frequencies reduces the amplification of voltages and currents which may result from the interaction.

DC side blocking filters can be used to avoid interaction. The filters typically consist of parallel capacitor-reactor-resistor components connected in series with the DC converter. The filter restricts the current flow at the tuned frequency, thus decoupling the DC network at the interaction frequency. Often, this is all that is required to eliminate the interaction.

Interaction can often be avoided by selecting an appropriate value for the inductance of the smoothing reactor(s) and suitable selection of DC filter parameters to avoid series or parallel resonances at critical DC interaction frequencies. Smoothing reactors are an effective means of limiting interaction due to crossmodulation effects.

3.14.2 DC control design

DC controls are an extremely cost effective way to counter harmonic interaction. They are most effective inlimiting interactions induced by driving forces external to the converter at low harmonic interaction frequencies. Typical control design involves the implementation of a circuit which responds to voltage or current of one of the interaction networks at the corresponding interaction frequency. The circuit adds a small correction to the firing angle of each valve in such a way as to reduce the magnitude of the measured quantity. Changing control parameters effectively alter the gain and phase of the mathematical coefficients which couple the networks at the interaction frequencies.

3.14.3 Operating restrictions and design protections

Although undesirable, the most cost effective solution to an interaction problem may be to avoid the operating condition which results in the interaction. If the likelihood that such an operating condition could occur is extremely remote, imposing an undesirable system operating restriction may be more attractive than the expense (and possible inconvenience) associated with a large capacity low order AC harmonic filter. If such a strategy is adopted, it would be prudent to ensure that filter and system protections detect and respond to the interaction (should it occur) and smoothly bring the AC-DC operating conditions to a safe situation.

3.15 Recommendations for technical specifications

3.15.1 General

A technical specification should be absolutely clear about the performance and rating requirements with respect to harmonic interaction issues and the conditions under which they are met. To support a comprehensive design, the specification should include all system data which could influence the performance of the HVDC plant in this respect. 3.15 should serve as a guideline for writing a complete and detailed specification.

From experience, it is likely that the customer will be presented with rather different methods of calculation from different bidders, and indeed significantly different calculation results for harmonics which depend on cross-modulation effects. Furthermore, during the limited time of a bidding process, suppliers may tend to simplify their design approach and estimate the resulting risk for possible increased costs when the final detailed design is made during the contract stage.

The bidders may be asked to explain their respective methodologies and justify their calculation results, but it may be difficult for a customer with limited specialized technical experience in this area and no independent calculation tools to assess which, if any, of the presented study results is accurate, and to compare the resulting bids. The best protection for the customer is to state in the technical specification that the contractor is ultimately responsible for fulfilment of all related requirements, which should be verified by test measurements during and after commissioning. The onus is on the customer to ensure that such testing and measurements are later carried out. The technical specification could also require that the contractors prove their results by time domain simulation of critical selected cases using a detailed HVDC model with appropriate representation of AC networks.

3.15.2 Specified design data

The following information is required by contractors.

- Fundamental frequency

  This shall include information on the range of positive and negative phase sequence voltages. The definition of the pre-existing negative sequence voltage shall make clear whether this value is defined at the converter bus or behind a network impedance (3.12.2).The range(s) of frequency deviation should also be defined. The customer should note that in some cases there could be an increase in NPS due to increased loading in untransposed transmission lines when the converter is operating.

- Pre-existing harmonics

  The magnitudes of pre-existing harmonics should be provided, and whether these values apply to the converter bus or behind a network impedance. Ideally, information on phase angles relative to the fundamental as well as the corresponding phase sequence of the harmonic should be included, but in most cases this information is not known to the customer and it may vary with time. The required rule for superposition of harmonics originating at the two terminals of the system (3.12.9) should be stated. Different pre-existing harmonic spectra may be specified (e.g. for filter performance and rating) and the specification should include guidance on the specific calculations the corresponding spectrum has to be used for.

- AC network impedance

  Impedances have to be determined and specified following the guidelines as given in Clause 4. Detailed information on allowable simplifications of impedance modelling is required. If several impedance areas are specified (e.g. for performance and rating), the specification has to include guidance on the specific calculations the corresponding impedance has to be used for. In case of differences between positive and negative phase sequence impedance of the AC network, these differences shall be stated. Such may be the case if the planned converter station is located close to a generator station.

- DC side impedance

  If the DC circuit, or part of it, is outside the contractor's scope of supply, the specification includes the relevant modelling data (line length, tower configuration, conductors).

- Parallel AC lines

  Possible parallel or near-parallel exposures of the DC line to AC overhead lines have to be specified. The factors listed in 3.13 are defined.

- Required limits

  It should be stated in the technical specification that harmonic interaction across the converters (or cross-modulation) should be fully taken into account in filter performance and rating calculations. If there are other limits on the external impact of harmonics likely to be affected by cross-modulation, such as the flow of 5^{th} and 7^{th} harmonic current in nearby generators, then these should be defined. With regard to induction from parallel AC lines, it should be stated that this should not result in saturation of converter transformers even during wide frequency variations, any adverse effect on the control system, or operation of any protection.

3.15.3 Requirements regarding calculation techniques

A bidder will need the latitude to select the procedure used to determine the impact of harmonic interaction during the tender stage as this decision is often influenced by non-technical constraints such as resources or time. The bidders shall be required to elaborate on the calculation procedure used in terms of the following items.

- Modelling techniques

  As elaborated in 3.6, a wide range of modelling techniques are in use. The bidder should be asked to describe the calculation method(s) to be used and to provide verification of its suitability and accuracy.

- Variation and tolerances

  Each element within an interaction model is subject to variations and tolerances. The bidder should detail procedures for sensitivity checks. Moreover, the treatment of filter and shunt capacitor outages and redundancy shall be clarified.

- Summation laws/superposition

  Depending on the used modelling techniques, the bidder includes information on the summation of individual contributions to an individual harmonic distortion. If applicable, the techniques to combine classical models (i.e. the converter as a current source on the AC side and a voltage source on the DC side) with an interaction model have to be addressed.

- Converter impedance

  The bidder shall elaborate on how his calculation procedure determines the converter impedance. If a simplified approach is chosen, the bidder shall qualify his method in more detail.

Many aspects of harmonic calculation and practical filter design are, for relative simplicity, based on an AC side current source model, assuming smooth direct current and DC side voltage source model assuming purely fundamental frequency AC side driving voltage. Harmonic cross-modulation is the factor which undermines the validity of such simplifications and hugely complicates the calculation process.

For normal filter design purposes, harmonic interaction tends to be of significance only up to the AC side 7th harmonic, although some significant influence is observed up the 13th, but usually has little practical impact at higher harmonics.

Even with the computing power now readily available, the complexity of a complete filter design for both of the AC sides and the DC side of a typical HVDC link, using a full and accurate representation of cross-modulation, is generally too great to be practical within the time and resource limitations of a tender period or contract design period. Simplifications therefore have to be made, and parts of the design de-coupled from other parts. This introduces some degree of risk, which should be covered by the addition of suitable margins to the calculated results.

Customers should be aware of the complexities involved in specification of performance and rating when appreciable cross-modulation is likely, and seek technical advice if required. The customer should also be aware of significant differences in calculation techniques typically used by different HVDC suppliers and be prepared to question the resulting differences in calculation results and filter design both during the bid evaluation and also in the project design phase and to request verification of the validity of the techniques and simplifying assumptions applied.

4 AC network impedance modelling

4.1 General

IEC 62001-1 and IEC 62001-4 discuss the important influence of network harmonic impedance on both the performance and rating aspects of the AC filter design. For a customer, it is one of the most difficult aspects to specify, especially if the customer is not the owner of the network and has little direct knowledge of its composition and possible future development. The purpose of Clause 4 is to amplify the reasons why the correct specification of network harmonic impedance is crucial to an optimal design of AC filters and also to provide further detailed guidance as to its assessment.

IEC 62001-1 discusses that normally the customer defines the range of network impedance to be used for filter design but that in some cases the customer leaves the prospective contractors to perform this assessment.

Clause 4 reinforces a recommendation that in the production of the technical specification by the customer for an HVDC system, the customer rather than the prospective contractors is generally best suited to, and should be responsible for, the definition of the AC network impedance characteristics. This means that the study is done only once and avoids all prospective contractors having to make their own individual assessment of the provided data, such as system single line diagrams and associated relevant data, details of normal and abnormal operating conditions and loading, and the effects of future network expansion (such data are often only known to customer or utility). This would then have the inevitable risk that each prospective contractor would assess the network impedance in a different manner with differing results, leaving the customer to determine which is correct or whether any of them are adequate. The customer should therefore take responsibility for these studies, either directly or through a consultant. He can take advantage of the longer period that is generally available before the issue of the technical specification to prepare this information, rather than requiring the prospective contractors to individually make the assessment during the shorter tender stage.

It has become common practice that the specifications and design of the AC harmonic filters established at the tender stage form part of the later contract. If the customer decides to postpone the detailed network impedance study until execution of the contract, he will need to be aware of the following disadvantages and manage the risks.

- Received bids may not been based on the same assumptions, hence may not be comparable.
- Cost and space requirements of the AC filter scheme determined during the tender stage may not be sufficient.
- The contractor may have to claim change/variation orders.
- The time needed for the final design stage may be prolonged.

There are some instances in which the methods for determining the network harmonic impedance described in [11] or in this document may be inappropriate or require special consideration. Such situations include the following.

- Where a proposed HVDC scheme is to be connected in parallel with an existing scheme which is operating with adequately designed AC harmonic filters and there is a preference for the filters to be associated with the new scheme to have identical characteristics as the existing units, at least for the converter characteristic harmonics. In this case, any change in the definition of network harmonic impedance from that used for design of the original scheme will require careful consideration of the continuing viability of the existing filters and of the combined operation of the original and new filter designs.
- Where a proposed HVDC scheme will be connected to an AC network that is only operated in an "islanded" mode; that is a small and well defined network for which it may be preferable to model the transmission lines, cables, transformers and generators etc. explicitly rather than to employ impedance envelopes.

4.2 Implications of inaccurate definition of network impedance

Due to the difficulties in accurately assessing the network harmonic impedance, it can be attractive for a customer to base his specification on a simplified network definition with fairly arbitrary parameters, probably biased towards conservative values. However, a too conservative assessment of network impedance (e.g. an impedance having excessively high damping angles and/orexcessive range) can have several significant disadvantages in respect of AC filter design:

- an increased number and/or different types of filters may be required to cater for network impedance conditions that in practice may not occur;
- an increase in switchyard space would be needed to cater for redundancy requirements as a result of the provision of a larger number of different filter types;
- the requirement for a greater number of sharply tuned filters, the application of which can incur excessive harmonic ratings especially when considering the effects of pre-existing harmonic distortion;
- the need, especially at low transmitted power levels, for AC filters with a total reactive power in excess of that which can be accepted by the AC network and therefore the requirement for the converters to operate at either increased control angles or often the use of high capital cost shunt reactors, both of which give rise to increased losses;
- higher initial and project lifetime operating costs.

Conversely, however, a design which is based on too narrow an assessment of network impedance may fail to meet the required harmonic performance criteria and/or sometimes cannot remain in service due to component overloading because of resonances between the AC filters and the network which were not predicted. In such cases, the economic consequence of such shortcomings could be more serious than those listed above due to an over-conservative design.

It is therefore evident that efforts should be made to achieve as accurate as possible an assessment of the network harmonic impedance.

4.3 Considerations for network modelling

4.3.1 General

IEC 62001-1 gives references [14] [15] to various methods of deriving network harmonic impedance.

In attempting to postulate criteria to be considered in determining network harmonic impedance, there are very few generic rules that can be applied universally for all networks worldwide; therefore each network should be treated on a case by case basis.

The extent of the network to be modelled is also system dependent and no general rules can be defined. One approach is to start by modelling a relatively small area of the system, but retaining sufficient to incorporate all of the contingencies required to be studied. The analysis is then repeated a number of times with more of the AC network retained each time, until there is no significant change in the harmonic impedance characteristics.

4.3.2 Project life expectancy and robustness of data

The specified life for an HVDC project can typically vary between 25 years and 40 years. The cost of AC harmonic filters forms a substantial part of the overall converter equipment costs, as they are inevitably custom-made items with unique layouts and component sizes. Also they are very difficult to alter significantly once constructed. It is obviously desirable that their design, in terms of compliance with performance requirements and their rating, is sufficiently robust such that a redesign or reconfiguration with attendant lengthy outages is not required part way through their service life. For mature and strongly interconnected networks such as those in the UK and continental Europe, it should be easier to predict network developments than it is for a rapidly developing country. However, many so-called mature networks are now also subject to significant infrastructure developments to accommodate the requirements of renewable energy sources. Such developments were not foreseen until recently.

4.3.3 Network operating conditions

In deriving the variation of network impedance the following effects should be considered as a minimum to ensure that all practically feasible and likely operating scenarios are captured:

- System load/generation variation for a maximum demand day.
- System load/generation variation for a minimum demand day.
- System load/generation variation for intermediate demand day(s).
- Different AC system generation connection conditions, for example differing mixes and locations of hydro, nuclear, thermal, wind, other HVDC links. Where nearby generation exists, it is generally recommended that the lowest practical levels of such generation are used for the various scenarios, in order to model the weakest system which for low orders generally gives the largest impedance envelopes.
- Status of reactive compensation plant, both dynamic and fixed (e.g. mechanically switched capacitors and reactors) types. In this respect, all possible combinations of shunt reactive compensation at or close to the converter station AC busbar are considered because where more than one such device is connected, these are likely to interact, thereby forming differing resonance conditions.
- Similarly, where there is another HVDC link electrically close enough to have a significant impact on the network impedance, it is modelled explicitly, rather than being included as a lumped element within the network, with its associated AC filters being subjected to the effects of their detuning (due to changes in system frequency, ambient temperature, capacitor element failures, etc.) together with the variation in the number and types of filters which may be connected with varying load.

- AC network transmission outages (contingency and planned). The contingency outages, i.e. single or double circuit etc., that need to be considered are a function of the manner in which the utility operates the network (i.e. n-1, n-2 etc. criteria according to its security standard) and for which it either requires harmonic performance limits to be met, or requires AC harmonic filters to be rated while not necessarily achieving performance limits. The classification of these contingency and planned (e.g. maintenance) outages should be defined by the utility. Depending on the complexity of the network under consideration, it would be usual that at least 50 significantly different network conditions would need to be studied for each loading condition to give a suitable and reliable range of possible impedances.

However, any network conditions that are unrealistic particularly in terms of generation and load scenarios (i.e. those conditions which imply impossible operating scenarios or which might fail to provide a convergent fundamental frequency load flow) should not be included. If the software does not allow for load-flow calculations, it should at least be verified that the fundamental frequency short circuit impedance, calculated for the same cases as the harmonic impedance, is within the anticipated range.

It needs to be recognised that the aim is to develop a network impedance characteristic which is valid for all reasonably possible system developments over the expected life of a project. Even mature networks do not usually have plans beyond the next 20 years to 25 years. The network impedance definition therefore may have to cover a period up to twice as long as the planning horizon. There is therefore some difficulty in how to cater for the years after the planning horizon and the resultant uncertainties. Some guidance is given in 4.5.4 and 4.5.5 on this topic.

4.3.4 Network impedances for performance and rating calculations

Generally, it is necessary to determine the network harmonic impedance characteristics for both AC harmonic filter "performance" and "rating" conditions. Generation and load scenarios and contingency conditions for these two requirements can often differ significantly as discussed below.

IEC TR 61000-3-6, other similar standards and national grid codes relating to the assessment of harmonic emission limits discuss planning levels for harmonic voltage distortion based on conditions that cover typically 95 % of the time annually based on a statistical average, and discuss "normal" operating conditions of the network. "Normal" generally includes all generation variations, load variations and reactive compensation states, planned outages and arrangements during maintenance and construction work, non ideal operating conditions and normal contingencies under which the considered network and the disturbing installation (e.g. the HVDC converter) have been designed to operate.

However, "normal" network operating conditions typically exclude those conditions which arise as a result of a fault or a combination of faults beyond those planned for under the network’s security standard. These include exceptional situations and unavoidable circumstances (e.g. force majeure, exceptional weather conditions and other natural disasters, acts by public authorities, industrial actions), cases where other network users may significantly exceed their emission (performance) limits or do not comply with the connection requirements, and temporary generation or supply arrangements adopted to maintain supply to customers during maintenance or construction work, where otherwise supply would be interrupted. Such scenarios typically form the basis of "rating" conditions, in addition to those described above relating to performance conditions.

The resultant differences in the variation of network harmonic impedance when comparing "performance" and "rating" conditions can be significant, especially at higher order harmonics. This is discussed in 4.5.8.

4.3.5 Modelling of network components

The reader is directed to [14] to [16] for methods of representing frequency dependent power system elements such as overhead transmission lines, cables, generators and transformers in determining the network harmonic impedance.

In deriving the harmonic impedance envelopes, the following should be accounted for:

- the accuracy of the network component data;
- the limitations of component impedance models in the frequency domain;
- the variation of component impedance with ambient and system conditions.

Some of the data on existing network components are modelled as measured during routine manufacturing tests, others are set to the nominal value. For the latter, the calculations take into account the effects of manufacturing tolerances, and for consideration of future additions in the network, a suitable range of possible component values should be taken into account.

The variation of ambient temperature has an effect on some network components, and the operational variation of network frequency also affects the component impedance (refer also to 4.5.5).

The basic network data is generally easily available and is normally relatively accurate at the fundamental frequency because utilities make extensive use of load flow programs for their operational needs. In some instances, the data is transferred from a load flow program directly to a harmonic analysis program. However, as the frequency increases, the models become less accurate or require additional data that is often not available. Furthermore, some harmonic impedance calculation programs may not have the capacity to perform a prior load flow which can cause an incorrect impedance to be transferred from one voltage level to the other due to the effects of an inappropriate transformer tap changer position. Sometimes, fundamental frequency loadflow datasets have the parameters of disparate components in a branch lumped together. For example, a series current-limiting reactor may be added to the series reactance of a transmission cable, or the susceptance of a permanently-connected line shunt reactor is netted out of the total line charging. While sufficiently correct at fundamental frequency, such combination of branch component parameters is not acceptable for harmonic analysis. Load flow data are screened to identify and separate the components of any such branches, especially those that are located near the busbars under study.

The accuracy of network harmonic impedance derived by the use of such network element models tends to reduce at higher order harmonics, above approximately 20^{th} harmonic. The need for accurate modelling at such harmonic orders can often become less critical because both the magnitude of converter harmonic current generation is lower (for line commutated converters) and hence the resultant voltage distortion is also often lower, and also because filtering at such orders is often provided by damped type filters, and so the effects of inaccuracy in the magnitude of network harmonic impedance become less important in the calculation of harmonic voltage distortion. However, where a telephone interference criterion is specified, the need for accurate (as far as is practicable) modelling at these high order harmonics is still desirable.

The correct modelling of the variation of resistance of the network components with frequency is particularly important in determining the damping of the network at harmonic frequencies. Its influence on harmonic performance and rating is discussed in B.3.2 and Clauses B.4 to B.6 and provides in greater detail a discussion regarding techniques for modelling network component resistances.

4.3.3 has emphasised that the effects of reactive compensation plant, especially plant near to the busbar of interest should be included in determining network impedance. In this respect, most plainshunt capacitor banks are configured with inrush/outrush current limiting reactors. Often, the tuning frequency of such capacitor/reactor combinations falls within the relevant frequency range of the study. It is therefore advisable to collect detailed data for all relevant shunt elements in the network. Generally, load flow data is used as basic input data for harmonic modelling, and detailed data on current limiting reactors or the tuning frequency of reactive power elements is often not included in such data sets. Further, if a shunt element is located electrically close to the point of interest, it is also necessary to include the resistive loss of any shunt reactors in the model.

Detailed discussion of some aspects of the harmonic representation of loads, transformers, transmission lines and machines is given in Annex B, which includes some numerical guidelines as well as calculations and measurements which call into question some conventional assumptions.

4.3.6 Representation of loads at harmonic frequencies

Of critical importance in deriving network harmonic impedance is an adequate representation of the load at harmonic frequencies, particularly in the network close to the converter station AC busbar under consideration. Utilities should be encouraged to develop databases of their geographic electrical regions with as much information as possible on the composition of the load and power factor correction elements. In practice, this has not always been forthcoming, generally because of the difficulties in obtaining the necessary detailed information, and some further guidance is therefore necessary.

It is incorrect to assume that, where load data is either unknown or difficult to assess, to exclude its representation from the model will lead to a conservative (i.e. safe) assessment of network harmonic impedance. Whilst the level of network damping at harmonic frequencies may be reduced by neglecting to include any form of load model, more importantly the network resonant frequencies, especially at low order harmonics, will also shift. Hence, the absence of any load model can produce even greater errors than would occur if an incorrect or inappropriate model were used.

At its extreme, the most accurate network model would arise from the inclusion of all low voltage (e.g. 400 V) nodes, which is clearly impractical because of the lack of detailed knowledge of such networks and because the detailed representation of such a network would be extremely time consuming if not impossible. Therefore, an equivalent representation of the downstream impedance is often used. The required accuracy of an equivalent depends on the proximity (both in terms of relative voltage levels and physical distance) of the particular distribution busbar to the converter station AC busbar.

Accurate load modelling of course requires detailed knowledge of the load itself in terms of its de-composition into residential, commercial, industrial, traction, etc. and combinations thereof. Many utilities often possess little detailed data regarding this, and care should be taken in applying generic assumptions regarding load modelling and its composition. For example, in the United Kingdom, domestic load is currently predominately resistive (lighting and heating) and hence can provide damping to any distribution network resonances. However, in much of the USA for example, the peak domestic load is dominated by motor load (air conditioning), which provides very limited harmonic damping.

Irrespective of the load composition, its magnitude will vary significantly (between minimum and maximum day levels) and it is modelled so as to provide a convergent load flow at fundamental frequency. More detailed discussion of the harmonic representation of loads is given in Annex B.2.

4.4 Network harmonic impedance envelopes

The harmonic impedance of the AC network is different at each harmonic frequency and also varies significantly with the topology of the network. It therefore varies as:

- transmission elements are switched in and out as a result of protection sequences and/or for maintenance,

- network load changes and as generators are connected or disconnected to meet the load,
- reactive compensation is adjusted to support the AC bus voltages throughout the network,
- transmission characteristics change as result of ambient temperature changes.

Figure 5 shows the variation of network impedance between harmonic orders 2nd to 49th as seen from a typical HVDC converter station busbar for one network condition. The figure demonstrates that whilst the impedance is normally inductive at fundamental frequency, it can change from inductive to capacitive and back again a number of times with increase in harmonic order, producing a number of major resonant points (both series and parallel) at which the impedance is entirely resistive. There are also resonances occurring where the sign of the impedance does not change (known as minor loops).

Each different network configuration specified will possess an associated impedance locus, enabling a family of loci to be constructed.

The figure also demonstrates that the change in impedance (both magnitude and sign) can be very rapid for a small change in harmonic order (for example, study the change in impedance between 11th and 13th harmonics). It is therefore emphasised that the calculation tool determines the variation of impedance with harmonic frequency on a quasi-continuous basis in respect of variation of frequency, typically at intervals as low as 1 Hz, rather than performing the calculations at integer ("spot") harmonics only. If the latter method is employed, resonances occurring at non-integer multiple of fundamental frequency may then not be evident. Any such resonances could be important if frequency variations, tolerances and modelling inaccuracy mean that they could in practice actually occur at a neighbouring integer harmonic at which there is a significant harmonic source.

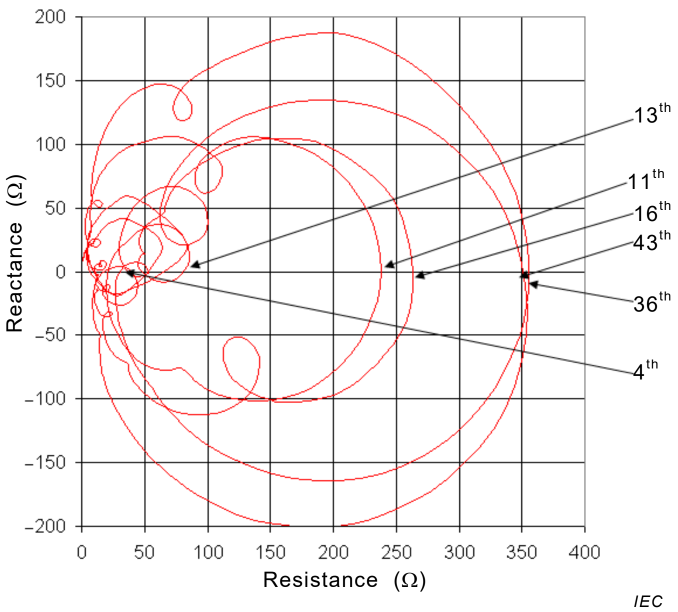


Figure 5 – Example of a single impedance locus for harmonic orders 2 to 49

The calculated network impedance at the different harmonic orders for all the various network configurations studied, both those of performance and rating categories, can be presented in terms of envelope diagrams in the R-X plane. The use of such envelope diagrams enables simplification of the AC filter design process and also provides a degree of conservatism in the design. It also ensures that at the bidding stage of a design, all prospective contractors design on a common basis rather than being left to determine exactly which impedance should be employed. The manner in which the results of the many individual network impedance calculations (commonly termed scatter plots, or clouds of points) are translated into such envelopes, i.e. the width of harmonic frequency band to be included and the complexity of each envelope shape, however requires careful consideration to avoid either under- or over-design of the AC harmonic filters.

At the simplest extreme, some technical specifications have simply indicated that the network impedance at any harmonic between 2nd and 49th (say) orders lies anywhere in a circle of defined radius with associated maximum and minimum angles that encompass the impedance scatter plots for all network conditions studied and for all such harmonics. This simplifying assumption might apparently relieve the customer of a significant amount of work. It will also generally produce a safe filter design, but it probably will be an unnecessarily complex and expensive design and may comprise harmonic filters (especially those for low order harmonics) that in reality may be either unnecessary or larger in Mvar terms than is really required.

Figure 6 shows, for a typical HVDC converter station network impedance study, the defining parameters of a simple circle envelope that would encompass all of the scatter points over the range 2nd to 49th harmonic orders. The limiting (minimum and maximum) damping angles required to include all points actually only occur for harmonics around the 15th and 17th orders, and the radius of the circle is dictated by the need to accommodate impedance values occurring at the 23rd harmonic order for another and different particular network operating condition. It can therefore be seen that the definition of such a single envelope to cater for all harmonic orders is particularly pessimistic, with the greater majority of the harmonic impedance values being confined to a far smaller area.

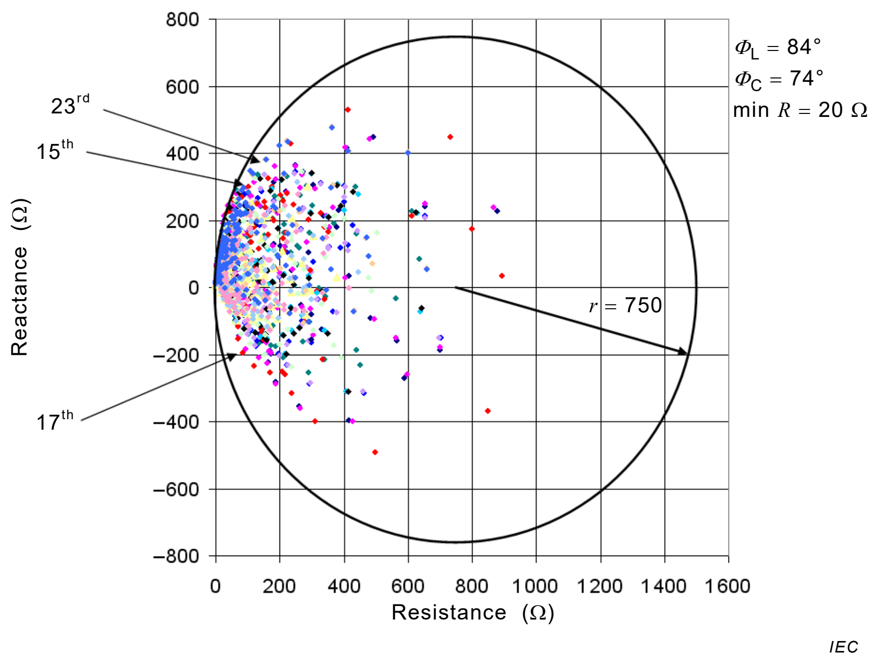


Figure 6 – Example of simple circle envelope encompassing all scatter points for harmonic orders 2 to 49

It needs to be remembered that in the assessment of worst-case resonance between the AC filters and the network for deriving either performance or rating (see also [11], 7.1.6 and 9.5) this worst-case resonant network harmonic impedance is a value lying on the boundary, rather than within, the envelope (refer also to Annex A for further detailed discussion on this issue) and that in general it is an impedance close to the origin of the R-X plane and often along the R_{min} line or the minimum/maximum damping angle lines. The correct definition of the network impedance in these areas of the envelope boundary at the critical harmonic frequencies is therefore vital to achieve an optimal filter design.

It is therefore appropriate that in most circumstances the scatter plots should be broken down into a greater number of envelopes each covering a smaller frequency band and each having unique parameters. Each envelope should include the minimum possible area of non-realistic impedance points. With the advent of advanced design software and study techniques, the customer should not feel constrained to specifying envelopes of relatively simple shape such as circles, arcs, sectors; rather he should specify any shapes (e.g. discrete polygons) which avoid the inclusion of non-relevant points. Note that parts of the boundary of typical impedance scatter plots are often most accurately described by arc sections and these may be incorporated in a total polygonal envelope whose other boundaries may be straight lines, thereby avoiding the inclusion of extraneous impedance areas.

4.5 Methods of determining envelope characteristics

4.5.1 General

In determining the manner of subdivision of the scatter plots into envelopes covering smaller frequency bands and the defining their characteristics, the following guidelines should be noted – with however an important cautionary note. The variation of network impedance with harmonic frequency, particularly in terms of the numbers of resonant frequencies and where these occur, will differ significantly from one network to another due to their different geographic characteristics, inherent mixes of generation and load characteristics and their composition of overhead lines and cable circuits. Networks comprised predominately of overhead lines and significant levels of generation often tend to possess a first resonant frequency at a much higher order than one comprised mainly of cable circuits and a lower level of generation. The guidelines discussed below are therefore general in nature and each network should be studied on a case by case basis.

4.5.2 Low order harmonics

At lower order harmonics (often say up to the 13th order, but this is dependent on the characteristics of the network), it is general practice to subdivide the scatter plots into bands each covering only a few harmonics, say 2nd to 4th, 4th to 7th, 7th to 13th , or even smaller bands such as a single harmonic order. The viability of subdividing into relatively small bands does however strongly depend on the behaviour of the network impedance vs. frequency characteristics; if there are no, or only one or two, series and/or parallel resonances at these lower order harmonics, the plot will not be characterised by rapid changes in impedance value (both magnitude and sign) with frequency.

Therefore, ascribing relatively small size envelopes to a band covering only a few harmonics can be done with some confidence in these cases. 4.5.5 discusses in greater detail the important requirement to take account of the effects of data relating to harmonic orders at both ends of the band under consideration. Figure 7 shows an example of an envelope encompassing data for 7th to 13th harmonics arising from the study of several network conditions together with the associated scatter plots.

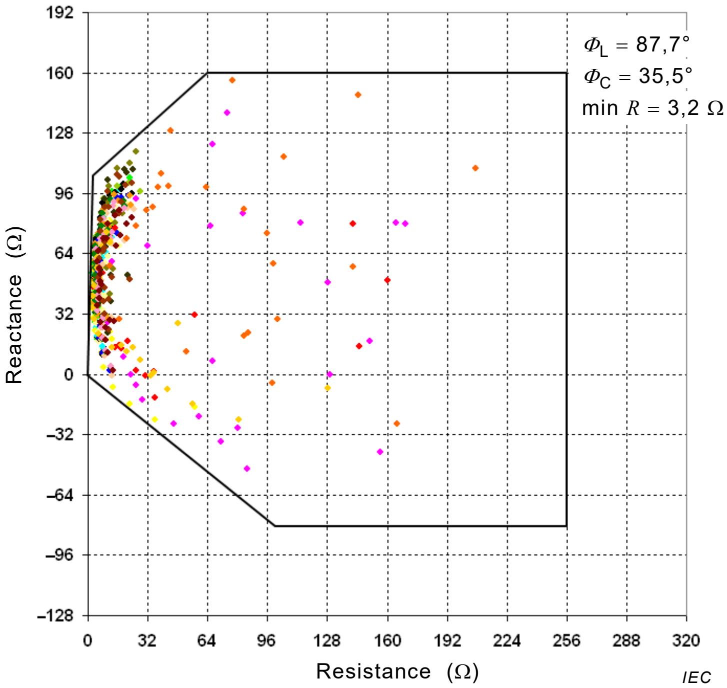


Figure 7 – Example of an impedance envelope for 7th to 13th harmonic with associated scatter plots

4.5.3 Mid-range and higher order harmonics

With increasing harmonic order (say above 13th order, but this depends entirely on the characteristics of the particular network), it is likely that the number of series and parallel resonances will increase significantly, both major resonances (where the value of reactance changes sign) or a minor loop (where reactance does not change sign). Because of these rapid changes in network impedance values with small changes in frequency, it therefore becomes increasingly difficult to draw the envelope with confidence to either a single or only a small number of harmonic orders. Some of this difficulty relates to the effects of accuracy (tolerance) on the input data to the network impedance reduction studies. For example, a small variation in input data parameters for say overhead line impedances or due to change in transformer impedance with tap position can move a high order resonant frequency by one or two (or even more) harmonic orders. It therefore often becomes necessary to include several harmonic orders in a particular band, for example 13th to 19th, 19th to 25th, 25th to 31st, 31st to 40th (again noting the requirements of 4.5.5) as typically demonstrated in Figure 8 and Figure 9.

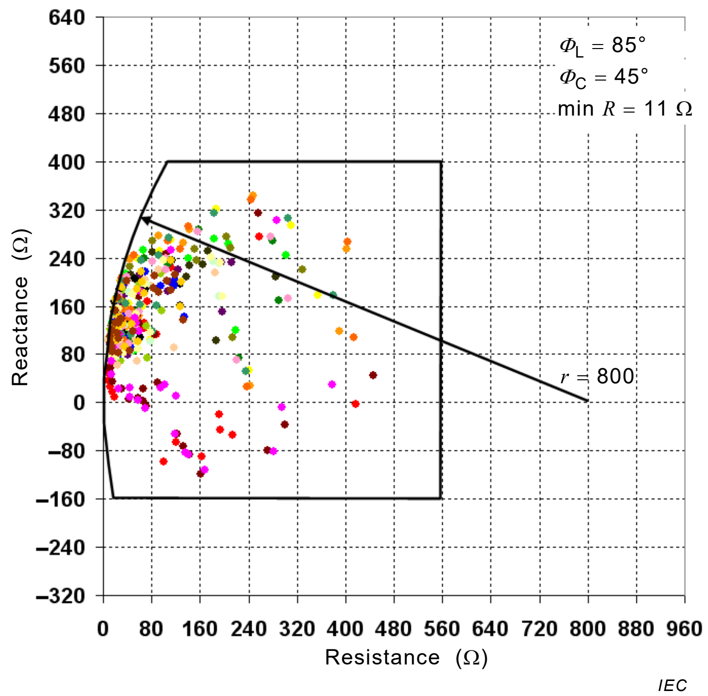


Figure 8 – Example of an impedance envelope for 13th to 19th harmonic with associated scatter plots

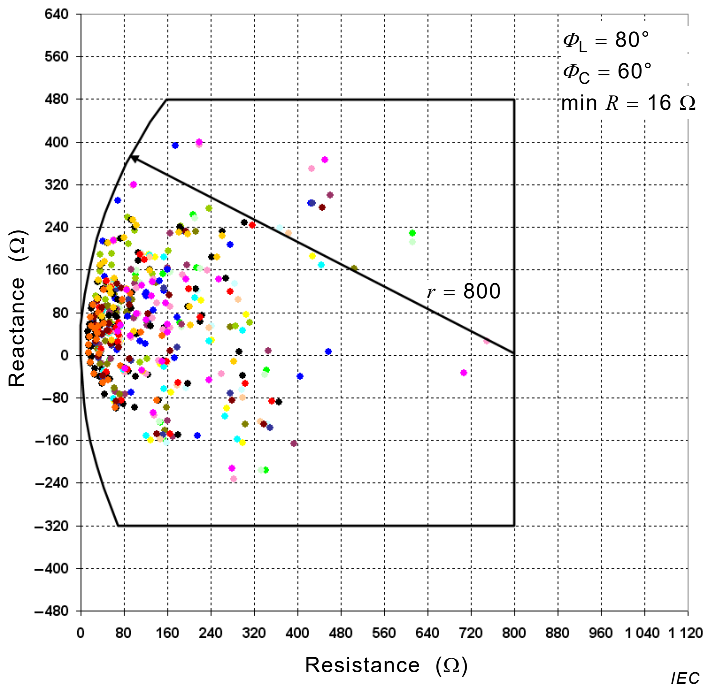


Figure 9 – Example of an impedance envelope for 19th to 25th harmonic with associated scatter plots

4.5.4 Balancing of risk and benefit

On occasions, there may be a need to balance the potentially conflicting risks and benefits of certain aspects of network impedance specification. For example, the contractor's AC filter designer might calculate that the provision of separate smaller (and hence less restrictive) impedance envelopes for each of the 35th and 37th orders, that possess different characteristics from a wider envelope specified for all higher order harmonics, could mitigate a possible difficulty of performance compliance. This would not have been obvious to the customer when specifying the network impedance.

However, the customer on the other hand should be aware that the accuracy of modelling tends to decrease with increasing harmonic order (this can occur typically beyond approximately 20th harmonic) and that around these particular high harmonic orders the impedance characteristics may include many major and minor resonances. He may therefore wish to exercise caution and prefer to specify an impedance envelope covering (say) 31st to 40th harmonic orders to ensure that overly optimistic impedance data is not provided.

The initial studies to define network impedance scatter plots, and hence impedance envelopes will typically include all feasible operating configurations, load levels, etc. Later in the design process, the filter designer may find that there is one particular small extremity of the impedance envelope which makes a large difference in the required filter solution, with associated cost and complexity issues. In such cases, it may be desirable for both customer and contractor to re-examine the original studies to determine which case(s) gave rise to that particular impedance area, and consider whether for example that case is so rare that higher distortion levels could be tolerated, thus permitting the simpler filter design to be used. An intelligent discussion should result in the optimal balance of risk and benefit.

4.5.5 Consideration of tolerances on harmonic bands

For whatever band of harmonic orders is chosen for a particular envelope, some care is also needed to ensure that data relating to frequencies immediately above and below that band is also included in deriving the characteristics of the envelope. This is to take account of the effects of the variation of network frequency from the nominal value (both steady state and those applicable to short time rating), tolerances of the input data parameters, other uncertainties in data and assumptions, and also the fact that at higher order harmonics, the modelling itself becomes increasingly less accurate.

As an example, when the network impedance characteristics have no, or few, resonances in the range under consideration, it is probably only necessary to include data relating to say only half a harmonic order at both ends of the band considered. Thus, for an envelope nominally describing 13th to 19th harmonic orders, data for 12,5th to 19,5th could normally be included in the assessment. However, if there are significant resonances appearing in the impedance characteristic close to the beginning or end of the band, it should be widened accordingly. Figure 10 shows that because of a major resonance occurring for two particular network operating configurations close to the end of the envelope band (data relating to the other operating configurations are not shown for clarity), it is necessary in this example to extend the band to also include (at least) harmonics of the 20th order where, because of a major resonance, the reactance changes rapidly from inductive to capacitive near that order.

Blue and red dots in Figure 10 are for two different operating configurations.

Some specifications of network impedance characteristics have required that the calculated results for a tolerance of say ± 1 harmonic orders should be included for the harmonic in question. While that methodology may be reasonable for higher orders, its use for low orders is treated with caution. For example, it would mean including the 2nd harmonic impedance when calculating the network impedance to be used for the 3rd harmonic. The variation in impedance over this range can be very large, and unnecessarily including a too wide band of tolerance may lead to a difficult filter design. A good guide would be to use a similar tolerance range in percentage of the harmonic in question, rather than as a fixed number of harmonic orders.

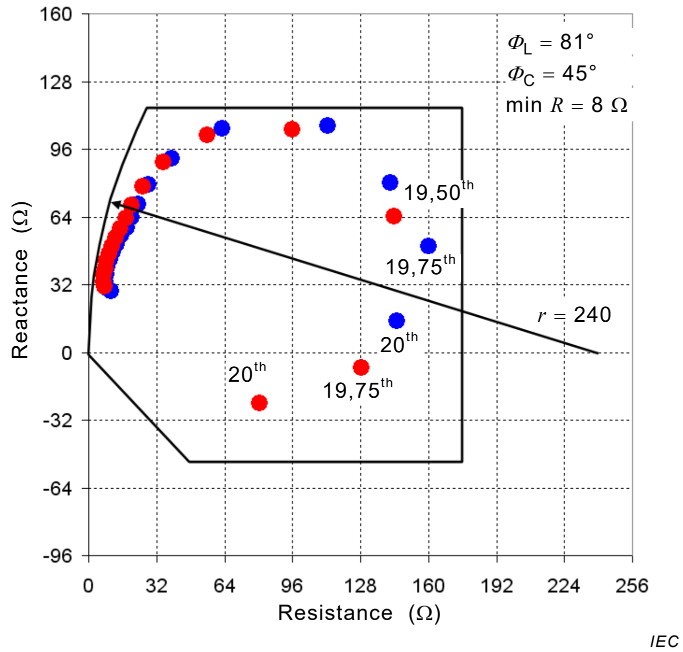


Figure 10 – Example of the need to extend the band of harmonics to allow for resonance effects

An example of applying a percentage tolerance range to the maximum network impedance characteristic is shown in Figure 11, for a 60 Hz system. The blue curve is the maximum calculated impedance magnitude for all of the 800 000 operating conditions studied, which included variations in network development with time, system loading conditions, generation dispatch conditions, contingencies etc. In this example, impedances were calculated in 1,0 Hz steps from 60 Hz to 3000 Hz. The maximum impedance envelope to be used in the filter studies, taking into account a percentage tolerance, is shown in red. For the majority of frequencies, a ±10 % tolerance was assumed to take into account shifts in resonant frequencies that may occur as a result of uncertainties in data and AC system operating conditions that were not studied.

If, however, there is reason to believe that the calculated impedance at certain frequencies has a lesser susceptibility to such variance, then a narrower tolerance band could be used. For example, in this case the AC network included nearby high-pass 12th harmonic filters at another substation, for which there is a very high certainty in modelling data. The impedance of these filters dominated the total AC network harmonic impedance around the 11th and 13th harmonics so a ±10 % tolerance was unreasonable. A ±2 % frequency tolerance was therefore assumed around 660 Hz and 780 Hz corresponding to the equivalent detuning of the other substation filters due to all causes, as shown on an expanded scale in Figure 12. For the subsequent filter design studies, the maximum impedance at each harmonic was then taken directly from the larger envelope (red) at the nominal harmonic frequency.

The advantage of doing this is that the consequent reduction in the maximum impedance (together with similar actions on the other network impedance parameters) may permit a more efficient design of the new filters. Applying a percentage tolerance range in this manner results in maximum impedances close to the calculated values at low order harmonics where the AC network and its harmonic impedances are well defined. At higher frequencies, where a small change in parameters could have a greater impact on resonant frequency, the maximum selected impedance could overlap several harmonics. For example, the maximum impedance characteristic selected would be the same (about 12 p.u.) for the 35th to 42nd harmonic.

The same procedure can be applied to each of the other R-X diagram characteristics such as minimum impedance, maximum and minimum impedance angle, maximum and minimum resistance.

The choice of the specific tolerance values on how far to extend the band of harmonics is therefore critically dependent on the particular characteristics of the network under consideration and can only be determined from detailed studies. The use of simple generic values to be applicable for all cases cannot be recommended. It is also dependent on whether the input data is applicable for the entire project lifetime, or whether it applies only for the early life of a project, in which case wider tolerances are desirable to allow for unknown future developments.

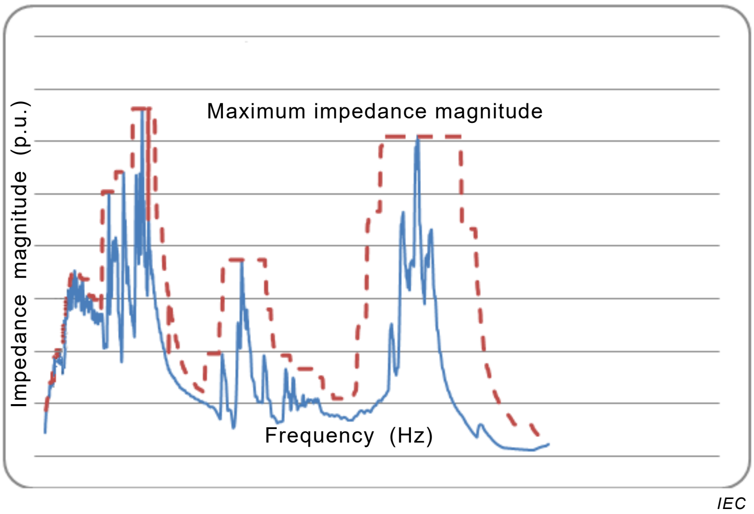


Figure 11 – Application of tolerance range in percentage of the harmonic number

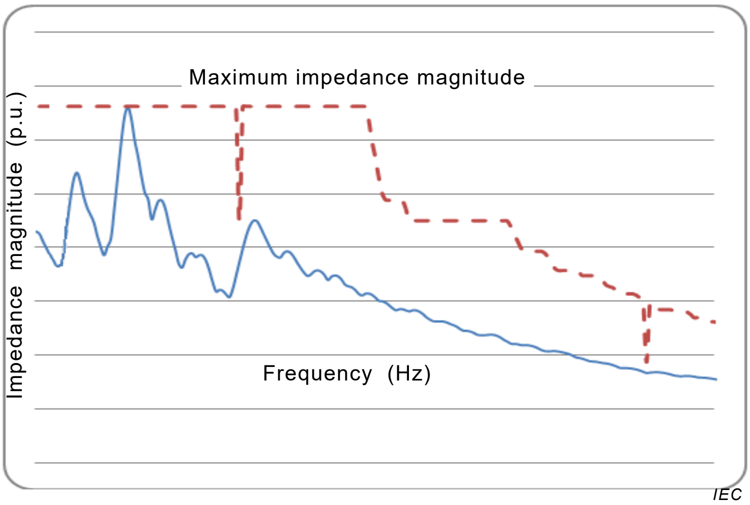


Figure 12 – Application of tolerance range in percentage of the harmonic number, zoomed to show 11th and 13th harmonics

4.5.6 Two separate envelopes for one harmonic band

If, in deriving the envelope parameters for a particular band of harmonics under consideration, it is evident that for certain network operating condition(s) the resultant harmonic impedance scatter points lie in an area of the R-X plane distant from all other points, then it may be appropriate to specify two or more distinct envelopes for that band to avoid the inclusion of non-relevant points that would arise from the use of a single large envelope. Figure 13 provides an example of this in which, under a particular set of outage conditions only, the impedance characteristics lie in an area of the R-X plane significantly distinct from those for all other conditions.

4.5.7 Critical envelope parameters

The correct choice of network minimum resistance (R_{min}), and maximum/minimum damping angles in particular, is often crucial in the assessment of AC filter performance and rating. Care should be taken when determining these parameters, bearing in mind the possible significant implications for filter design. It is more important to avoid unnecessary restrictions on the filter design than to simplify the number or format of impedance envelopes for ease of specification or calculation. For wide bands covering several harmonic orders, it may be prudent to provide additional data, should the chosen value of a critical parameter (e.g. R_{min}) only relate to one harmonic order (say 15th only in a band covering 13th to 19th), and a less limiting value could be permitted for all other orders.

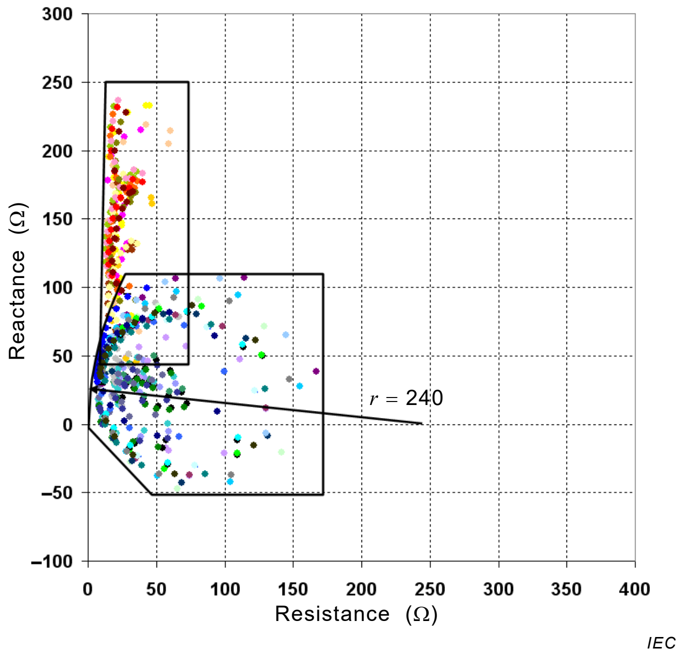


Figure 13 – Example showing two impedance envelopes for a particular band

There are instances when assessing "aggregate" harmonic voltage distortion (i.e. sum of effects of distortion due to converter and that due to pre-existing distortion) that the resonant network harmonic impedance can lie at a point remote from the origin rather than close to it. Therefore, the choice of R_{max}, X_{lmax} and X_{cmax} also requires careful consideration.

4.5.8 Impedance envelopes for performance and rating conditions

Under "performance" and " rating" conditions the resultant harmonic impedance variation may be significantly different. Figure 14 shows the impedance envelopes relating to performance and rating conditions (for the same network) for the band 4th to 7th harmonics. Despite the differences in criteria relating to their respective assessments, the resultant envelopes have similar parameters, especially in that part of the envelope which is critical for AC harmonic filter design, i.e. close to the origin and along the inductive boundary.

However, for this same network the resultant resonant frequencies start to differ significantly between "performance" and "rating" conditions as the harmonic order increases; this is shown in Figure 15 for the band 25th to 31st harmonics. Each of these figures also show the associated scatter plots used to define the characteristics of the relevant "performance" and "rating" envelopes. Clearly all "performance" points are also "rating" points.

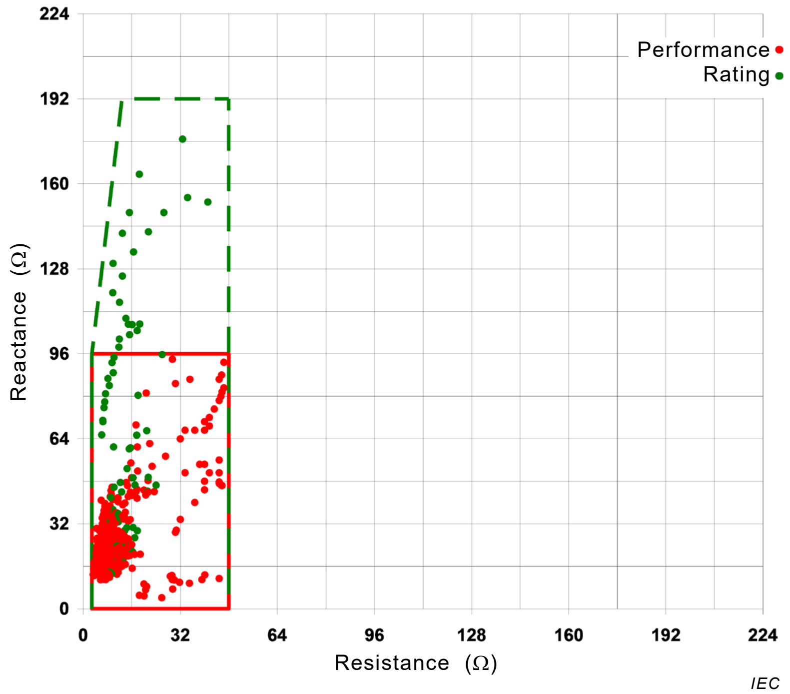


Figure 14 – Example of impedance envelopes under "performance" and "rating" conditions for harmonic orders 4th to 7th

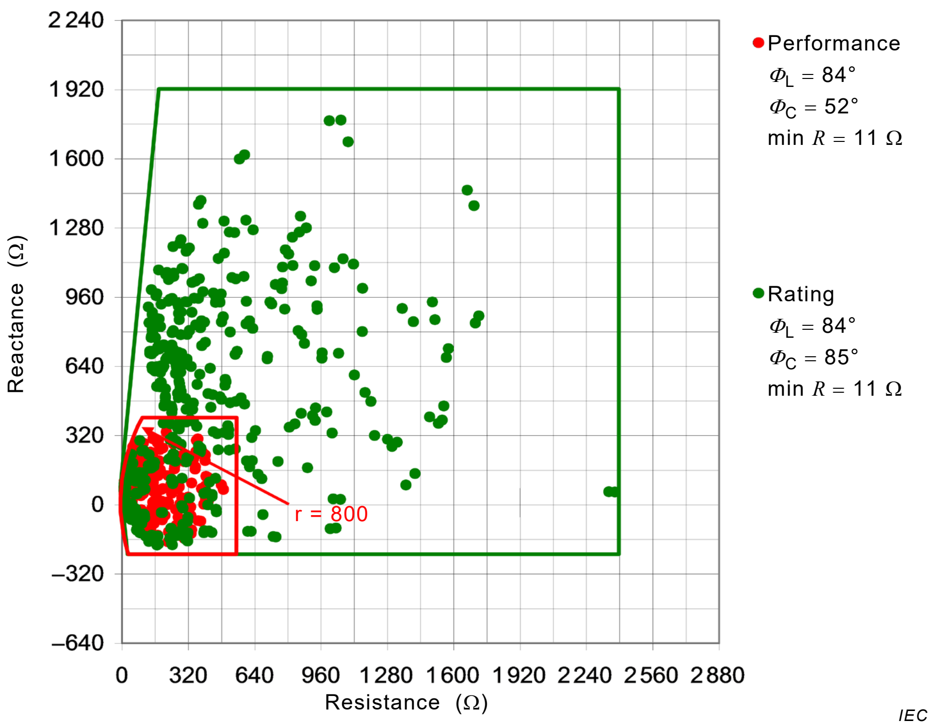
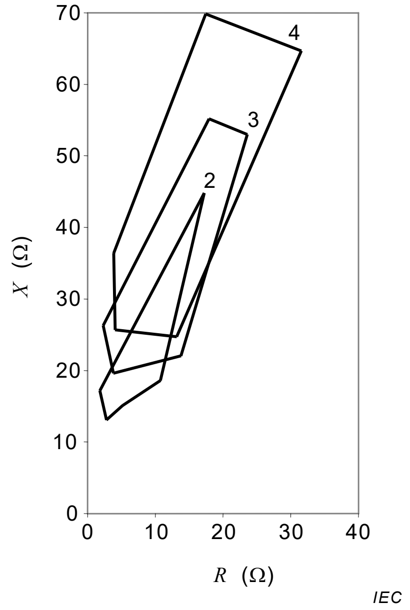


Figure 15 – Example of impedance envelopes "performance" and "rating" conditions for harmonic orders 25th to 31st

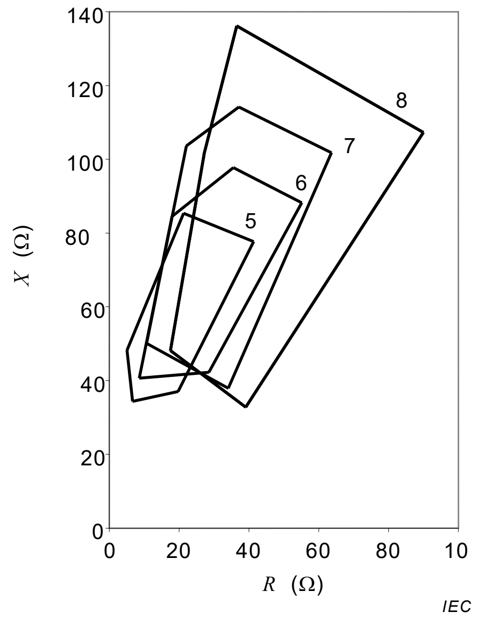
4.6 Examples of the impact of different network impedance representations

4.6.1 Effect of network envelope parameters on resultant distortion

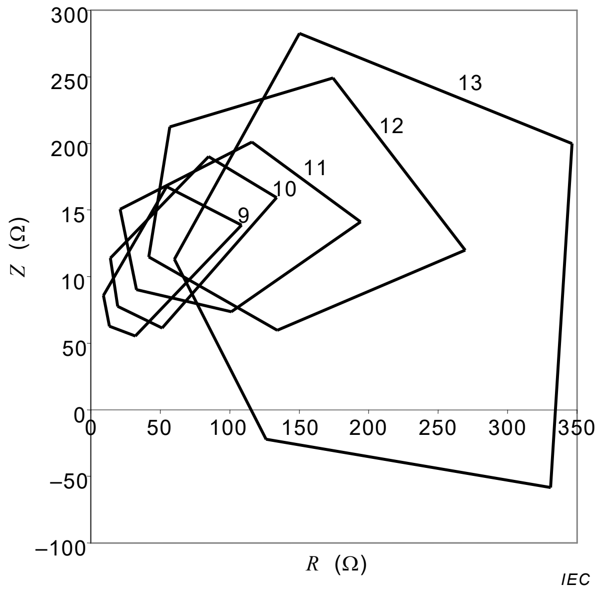
Examples of "discrete envelopes (polygons)" for individual harmonic network impedances and related to the specified envelopes (performance conditions) as of 1980 for the UK converter station of the Cross Channel HVDC link for harmonic orders 2nd to 49th inclusive are shown in Figure 16 (a) to 16 (d) respectively.



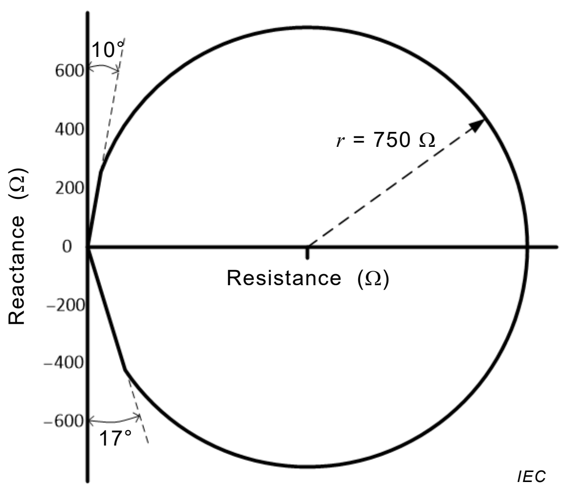
(a) Example of harmonic impedances for harmonics of order 2 to 4



(b) Example of harmonic impedances for harmonics of order 5 to 8



(c) Example of harmonic impedances for harmonics of order 9 to 13



(d) Example of harmonic impedances for harmonics of order 14 to 49

Figure 16 – Discrete envelopes for different groups of harmonics

However, at an earlier stage during the development of this particular project, the impedance envelope as shown in Figure 16 (d) was declared by the customer to be relevant to all harmonic orders (2nd to 49th) for the purpose of assessing harmonic performance. Resultant detailed design studies indicated that compliance with the specified limits at low order harmonics could not be easily achieved without recourse to either further subdivision of the available shunt capacitive compensation into a greater number of filters and/or the inclusion of single tuned filters to cater for specific harmonics. Following further detailed studies by the customer, the representation of AC network harmonic impedance at individual low order harmonics was then re-assessed to provide a more accurate definition in the form of "discrete envelopes (polygons)" as shown below. The significant difference in scales between Figure 16 (a) and Figure 16 (d) in particular should be noted.

Table 2 compares the resultant harmonic performance when considering both types of representation of AC network impedance at low harmonic orders for a given (and identical) AC harmonic filter design.

Table 2 – Comparison of calculated harmonic voltage distortion between two methods of representing network harmonic impedance

Harmonic order	Permitted voltage distortion[a] %	Harmonic voltage distortion based on Figure 16 (d)[b] %	Harmonic voltage distortion based on Figure 16 (a) to Figure 16 (c)[c] %
2	1,0	1,10	0,74
3	1,0	1,75	1,28[d]
5	1,0	1,20	0,98
7	1,0	1,05	1,05
11	1,0	1,05	0,77
13	1,0	0,85	0,74

[a] Maximum permitted voltage distortion (%) at each harmonic order from all sources (converter, SVCs, pre-existing harmonic voltage distortion).

[b] Maximum individual harmonic voltage distortion in % (total arithmetic addition of all sources) under resonant system conditions based on Figure 16 (d) harmonic impedance characteristic (circle) at all harmonic orders, for the particular worst-case combination of DC load/filters.

[c] Maximum individual harmonic voltage distortion in % (total arithmetic addition of all sources) under resonant system conditions based on Figure 16 (a) to Figure 16 (c) harmonic impedance characteristics (polygon) at each harmonic order for the worst-case combination of DC load/filters.

[d] Whilst this level of distortion is greater than the permitted limit, it was deemed acceptable by the customer due to the particular operating condition giving rise to it.

It can be observed from this example that for 2nd, 3rd, 5th and 11th harmonics in particular, the more restricted envelopes of network harmonic impedance give rise to substantially lower values of resultant harmonic distortion (which were also compliant with the specified performance requirements). For this particular example, the reduction in distortion at these harmonics arises because the value of network damping resulting from the application of the 80° inductive impedance angle shown in Figure 16 (d) is less than that as described by the discrete envelopes (polygons). Further, in this example for 7th and 13th harmonics, the calculated distortion from the consideration of both types of representation of network impedance is either similar or identical because the resonant network impedance under the discrete envelope criteria is also similar to that from the circle criteria.

The choice of network harmonic impedance damping angle can have a crucial influence on the resultant calculated values of harmonic voltage distortion both for performance and rating conditions, particularly for the harmonic order(s) where the AC filter configuration itself has low damping. As a further worked example for the Cross Channel HVDC scheme, under the same conditions as described in Table 2 (and based on Figure 16 (d) harmonic impedance characteristics, i.e. a circle at all harmonic orders), the effect of hypothetically varying the inductive impedance limiting angle from the specified value of 80° to either 87° (less damping) or 78° (more damping) is demonstrated in Table 3.

Table 3 – Comparison of calculated harmonic voltage distortion considering the variation of network impedance angle

Harmonic order	Harmonic voltage distortion based on Figure 16(d) with impedance circle limited by 80° inductive and 73° capacitive angles %	Harmonic voltage distortion based on Figure 16(d) with impedance circle limited by 87° inductive and 73° capacitive angles %	Harmonic voltage distortion based on Figure 16(d) with impedance circle limited by 78° inductive and 73° capacitive angles %
2	1,10	1,54	1,02
3	1,75	1,95	1,70
5	1,20	1,45	1,13
7	1,05	1,31	0,96
11	1,05	1,07	1,04
13	0,85	0,85	0,85

Table 3 demonstrates that at 2nd harmonic, where the particular AC filter configuration itself has a low value of damping (relative to other higher harmonic orders), the effect of varying the inductive impedance angle has a significant effect on the resultant distortion. For other harmonic orders (excluding 13th, for which the resonant network impedance is capacitive rather than inductive), the effect is nonetheless still noticeable. As discussed above, care should therefore be taken to ensure that the limiting impedance angles for a given harmonic (or band of harmonics) are appropriate, rather than being the worst-case values applicable to the whole harmonic range.

Similarly, the effect of an appropriate choice of network minimum resistance ($R_{\min}$) can also have similar significant effects. In the above examples, the resultant resonant network harmonic impedances are relatively distant from the origin so the effects of typical $R_{\min}$ values do not have an influence; this is not always the case, especially for an AC filter configuration comprising sharply tuned (high q factor) filters.

4.6.2 Effect of network minimum resistance on filter rating

The minimum resistance of the AC network can have a significant impact on the filter ratings, as illustrated below. Consider a typical 13th single frequency tuned filter forming part of the AC filter scheme associated with an HVDC converter and having the following parameters:

- Voltage of connection: 220 kV
- Fundamental frequency Mvar rating (three phase) at 220 kV, 50 Hz: 80 Mvar
- q factor at tuned harmonic order (13th): 100
- Nominal fundamental frequency filter current: 210 A
- Maximum equivalent detuning frequency: ±2 %

Consider also that the minimum resistance of the network impedance at 13th harmonic is either 4,6 Ω (0,0095 pu on 100 MVA) or alternatively 1,0 Ω (0,002 pu on 100 MVA). Both of these values are typical. It is also assumed for simplicity that the effects of other AC filters forming part of the total configuration are negligible at 13th harmonic. Table 4 shows the resultant magnification factor of a pre-existing voltage source behind a resonant network impedance, as well as the voltage distortion on the AC filter busbar and the filter current at 13th harmonic. The study is performed for both conditions of perfect filter tuning and at maximum detuning, each considering both values of network minimum resistance. For this simple study, the effects of any converter generated harmonic currents are neglected.

Table 4 not only indicates the expected variation of magnification factor and harmonic filter current with tuning, but clearly demonstrates the significant effect on both of these values of what might appear to be only a small change in network minimum resistance. The value of 13th harmonic current in the filter remains constant throughout the detuning range in this calculation because whilst the 13th harmonic voltage distortion increases as the filter progressively detunes, so also does the filter impedance.

Table 4 – Comparison of calculated filter harmonic current considering the variation of network minimum resistance and filter detuning

Case	Filter impedance (Z_f) at 13th harmonic Ω	Resonant network impedance (Z_s) at 13th harmonic Ω	Magnification factor ($Z_f / Z_f + Z_s$) of pre-existing distortion	Magnitude of pre-existing 13th harmonic voltage distortion behind resonant network impedance %	13th harmonic voltage on filter busbar %	13th harmonic current in filter A
Filter on tune, network R_{min} = 4,6 Ω	0,46 + j0	4,6 + j0	0,091	1,5	0,136	375
Filter detuned capacitively by 2 %, network R_{min} = 4,6 Ω	0,46 – j1,91	4,6 + j1.91	0,388	1,5	0,582	375
Filter on tune, network R_{min} = 1,0 Ω	0,46 + j0	1,0 + j0	0,315	1,5	0,472	1 305
Filter detuned capacitively by 2 %, network R_{min} = 1,0 Ω	0,46 – j1,91	1,0 + j1,91	1,35	1,5	2,02	1 305

4.7 Interharmonic impedance assessment

Interharmonics are often thought to be of little significance in the design of HVDC converter station filters, as the typical converter and pre-existing harmonics are at integer frequencies.

However, some network owners intentionally use interharmonic frequency signals (termed ripple control signals) to control their network devices or to change electrical tariffs at centralised time instants. The range of ripple control frequencies extend from 175 Hz up to several kHz depending on the particular application, but these control frequencies are never at integer harmonic frequencies. A ripple control signal generator is normally a voltage source converter installed in series at medium or high voltage level. Each network owner dictates a minimal ripple control signal level for all points of its network. As for any harmonic, the effectiveness of ripple control signals depends on LV impedance, HV impedance, background ripple frequency level and downstream ripple frequency emission level. Any customer whose installation provokes excessive attenuation of the ripple control signals should apply necessary solutions such as a blocking filter or an active filter. Generally, all power electronic devices and distributed generators cause a certain degree of attenuation in ripple control signals. Hence, ripple control signal analysis is a compulsory study prior to connection of any disturbing load or generation load to the grid where ripple controls are used.

For this reason, where applicable in areas where ripple control signals are used, an interharmonic assessment should also be carried out for a HVDC project as part of the design process. As recommended in 4.4, the network impedance computation should be performed as a near-continuous spectrum (covering both harmonics and interharmonics). In the same manner as for integer harmonics, bidders/contractors should perform specific interharmonic assessments by using network impedance data, proposed AC filter data and interharmonic current levels of the HVDC converter station.

As an example, the following case study shows that a distributed generation (DG) has caused about 15 % attenuation of ripple control signal at the PCC (see Figure 17).

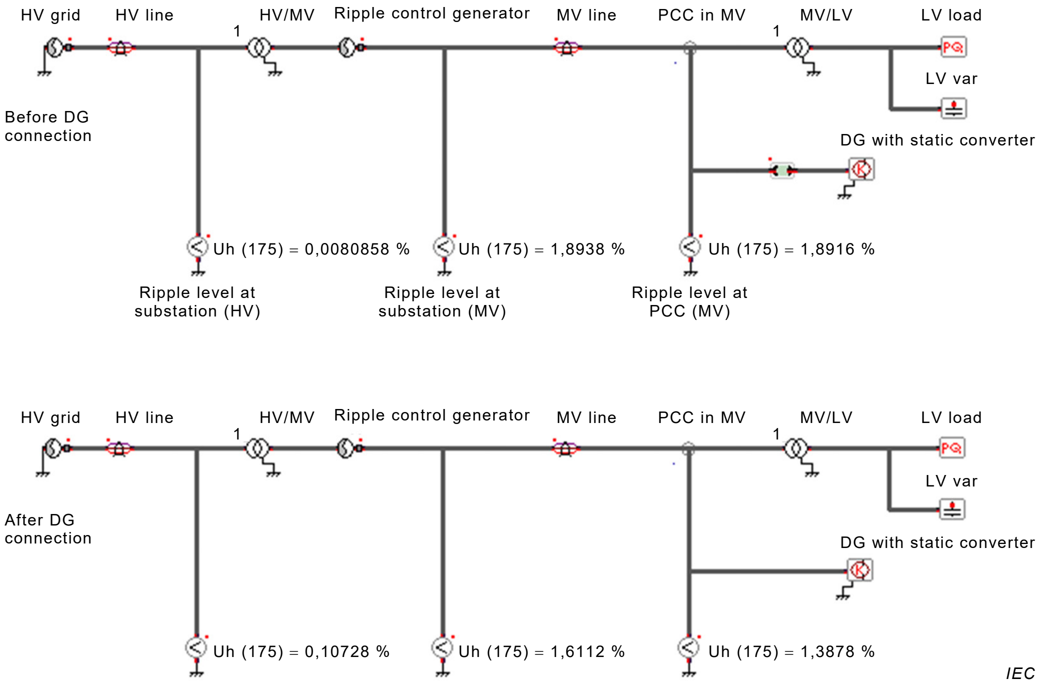


Figure 17 – Example showing a distributed generation causing about 15 % attenuation of ripple control signal at the PCC

The relevant network owner(s) (HV, MV and LV) should provide the following necessary technical information in order that the HVDC contractors would be able to perform a ripple control voltage assessment:

- the ripple control frequencies;
- the rated ripple control signal level;
- the ripple control limits on HV and MV sides;
- the upstream grid impedance at the ripple control frequencies.

For example, the characteristics of the ripple control signal used by the distribution supply operators in France are:

- three phase ripple control signal at 175Hz;
- limits are represented in % to the fundamental voltage;
- DSO's rated ripple control signal level is 2,3 % at MV side of substation;
- minimum ripple control signal level at MV busbar of HV/MV substation: ≥ 1,37 %;
- maximum ripple control signal level at HV side of HV/MV substation: ≤ 0,43 %.

Two aspects should be studied when integrating an HVDC link into the existing networks:

- Emission level of the HVDC converter station at the ripple control frequencies. If the HVDC converters generate interharmonic current at the relevant ripple control frequencies, the voltage interharmonic level at the HVDC converter station busbar/PCC should be assessed.

- Attenuation effect of the ripple control signal by a small impedance or a resonance. Even if the HVDC converter does not generate the interharmonic current at the relevant ripple control frequencies, it may attenuate the existing ripple control signal due to its filters. This attenuation effect should be studied.

If these studies show that satisfactory ripple control levels cannot be maintained after the integration of HVDC link, special filters should be added.

4.8 Measurement of network harmonic impedance

Information on the measurement of network harmonic impedance is available in [17]. There have been further developments in techniques, as described in some of the references quoted below.

Aspects of network harmonic impedance measurements and the relative merits and uses of these are discussed below.

- Measurement of network harmonic impedance is generally only relevant for the particular operating condition(s) at the time of measurement. Prediction of how the network impedance changes as a result of variation in load pattern, outages, etc. and of the effects of future network developments is generally not possible because it is not feasible to extrapolate measurements from one operating condition to another.
- For certain techniques, the accuracy of network impedance by measurement is greater at those harmonic orders where the magnitude of pre-existing harmonic distortion is low. Several of the techniques employed assume that during the period of measurement the magnitude of pre-existing distortion remains constant, but in reality this may not always be the case.
- Comparison of network impedance by measurement with that by calculation has shown that in general there is good correlation regarding where the network resonances occur and also in terms of the reactive component of impedance. However, there appears to be poor correlation in terms of the resistive component (damping), with measured results generally showing greater damping than calculated. This could be due to errors in the calculation method regarding the modelling techniques employed for the variation of resistance with frequency for the various power system elements as discussed in 4.3.5 and Annex B.
- Measurement techniques that monitor the response of the network to the energisation/de-energisation of mechanically switched capacitors, shunt reactors or transformers, etc., and hence derive harmonic impedance by use of various algorithms, can usually be undertaken with minimal physical intrusion of the network for the connection of required instrumentation, as often the required suitable transducers already exist but may need to be calibrated to ensure accuracy at harmonic frequencies [18].
- Techniques for measurement of network harmonic impedance that are based on the measurement of voltage (and current) distortion resulting from the operation of a large disturbing load, such as an AC-DC converter (pulsed) load have been found to be accurate compared to calculated values of network impedance at the characteristic harmonic orders of such systems. However, such techniques are less reliable for the lower order non-characteristic harmonics where the magnitude of the disturbing harmonic is either too low and/or there is a significant level of pre-existing distortion. The use of such techniques is of course limited to the measurement of network impedance at the relevant node of connection [19].
- The preceding method evaluates the network impedance only at the harmonic frequencies which makes it mandatory to take into account the pre-existing distortion and this leads to the mentioned limitations. However the pre-existing distortion is usually very low at interharmonic frequencies. It is relatively easy to increase the interharmonic spectrum by injecting a noise signal in the control loop of the same large

disturbing load (AC-DC converter or SVC). This allows evaluation of the network impedance at the interharmonic frequencies, and interpolation can be used to estimate the impedance at the integer harmonic frequencies [20]-[23]. Use of autocorrelation techniques and a large number of samples allows extraction of the impedance values using only very low, essentially imperceptible, levels of noise injection.

- Techniques for deriving the network impedance by the injection of a disturbance signal from a relatively small electronically commutated single or three phase load connected to the HV system via a coupling capacitor have given reliable results for those harmonic orders where there is either little pre-existing distortion and/or there is not an adjacent strong source of harmonic injection. A possible drawback of this method, however, is the requirement for an "intrusive" connection (by virtue of the coupling capacitor) into the HV system [24].

To conclude, the derivation of network impedance by measurement, where it is practicable, should be encouraged and viewed as a method to confirm the calculation of impedance rather than a substitute for network harmonic impedance calculations. Such verification is much needed to validate the existing harmonic network models and potentially to improve them. The results of any available harmonic impedance measurements should be taken into account by the customer when choosing the network impedance loci to be used for AC harmonic filter design.

4.9 Conclusions

The network harmonic impedance has a profound influence on the design of the AC filters of an HVDC scheme, with substantial implications for the cost and complexity of the filters as well as for the risk of inadequate harmonic performance or overloading of filter components. It is therefore important to apply adequate and timely resources to the determination of the correct values to use in the design studies.

The issue of who should define the network harmonic impedance (customer or contractor), and at what stage of the tender and design process, is fundamental, and the implications are discussed.

Computer modelling of the network impedance uses suitable models of all system components, including loads, at harmonic frequencies, which are very different to those used for fundamental frequency studies. The degree of resistive damping in the network and the manner in which it varies with frequency is highly important. The models recommended in the literature are varied and sometimes not solidly justified and more work is required in this area.

The variation of calculated network impedance due to both the validity of models and actual physical aspects, such as change of the network configuration and loading over time, should be considered, and various techniques for achieving this have been discussed. To facilitate the process of filter design, it is common to express the network impedance in terms of an envelope in the Z-plane, bounding all the calculated impedance values. The choice of such envelopes, their possible shapes and the harmonic bands to be included should be carefully considered as the implications for under- or over-design are significant. Guidelines are provided; however it is emphasised that they are general in nature and each network is studied on a case-by-case basis.

Although network harmonic impedances are mostly derived by computer simulation methods, in order to cover a full range of present and future scenarios, field measurements can be very useful as verification and are recommended where possible.

5 Pre-existing harmonics

5.1 General

As well as considering harmonics generated by the HVDC converter, AC filter design also has to take into account the influence of pre-existing harmonics in the AC network. The term “pre-existing harmonic distortion" refers to the level of harmonic distortion present on the system in the absence of the HVDC link; other terms such as background distortion or ambient levels of distortion have the same meaning. This term does not have any time-related implication, i.e. it does not necessarily mean the distortion existing previous to the commissioning of the HVDC link, but rather the background level existing at any time.

The motive for a detailed examination of this topic is that it continues to be a problematic area of AC filter specification and design in many HVDC projects. For example, pre-existing harmonics are frequently specified as a fixed voltage distortion source behind a network impedance chosen such as to maximize the component ratings. This can result in extremely high filter ratings, which in many cases are quite unrealistic. The essential issue is that both the specified pre-existing distortion, and the chosen network impedance can occur in reality, but perhaps not simultaneously.

The aim of Clause 5 is therefore to give additional guidance on suitable methods of considering the effects of pre-existing harmonic distortion on the design of the AC harmonic filters, without either compromising the harmonic planning requirements for the transmission network or creating an over-conservative filter design. In this respect, there is a need to examine whether certain existing rating methodologies which can result in filter component ratings becoming excessive are appropriate, especially if they could detract from the economic viability of the HVDC station.

If the levels of pre-existing harmonic distortion are already high, the network owner or regulator may enforce lower permissible performance limits for the proposed HVDC station, to ensure that the overall planning levels for the network are maintained. It may also be desirable to allow a "headroom" margin for future harmonic-producing installations. Although it has often been normal practice to apply "incremental" performance criteria for HVDC schemes, some customers may also now specify an "aggregate" performance requirement. The term "aggregate" rather than "total" is used in this document to avoid confusion with "total" (meaning the total over all specified harmonic orders) as employed in the term "THD". In the former case ("incremental"), the declared harmonic performance criteria will relate to the effects of the HVDC station alone, or more specifically in terms of the effects of the converter harmonic current spill into the network. In the latter case ("aggregate"), the limits will apply to the combination of pre-existing harmonic distortion and how it is modified as a result of connecting the HVDC station, together with the contribution generated by the HVDC station. In this latter case, a clear understanding of the levels of pre-existing harmonic distortion (and their variation) is therefore required. The measurement of such harmonic levels is discussed in Annex C.

The method of combining the contributions from the pre-existing distortion and the HVDC station for performance evaluation also has to be clearly stated. A typical method is described later in Clause 5 and further detailed guidance is also provided in Clause 6 of IEC TR 61000-3-6:2008. In a similar manner, when establishing the ratings of the filter equipment, the method of combining these two sources also needs to be clearly stated.

5.2 Modelling and measurement of pre-existing harmonic levels

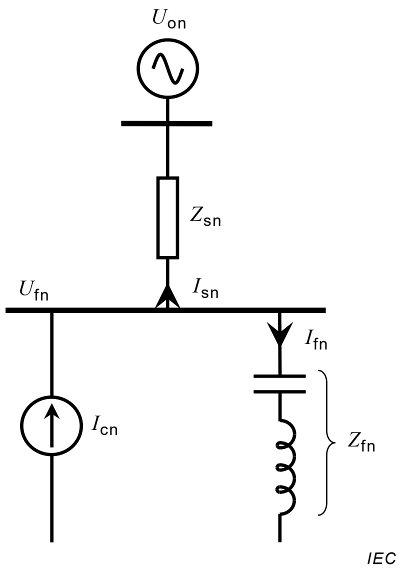
In reality, pre-existing distortion is generally not due to the effect of a single source alone, but is due to a multiplicity of harmonic current (and voltage) sources comprising both domestic loads (each potentially generating low levels of distortion at low voltage busbars) and industrial loads embedded within the LV, MV, HV and sometimes EHV networks. In filter design calculations, it is not practicable to model such multiple disparate sources, both because data for individual loads is not available and because the modelling of network impedance at the AC harmonic filter busbar by the use of an equivalent impedance envelope is not then feasible.

Therefore, for both convenience and practicality in either performance or rating analysis, it has been common practice that a voltage source is modelled behind the AC network harmonic impedance as shown in the generic model illustrated in Figure 18, to create an open circuit voltage distortion at the filter busbar, i.e. the level of distortion representative of conditions prior to connection of the AC harmonic filters.

The magnitude of the individual harmonic voltages U_{on} used in this model can be based on actual measurements, performance limits, planning pevels or compatibility levels depending on the particular application under consideration. When these voltages are based on the results of measurements, some allowance should be made for future growth or developments of the system, especially if the measured levels are low when compared with planning or compatibility levels. With respect to the method of measuring existing harmonic voltage distortion, some further guidance is given in Annex C.

The various applications, advantages and disadvantages of the use of this model in the assessment of both filter performance and rating are discussed in further detail in 5.3 and 5.5 respectively.

The above model is sometimes referred to as the "Thévenin model" or approach. That would be correct, if the voltages used are those which could be measured at open circuit (i.e. with the filters and converter disconnected) and if the network impedance used is the same as for that particular voltage measurement. That is by definition a Thévenin equivalent. The problems arise when the voltages applied are set to some arbitrary levels and the network impedance to worst-case values to resonate with the filters, in which case the model is no longer a Thévenin equivalent but simply a voltage source behind a network impedance. In Clause 5 it is therefore referred to as the "voltage source/worst network" model.



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 point-of-common-coupling) busbar harmonic voltage

U_{on} specified pre-existing harmonic voltage source

Figure 18 – Generic circuit model for calculation of harmonic performance or rating

All of these models assume that the converter is a pure current source, but in fact the converter itself has an harmonic impedance, which may be significant especially at lower harmonic orders, as discussed in Clause 3.

The terms planning level, compatibility level and immunity level are further described in Annex C and also in Clause 3 of IEC TR 61000-3-6:2008. An illustration of basic voltage quality concepts with respect to planning level, compatibility level and immunity level is also provided in Figure 19. Whilst for the UK and some other utilities, compatibility levels for all voltage levels including EHV are defined, IEC TR 61000-3-6:2008 only discusses such levels for voltages ≤ 35 kV, since in general the greater majority of "end-user" equipment (for which the criteria of compatibility and immunity levels are of significant importance) are connected at such levels. However, HVDC installation are invariably connected at HV/EHV levels and thus where compatibility levels are not specifically defined, any such choice by the network owner requires a careful balance against planning/immunity levels. The planning levels at HV and EHV are selected such as to achieve co-ordination with rather higher percentage limits at the MV level.

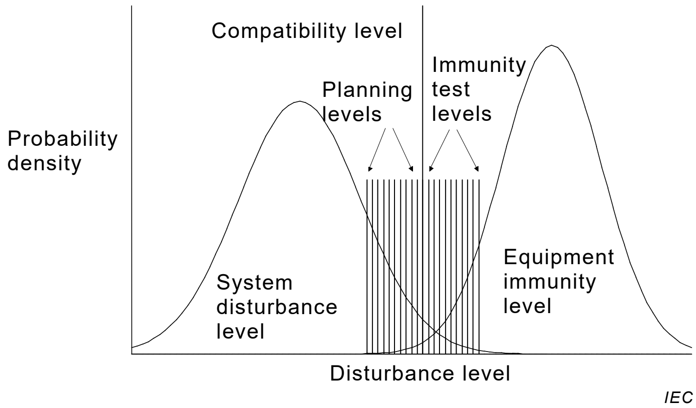


Figure 19 – Illustration of basic voltage quality concepts with time/location statistics covering the whole system

5.3 Harmonic performance evaluation, methods and discussion

5.3.1 General

The main requirements for the AC filter performance specification are generally related to the maximum permissible voltage distortion, this being a directly measurable quantity at the point of connection. The intention is that by limiting the voltage distortion, the harmonic currents injected into the AC system, by the HVDC converter and the resultant harmonic voltages elsewhere, should also be limited to levels that will ensure service quality to the network owner and to all other connected customers of the AC system.

5.3.2 "Incremental" harmonic performance evaluation

Figure 20 shows an adaptation of the generic model of the equivalent circuit shown in Figure 18 in which U_{on} (specified pre-existing harmonic voltage source) is set to zero. This is the model used for the calculation of the incremental impact of the converter generated harmonics.

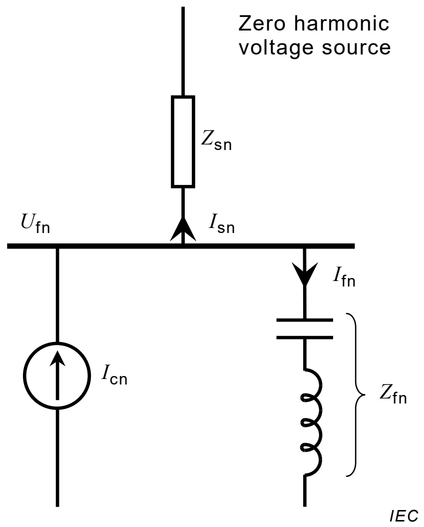


Figure 20 – Circuit model for calculation of incremental performance

For the "incremental" criterion, the permitted distortion at each harmonic at the point of connection of the HVDC converter is based on the requirement to ensure service quality to the network owner and to all connected customers within the interconnected AC network, on connection of the converter. The method of determining such limits is discussed in detail in IEC TR 61000-3-6:2008, Annex D, which provides a worked example.

When implemented correctly, this method requires determining the maximum allowable contribution from the HVDC converter at all remote busbars, while taking their own levels of pre-existing distortion and allowance for future network extensions into account. The corresponding local permissible "incremental" limits (i.e. at the point of HVDC converter connection) are then calculated using the transfer harmonic impedances from those remote busbars to the point of connection.

Care should be taken in those cases where, because of a series resonance, the network harmonic impedance is very low, as this could result in harmonic voltages exceeding planning levels in remote parts of the network. The magnitude of the "incremental" limits permitted at the point of connection may therefore be restricted by the occurrence of high levels of pre-existing distortion at a particular remote busbar, possibly coupled with an adverse transfer impedance between that remote busbar and the point of connection. This may result in limits being specified for the point of connection at far lower levels than would be otherwise applicable for that particular location when considered in isolation. It is therefore important that the level of pre-existing distortion at that remote busbar and the defined self and related transfer impedances from the point of connection relate to consistent conditions. This can be extremely difficult to achieve in practice (refer also to Annex C).

D.2.3 of IEC TR 61000-3-6:2008 suggests that, where there is a parallel resonance within the network that is causing a magnification factor greater than 2 or 3 (and leading to restricted "incremental" limits at the point of connection), the network owner should examine possible measures to reduce such magnification. For example, where this is due to the presence of plain capacitor banks within the network, these could be detuned. However, where the resonance is due to the effects of overhead line or cable capacitance, it may be impractical to change the resonance conditions. In the former case, it may also be commercially unjustified to detune capacitor banks within the ownership of the network simply to accommodate and ease the connection of a third party asset, i.e. an HVDC converter.

5.3.3 "Aggregate" harmonic performance evaluation

The "aggregate" criterion (as represented in Figure 18) permits either the full planning levels of harmonic voltage distortion at the point of connection, or a proportion thereof based on consideration of the relative rating of the converter to the network supply capability at that point (as per the requirements of IEC TR 61000-3-6:2008, 9.2.1). The combined effects of the converter-generated harmonics and magnification or attenuation of pre-existing distortion by the connection of the converter station AC filters (as discussed in IEC TR 61000-3-6:2008 6.2, Note 1) are both accounted for. In respect of the method of summating the contributions of the converter-generated harmonics and pre-existing harmonics for a particular harmonic order, Clause 7 and Table 3 of IEC TR 61000-3-6:2008 also provides some detailed guidance.

In this case, the levels of pre-existing voltage distortion to be specified by the customer at the point of connection shall be representative of those occurring in practice with an allowance for future growth where this can be predicted and justified, rather than being arbitrarily based on the (full) planning levels.

This method is inherently conservative, as it combines the maximum possible pre-existing harmonic voltages with the worst-case (resonant) intervening network harmonic impedances. However, it may risk being too conservative. This is because of the use of source (pre-existing) voltages which in practice may not occur simultaneously with a particular network impedance. For example, if the applicable worst-case network impedance was for a configuration which included large shunt capacitors or filters within the network, their presence would generally tend to reduce the pre-existing harmonic voltages. It is therefore highly desirable that when the generic (Figure 18) model is used, the source (pre-existing) harmonic voltages and the specified network harmonic impedance should be self-consistent, i.e. it should be physically possible for them to occur simultaneously.

It is however recognised that in a practical design situation, this requirement of consistency between pre-existing harmonic voltage and impedance data may be difficult to achieve, especially when preparing a technical specification in the short time period typically available. It requires a detailed history and correlation of the various loadings and operating modes of the network with the various measurements of pre-existing harmonic distortion. However, all parties should at least be aware that it is an area which can lead to an assessment of excessive harmonic voltage distortion and should be prepared to re-examine particular critical cases following the initial filter design calculations.

It is suggested that, for those networks which do experience significant seasonal variations in system load/generation (and hence also similar seasonal variations in their associated network harmonic impedance) and also seasonal variations in pre-existing harmonic distortion (due to variation in disturbing load patterns), it may be an advantage to provide several "more consistent" data relating to impedance and pre-existing harmonic voltage, for example representative of different seasons. Whilst it is inevitable that this provision could lengthen the filter design process, the improvement in consistency could alleviate certain issues regarding unrealistic filter performance and/or component ratings. However, it should be noted that this approach can generally only relate to present network conditions; it may be difficult to attempt to predict such correlation between pre-existing distortion and system load/generation for future conditions, especially over a period of some 30 years to 40 years.

It is generally also assumed in the application of the "aggregate" criteria that, whilst the levels of pre-existing voltage distortion at the converter station will be modified by the connection of the associated AC filters because of resonance between the AC filters and the network harmonic impedance, the effects on pre-existing voltage distortion at busbars more remote from the converter station due to the effects of these filters will be small. The calculation of such effects on remote busbars is a complex issue; however, practical experience in the UK network, which is strongly interconnected, has confirmed that such an assumption is reasonably valid.

5.3.4 Both "incremental" and "aggregate" performance evaluation

Where significant levels of pre-existing harmonic distortion exist not only at the HVDC converter station point of connection but also at surrounding busbars (either EHV/HV or MV types and within the responsibility of the network owner), consideration should be given to specifying both "incremental" and "aggregate" types of voltage distortion performance criteria to ensure that the overall planning levels for the network are maintained.

5.3.5 "Incremental" and "maximum magnification factor" harmonic performance evaluation

This is a similar performance criteria to that discussed in 5.3.4 and has been specified in a few HVDC schemes. Rather than specifying an "aggregate" harmonic performance criterion, a separate criterion relating to the "maximum magnification factor" is specified. This criterion relates to the maximum permissible magnification of pre-existing harmonic voltage distortion at the HVDC converter station point of connection due to resonance between the converter station (i.e. the AC harmonic filters) and the network harmonic impedance. In this case, the value of I_{cn} in Figure 18 is set to zero. The network impedance is selected as that value which results in the greatest magnification factor at the harmonic order under consideration.

The application of the "maximum magnification factor" criterion has generally been considered as being less appropriate for HVDC schemes but more appropriate for passive types of static var compensation equipment such as thyristor switched capacitors (TSCs) and MSC/MSCDNs (mechanically switched capacitors/mechanically switched capacitors with damping networks) which are not themselves sources of harmonic current/voltage but by virtue of their connection may modify, either magnifying or attenuating, the levels of pre-existing distortion. The maximum permitted values chosen are generally such that at the point of connection of the proposed equipment, the pre-existing distortion shall not increase beyond planning levels.

This criterion is generally not recommended to be used instead of an "aggregate" criterion in an HVDC converter application. In an "aggregate" criteria for each harmonic, there is a single value of Z_{sn} which, depending on the relative values of I_{cn} and U_{on} and the specified manner of summation of their relative effects, will lead to a maximum value of distortion U_{fn} when the effects of both converter injected harmonics and magnification or attenuation of pre-existing distortion are considered simultaneously. However, for a "maximum magnification factor" criterion, which relates only to a series resonant condition between the AC harmonic filters and the network impedance, the value of network resonant impedance only relates to that condition and will generally be different from that resulting from an "aggregate" type of assessment. Its use in terms of demonstrating whether the AC filter design ensures that the overall planning levels for the system are maintained is therefore questionable for an HVDC converter application.

5.4 Calculation of total harmonic performance indices

For the calculation of performance indices which combine all relevant harmonic orders, such as total harmonic distortion (THD), telephone interference factor (TIF) and telephone harmonic form factor (THFF), it is perhaps unrealistic to assume that resonance between the AC filters and the network will occur at all or many of the harmonic frequencies simultaneously.

Reference [11] suggested that THD, THFF and TIF could be calculated with the AC network impedance at values which result in the highest value of that parameter (i.e. in resonance) for say two harmonics; for all other harmonics, the AC network harmonic impedance should be considered as some other, artificial value, for example an open circuit. This methodology has been applied to numerous HVDC schemes, but it is at best an approximation.

Consideration should therefore be given as to whether the specification of such total indices (RSS or arithmetic total harmonic voltage distortion) are actually justified unless there is some meaningful or realistic manner for treating network harmonic impedance at non-resonant harmonics. Should only individual harmonic performance limits (in resonance) be specified, on the basis that in practice total voltage distortion will then be acceptable?

The most theoretically accurate assessments of "total" indices would be provided if the network impedance is modelled (to the extent needed) for each of its many configurations, rather than by an overall envelope, and the harmonic distortion calculated for each, but as it could take substantial time to convert, set up and calibrate such models another approach is proposed below.

For those applications where the specification of total indices is justified, and where the impedance data for each operating condition relating to the impedance envelopes is available, the following method of determining total distortion (of all harmonics) is suggested, based on the specification for the Cross Channel (United Kingdom-France) HVDC link:

1) For each filter configuration, its impedance is calculated at each of the lower order harmonics where resonance is a possibility, and at each of these harmonics a (resonant) point on the impedance envelope is chosen such that the arithmetic sum of the distortion produced by the converter, any SVC and by magnification of pre-existing distortion, is a maximum. Using this method, the harmonic which produces the greatest distortion for a given DC load (or range) may be detected and is termed the resonant harmonic. For this harmonic, the individual contributions from the various sources (converter, SVC, pre-existing distortion, etc.) are added arithmetically unless there is a known, definite phase relationship between these sources.
2) From the various plots of network impedance versus frequency for each of the network configuration cases studied (loading/outages/design year, etc.) which formed the scatter plots, determine that particular case/configuration which has an impedance at the resonant harmonic nearest in value to the envelope impedance calculated in 1) above.
3) The voltage distortion at other harmonics is assessed using the impedance values for the particular network configuration identified in 2) above. In this instance, the components from the various sources can be summed using an RSS relationship.
4) The individual harmonic frequency components as derived above are summed using an RSS relationship to derive the total (RSS) distortion.

This method (or variation on it) might appear complex to put into practice, because the individual network configuration impedance versus frequency data needs to be retained in some form of "look up" table for each network configuration/loading, but it does have the benefit that the resultant calculation of THD is realistic. This is because the network case giving the worst-case resonant harmonic is also used to determine the distortion at all other non-resonant harmonics. Because of the complexity this method entails, its application may not be feasible at the tender stage of a design, rather only at the detailed design stage, post-contract award.

5.5 Harmonic rating evaluation

The pre-existing levels of harmonic distortion together with the manner of their representation can have a significant influence on the harmonic contribution to the filter rating; whichever representation is chosen will inevitably be a compromise between safety and a risk of over-dimensioning the filters.

The earlier practice of applying an arbitrary 10 % or 20 % increase in converter-generated harmonics to allow for the effects of pre-existing distortion can now no longer be considered adequate or realistic, especially for the low order harmonics 3rd, 5th and 7th (see Annex D for an example of problems which have occurred due to use of this approach). Its use for proposed new HVDC schemes is strongly not recommended.

The following subclauses discuss various approaches to the treatment of pre-existing harmonic distortion in terms of determining the steady state rating of AC harmonic filters. The generic circuit model shown in Figure 18 is perhaps most commonly used for the steady state rating evaluation. When Figure 18 is employed as a model for AC filter rating, it relates to the effects of harmonic frequencies only, not to the effects of fundamental frequency which for rating should be considered separately by the application of a voltage source ($U_{f\ 1}$) directly to the AC filter busbar.

5.6 Difficulties with the voltage source/worst network model for rating

5.6.1 Background

In the application of the generic voltage source/worst network model for assessing the effects of pre-existing contribution on rating, as shown in Figure 18, for each harmonic under consideration there is a single value of Z_{sn} from within the specified network impedance envelope which, depending on the relative values of I_{cn} and U_{on} and the specified manner of summation of their relative effects, will lead to a maximum value of U_{fn}, and hence I_{fn}.

It is inevitable that for many designs of AC harmonic filters (especially for those comprising relatively high Q filters) and possibly where the network harmonic impedance characteristics are also adverse, there will be some magnification of pre-existing voltage distortion. This could be under de-tuned conditions for harmonic orders where there is specific filtering provided to cater for the converter characteristic harmonics, or for harmonic orders for which specific filtering for converter characteristic harmonics is not included, for example 3$^{\mathrm{rd}}$, 5$^{\mathrm{th}}$ and 7$^{\mathrm{th}}$ harmonics in an arrangement comprising filters for the 11$^{\mathrm{th}}$ harmonic order and above.

In the past, when using this approach for rating, if the values of pre-existing harmonic voltage distortion specified for rating purposes were relatively low, any high levels of magnification of pre-existing harmonic voltage distortion was not considered unduly costly, when considered relative to the effects of the converter contribution to rating, and the voltage source/worst network approach therefore remained acceptable.

However, more recently the magnitude of specified pre-existing harmonic distortion in Figure 18 for rating evaluation has often been set at either the full planning level or even at compatibility levels. For some schemes, this has resulted in filter designs which are robust but not excessively costly, but for others has given extremely high ratings, which sometimes had to be arbitrarily limited to more realistic values.

In recent years, there has been a trend for certain utilities to need to permit increasingly higher planning level limits and hence also compatibility level limits (this is reflected in the relevant planning standards) due to the significant and sometimes uncontrolled increase in the use of disturbing loads, often of the domestic type. Such a trend has generally been considered acceptable provided there are no adverse effects to other users of the network and a safe margin remains between compatibility levels and immunity levels for connected plant (refer also to Figure 19 and IEC TR 61000-3-6:2008, Figures 1 and 2).

But with such increasingly higher pre-existing levels often now being specified for rating purposes, in some cases arbitrarily chosen to be equal to compatibility levels (this is often the case at the tender stage for the apparent sake of simplicity), the application of the voltage source/worst network approach can result in voltages at the AC filter busbar often then becoming considerably greater than compatibility levels. For example, under such rating conditions, it is possible for a 1 % harmonic voltage distortion level represented behind the network impedance to be magnified to 10 to 20 times at the AC filter busbar. Clearly, such levels would both be intolerable to the network owner, and their resultant effect on filter component rating would also be dominant. It is also likely that such high levels could lead to HVDC inverter commutation failures.

This problem can prove to be particularly difficult at low order harmonics (typically $< 10^{\mathrm{th}}$) where levels of pre-existing distortion are generally greater than at higher frequencies and where the impedance of the higher order filters appears as purely capacitive.

The resultant effect is that, especially for AC harmonic filter components whose rating is predominantly based on harmonic rather than fundamental frequency contribution, for example resistor banks and auxiliary reactors in double/treble tuned type filters, their ratings can become unrealistically excessive (low order filter resistor ratings can readily exceed 1 MW per phase under such a rating assessment), perhaps even to a degree that an alternative design of AC filter configuration is required, solely to achieve reasonable ratings.

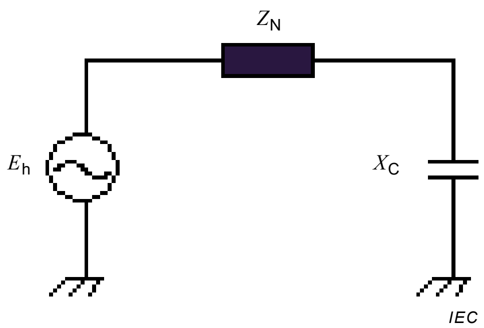
Even for other components where the fundamental frequency is dominant, such as high-voltage capacitors, the increase in cost can be substantial (being approximately proportional to the square of the voltage). Such high component ratings can arise even if it is assumed that resonance between the AC filters and the network impedance only occurs at one or two rather than many or all harmonic orders.

5.6.2 Illustration of the voltage source/worst network method

To demonstrate the amplification of pre-existing harmonics and the effect of the network impedance magnitude and angle, the following numerical examples are shown (see Figure 21).

Example I

- Assume that the harmonic considered, h, is below the tuning frequency of the filter, that is the filter impedance can be taken as approximately jX_C.
- Further assume that the network impedance at that harmonic, $Z_N \cos \Phi + jZ_N \sin \Phi$, is such that $X_C = Z_N \sin \Phi$.
- Then the voltage across the filter will be $\tan \Phi$ times the source voltage, as shown in Table 5 below. The amplification factor increases dramatically with network impedance angle, being around 11 times at 85°and reaching 57 times at 89°.



Key

E_h source of the h^{th} harmonic

Z_N network impedance at the h^{th} harmonic

X_C reactance of a filter with the tuning frequency higher than the frequency of the h^{th} harmonic

Figure 21 – Equivalent circuit of a network for the h^{th} harmonic

Amplification factor $\tan \Phi$ at different network impedance angles is shown in Table 5.

Table 5 – Amplification factor $\tan \Phi$ at different network impedance angles

Φ (°)	45	60	75	80	85	87,5	88	88,5	89
$\tan \Phi$ (%)	100	173	373	567	1 143	2 290	2 864	3 819	5 729

Example II

Figure 22 shows the voltage magnification factor across a sector impedance ($\Phi \leq 85°$) for a typical realistic filter design.

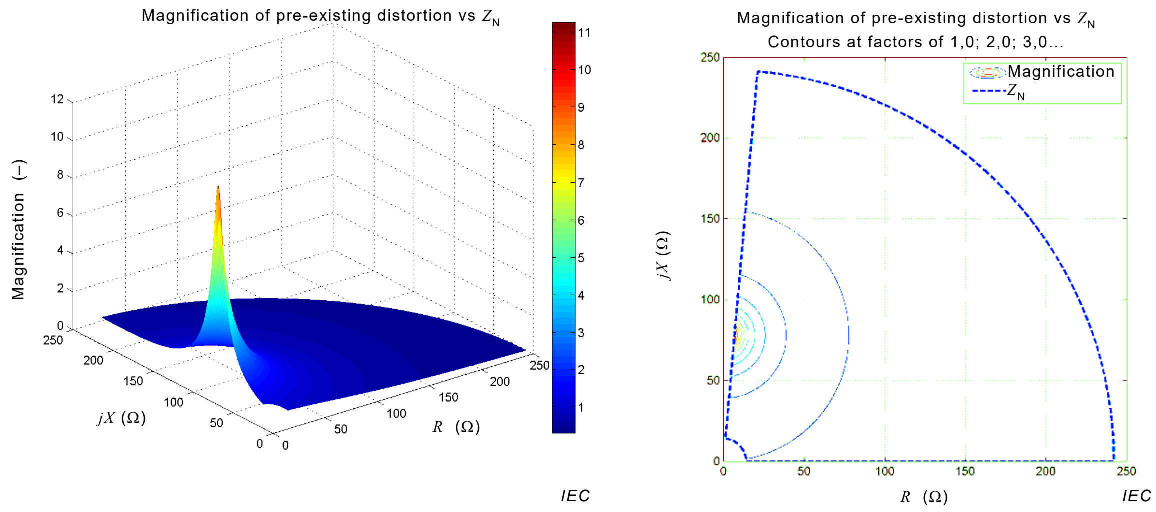


Figure 22 – Typical voltage magnification factor

The examples demonstrate two important factors:

a) the maximum magnification is highly dependent on assumptions (here expressed in terms of the angle Φ);

b) the extreme maximum is, typically, very local.

The conclusions to be drawn from these simple examples are:

- if there is confidence that the assumptions with respect to the network impedance envelope and pre-existing distortion levels are realistic and coherent, then, of course, it is necessary to consider the impact on the filter design and simply accept the additional complexity and cost of a filter design;
- if there is less confidence, for example say that wide frequency bands have been used to determine network impedance envelopes, then the impact on the filter design should be questioned, and the issue examined more closely.

Both examples above demonstrate that the harmonic impedance envelopes are crucial for any filter design and the following additional observations can be made.

1) The first approach should be to carefully review and analyse the frequency scanning study results to ensure that the network impedance being considered in the model is not more severe (wider limits) than is justified, and where possible revise harmonic impedance envelopes or other assumptions. Even so, this step does not eliminate the basic problem, that the assumed source voltage may not be coherent with (i.e. cannot exist under the same conditions as) the worst-case network impedance.

2) The validity of models used to derive harmonic impedance envelopes for higher order harmonics is limited and in view of this a more conservative approach is often used in selecting these envelopes. Consequently, it is probably not representative to use such envelopes for evaluating the impact of background distortion.

3) In evaluating the impact of pre-existing harmonics, not only their magnitude should be considered; distinction has also to be made between harmonics that have positive or negative sequences and those of zero sequence. Much of the pre-existing harmonic content of orders of 3, 6, 9, …, is of zero-sequence and so should only be evaluated using impedance envelopes which are derived for zero sequence harmonics. That is, different envelopes should be used from those derived for converter harmonics (which constitute positive and negative sequences only). Zero-sequence impedance envelopes can be expected to have a significantly different appearance, considering system earthing, increased losses, etc.

Given the problems described with applying the basic voltage source/worst network approach, it is therefore suggested that further calculation procedures may be considered and evaluated. Such alternative approaches are discussed in further detail below. At the tender design stage, the time available may not permit these more detailed procedures to be performed; but where feasible they should be considered during the detailed project design. This of course may lead to difficulties in judging the adequacy of individual bids, and their comparison with each other, in respect of an adequate allowance for pre-existing distortion.

Whatever rating procedure is chosen, it is suitably robust for the life of the plant (i.e. up to 40 years) even catering for future and possibly unspecified changes and developments in the network.

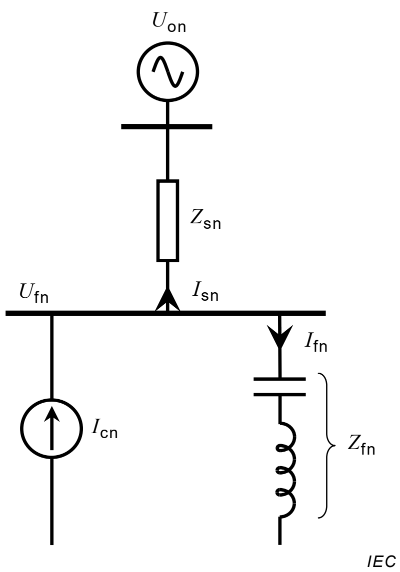
Examples showing impact of pre-existing distortion are considered in Annex E.

5.7 Further possible calculation procedures for rating evaluation

5.7.1 Using measured levels of pre-existing distortion

The following methodology considers the use of measured pre-existing levels of distortion, rather than maximum permitted (e.g. compatibility levels) as the voltage source.

Consider the equivalent circuit shown in Figure 23. This is identical in configuration to that shown in Figure 18 and differs only in that the voltage source U_{on} is set to a voltage distortion representative of levels measured prior to connection of the converter station AC harmonic filters (plus a margin for future growth where this can be reasonably estimated and justified), rather than simply an arbitrary choice of a compatibility level. Such data should be provided at the tender stage, especially for those applications where an "aggregate" type performance criterion is specified.



Calculate value of U_{fn} and compare with compatibility level.

Key

U_{on} measured level plus margin

Figure 23 – Pre-existing distortion set to measured levels (plus margin)

A calculation which also includes the effects of the converter-generated harmonic currents (I_{cn}) should then be undertaken to compare the resultant harmonic voltage distortion at the AC filter busbar (U_{fn}), with compatibility levels. Depending on the magnification factor of U_{on}

and of the contribution due to I_{cn}, the resultant voltage distortion U_{fn} may be lesser or greater than the compatibility level. This is of course synonymous with an "aggregate" performance calculation, but performed under rating conditions. The "performance" requirement in this case however is to compare and comply with a compatibility level target. Some care is also needed in interpreting the results of such calculations for high order harmonics, typically above approximately 20th, because of the possible inaccuracies in both determining the network harmonic impedance and the measuring of pre-existing harmonic distortion at such orders.

If the calculated value of U_{fn} for any DC power range and associated combination of AC harmonic filters, network harmonic impedances, converter generated harmonic currents and AC filter detuning effects applicable to continuous (i.e. steady state) rating conditions is less than the compatibility level, then the design should be considered satisfactory.

However, if the calculated U_{fn} does exceed the compatibility level at the AC filter busbar, and if this is also the point of common coupling with other consumers, the network owner may not permit this given his responsibility to other consumers.

Compatibility levels are generally based on either 99 or 95 percentiles and can therefore be exceeded for short periods of time. Thus under conditions for example of short time duration frequency excursions beyond the normal continuous values, and for which the AC harmonic filters remain connected, it is quite feasible, and permissible, for the value of U_{fn} to exceed the compatibility level, but it does not exceed the immunity level.

Therefore, if the calculation does give rise to harmonic voltages in excess of compatibility levels under continuous (steady state) rating conditions by virtue of the effects of excessive magnification factors of pre-existing distortion, one should first question and check whether such a filter design is satisfactory. If the filter design is reasonable, and cannot be improved without excessive added cost, then the validity of the assumed network impedance should also be examined. For example:

- Are the resonant network impedance values (Z_{sn}) consistent with the specified pre-existing distortion voltage levels, or does the technical specification simply give the non-consistent worst cases for each (refer also to 5.3.3 above)?
- Does the design also satisfy the specified performance requirements, especially where an "aggregate" criteria distortion is specified (refer to 5.3.3 above)?
- If it does, what are the differences between the performance and rating criteria especially in respect of network impedance and pre-existing distortion levels?

This should therefore become an important checkpoint during the calculation of AC harmonic filter rating. For those applications where only an "incremental" performance criterion is specified, such a problem with magnification of pre-existing harmonic distortion will only become apparent once such a rating study is performed.

Even if the resultant value of U_{fn} is less than the compatibility level it may also be prudent to consider the effects on the AC filter rating should the levels of distortion at the AC filter busbar eventually rise to compatibility levels, due to say increases in pre-existing distortion; this is of course something the network owner could legitimately permit (see also 5.7.3).

The acceptability of this checkpoint during the calculation of AC harmonic filter rating is of course dependent on the network owner ensuring that the harmonic voltage distortion levels at the point of common coupling do not exceed compatibility levels not only at the time of connection of the HVDC link but for all future operating conditions. This is probably a valid assumption for mature and strongly interconnected networks but may not be so for rapidly developing networks. In such latter instances, it would be wise to include a margin on the specified value of U_{fn} in excess of compatibility levels to cater for future unspecified conditions. Such a voltage is lower than immunity level and its choice would be project dependent and would be a balance between cost and security. For example, in certain areas of China during the development of their first 500 kV AC network, third harmonic voltage distortion levels reached a maximum value of 4 % at periods of light load/high system voltage due to grid supply transformer saturation; such levels were substantially in excess of compatibility levels, but lower than immunity levels.

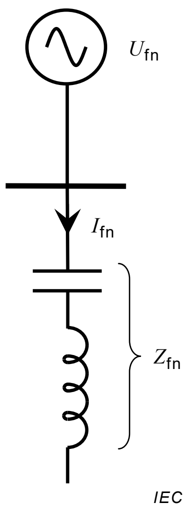
The use of this checkpoint is only relevant for those applications where the busbar to which the AC harmonic filters are connected is also point of common coupling type busbar and hence under the responsibility of the network owner. The application would be unsuitable for those types of HVDC link whose AC harmonic filters are either connected to an MV busbar (e.g. on a transformer auxiliary winding) which is not under the control of the network owner, or for example a back-to-back HVDC scheme which is connected to the AC networks by dedicated single AC lines, where the AC filter busbar is generally not the point of common coupling with other consumers.

A numerical illustration of this method is given in Annex F.

5.7.2 Applying compatibility level voltage source at the filter busbar

An alternative and simpler approach to considering the effect of pre-existing harmonics on filter rating would be to apply the voltage source, set to compatibility levels, directly at the filter busbar that the network owner is responsible for maintaining, regardless of any interaction with the HVDC installation. Compared to the method in 5.7.1, it therefore ensures some margin for future network operating conditions.

The equivalent circuit for this simpler rating approach is shown in Figure 24. There is no requirement to represent the converter or the network harmonic impedance, and the voltage source U_{fn} is simply set to the compatibility level. Hence there is no need to consider any additional amplification between the AC network harmonic impedance and the AC filters.



Key

U_{fn} compatibility level

Figure 24 – Pre-existing distortion applied directly at the filter bus

The application of this simpler equivalent circuit may be reasonable for AC filter designs comprising damped type filters (low q factor) but it is inappropriate for those comprising sharply tuned type filters (high q factor), which will draw extremely high currents using this model. This is unrealistic because in general for an application employing single frequency tuned filters, even when considering operation at the extremes of their (continuous) detuning range, the resultant magnification factor of pre-existing distortion at their tuned harmonic order can be significantly less than unity. It is extremely unlikely that for sharply tuned types of filters, when the filter is perfectly tuned, such a high harmonic voltage distortion equal to the compatibility level at the filter busbar could actually occur, as the harmonic current required to be drawn from the network would be unfeasibly high.

An example of this is shown in Table 6 (based on a simple AC filter configuration and parameters discussed in 4.6.2 and Table 4). This demonstrates that if a fixed value of distortion (equal to compatibility level) of U_{fn} is applied at the filter busbar for a sharply tuned filter, the resultant filter current – when perfectly tuned – can be unrealistically high.

Table 6 – Variation of calculated filter harmonic current as a function of detuning

Case[a]	Filter impedance (Z_{fn}) at 13th harmonic	U_{on} (compatibility level) at filter busbar	I_{fn} (13th harmonic current) in filter
Filter on tune	0,46 + j0 Ω	1,0 %	2 761 A
Filter detuned capacitively by 2 %	0,46 – j1,91 Ω	1,0 %	646 A

[a] Refer to 4.6.2 and Table 4 for definitions.

Another argument against applying pre-existing voltages directly on the filter bus is to ask, what would be the impact if this methodology were applied to other non-HVDC filter equipment? For example, what if the indicative planning levels of IEC TR 61000-3-6 were applied to a standard shunt capacitor. Figure 25 gives the consequent increase in voltage rating, which is up to about 28 % in a HV or EHV system, which equates to an extra 64 % in installed capacitor units. The corresponding harmonic current in the same shunt capacitor would be about 85 % of fundamental frequency rated current. It could also be questioned whether other equipment is designed to withstand such harmonic voltage levels, for example CVTs or any such equipment where dielectric stresses are critical. If this approach is not used for such equipment (and generally it is not), then it would appear inconsistent to use it for HVDC filter applications.

This method has however frequently been used for SVC applications, where there is a transformer impedance between the applied source voltage and where the low-voltage filter is located, thus preventing the excessive currents illustrated above.

A numerical illustration of this method is given in Annex F.

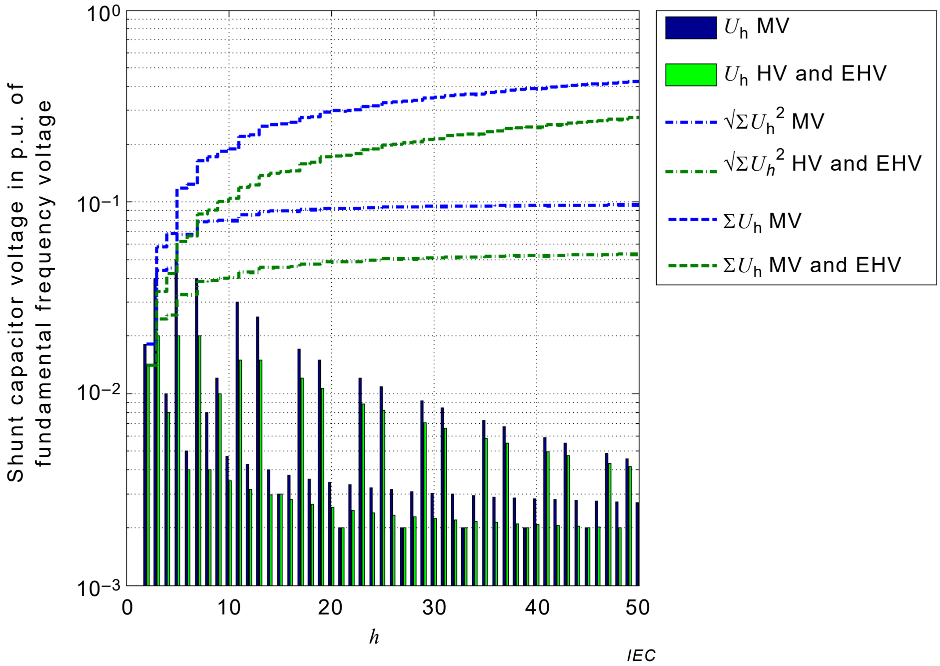


Figure 25 – Harmonic voltage stress on a shunt capacitor with IEC planning levels applied

5.7.3 Limiting the filter bus harmonic voltage to a maximum level for filter rating (MLFR)

So far, 5.7.1 and 5.7.2 have shown that there can be considerable uncertainty in the evaluation of the impact of pre-existing harmonics on the AC filter solution, in particular its rating. It is of course desirable, where possible, to remove or limit such uncertainty. But where that is not possible, the following procedure may be considered to limit the impact on filter rating and consequent cost of such uncertainty.

This is not to be seen as a firm recommendation, but as a suggestion which may be considered jointly by the customer and contractor.

Although the suggested limitation algorithm may appear complicated, it should in fact be easy to include in the calculation software of any HVDC supplier. The small additional effort in doing these calculations can be worthwhile in avoiding excessive and expensive component ratings.

It is assumed that the defined method of rating filter components for the contribution of pre-existing harmonics is to use a voltage source behind the worst-case network impedance. It is also assumed that the filter design for performance purposes has already been determined, and by whatever reasoning (as discussed in Clause 5) has been deemed satisfactory in terms of amplification of pre-existing harmonics.

Then, if an individual harmonic voltage on the filter bus, under rating conditions, due to pre-existing harmonics, is calculated to be significantly higher than the compatibility level (or other applicable limit), it may be that the calculation is simply unrealistic, possibly due to the use of inconsistent source voltages and network impedances, which is usually the case in the application of this model.

In reality, operation of the HVDC converter station would not be permitted with harmonic distortion considerably above the applicable limits. Whilst some excess may be allowed temporarily, extremely high levels would not be permitted. There is therefore no point in rating filter equipment for such excessive levels.

The maximum individual harmonic voltage level at the filter busbar, due to pre-existing harmonics, for which equipment is to be rated, can therefore be limited to some chosen ceiling, above which it is judged that continuous operation would anyway not be permitted. We will refer to this as the maximum level for filter rating (MLFR).

The algorithm to implement this would be as follows:

- during the filter rating calculations, also calculate the corresponding individual voltage distortion at the filter busbar due to the pre-existing harmonics (as discussed in 5.7.1);
- if such an individual harmonic distortion exceeds the MLFR, then calculate the component stresses due to the pre-existing harmonics for that harmonic using the MLFR applied on the filter busbar, rather than the values obtained by the initial calculation;
- these stresses are then added to the calculated stresses due to the converter harmonic generation (this may be optional – see discussion below).

In other words, calculate using the voltage source/worst network method, but limit the filter stress due to pre-existing harmonics to that which would result from the MLFR harmonic voltage level being applied at the filter bus.

The distortion levels selected for the MLFR may take into account the consequence for the particular HVDC project of the filters tripping (i.e. if the MLFR has been chosen too low and filter rating were to be exceeded on occasions in practice), the cost of filter rating, and the normal standards of harmonic distortion control to be expected on that particular AC network.

The chosen level of MLFR may be imposed by the technical specification, or could be proposed by a contractor. It is suggested that 2 × compatibility level would be a suitable limit, but different levels could be appropriate for different projects. Indeed, different relative levels may be appropriate for different harmonics, for example, an MLFR = say 2 × compatibility level may be suitable for h3, but MLFR= say 1,2 × compatibility level for h11 where a tuned filter may be present.

As the chosen MLFR only affects the filter rating, it needs only be agreed between the HVDC customer and contractor, with no reference being necessary to the network owner or regulator (except perhaps in view of possible implications for the reliability of the HVDC system).

It should be understood that this method does not guarantee successful operation of the filters in the presence of background harmonics. If, for whatever reason, resultant distortion levels due to the pre-existing harmonics in excess of the chosen MLFR did occur, then filters would trip on overload; but at such distortion levels continued operation would anyway have been unacceptable or even impossible. The MLFR limitation is simply a means of limiting filter rating to be coherent with maximum operable levels of AC system harmonic distortion.

Finally, note that in the proposed algorithm as stated above, any contribution from the converter to the distortion level is added on top of the MLFR. An alternative approach would be to define the MLFR to include both pre-existing and converter contributions. This would perhaps be more logical in that the concept of MLFR is based on the maximum total realistic distortion level which could be tolerated, which naturally includes both contributions. On the other hand, it might be considered that the contractor should be fully responsible for the converter contribution, with only the pre-existing contribution being subject to limitation. The choice of approach is left to the user to determine.

A numerical illustration of this method is given in Annex F.

5.7.4 Limiting total source distortion to the defined THD

This approach can be used together with any of the above three methods.

In certain International Standards which define emission limits for disturbing installations (e.g. IEC TR 61000-3-6), the quadratic sum of all individual harmonic voltage distortions substantially exceeds the specified THD.

When such pre-existing distortion levels are specified, the filter ratings consider the maximum levels of the individual harmonics which most affect them. But it is unrealistic and excessive to consider the maximum levels of all harmonics simultaneously when this would imply a total exceeding the specified source THD. The problem is – which harmonics to select at their maximum values, and which to limit or ignore?

The following suggested algorithm ensures that the sum of the contributions to the rating of each component uses the maximum contribution of the worst-case harmonics for that component, while not exceeding the maximum source THD.

The terms "source" harmonics and THD below normally apply to the voltage source behind the network impedance. However, it can also be applied if the methodology used applies the source voltage directly at the filter bus, as in 5.7.3.

For <u>each individual stress</u> (voltage, current) to be calculated for <u>each equipment</u>:

- calculate the stress at each individual harmonic as usual with the voltage source set to the applicable individual harmonic limits;
- sum the harmonic stresses, starting with the largest contributing harmonic and continuing until the total quadratic sum of the corresponding source harmonics reaches or passes the THD limit. Use only these harmonics in defining the rating for that item of equipment, and discard all remaining harmonic contributions;
- finally add the converter harmonic contribution to complete the component rating.

The above algorithm therefore conforms completely to the specified requirements while limiting excessive component ratings. A similar variant would be to not eliminate some harmonic contributions, but to reduce the magnitude of all except the largest. This variant would be slightly more complicated to execute and would give no clear advantage.

A possible extension of the above can be used if further arbitrary but reasonable assumptions about the typical composition of the pre-existing harmonic source voltages are made for example as follows (remembering that these are RSS totals):

- that all harmonics other than 3, 5 and 7 account for at most say 70 % of the THD limit (e.g. at most 2,1 % where THD = 3 %);
- that of these, harmonics $n \geq 15$ account for at most say 50 % of THD limit (e.g. 1,5 %).

These factors can then also be taken into account in the summation of harmonic stresses, and when either of these limits for the corresponding source harmonics is passed, then no further harmonics in that category are included in the specified stress for that equipment.

The limits of 70 % and 50 % quoted above are suggested values and may be adjusted by the customer in view of experience of the pre-existing harmonics of the particular AC network under consideration. They are probably conservatively high for most typical AC systems.

This extension can be valuable especially when dealing with higher order tuned filters where otherwise a large number of unrealistically high pre-existing contributions at high order harmonics can contribute significantly to calculated stresses.

A numerical illustration of this method is given in Annex F.

5.7.5 Limiting harmonic order of pre-existing distortion

Another option for restricting possible unrealistic impacts of pre-existing harmonics is to use the voltage source/worst network model but consider only low order pre-existing distortion harmonics, for example up to 10th, with or without a limitation in line with Clauses 3 and 4. Then to allow for higher order harmonics, a margin is applied to converter-generated harmonic stresses at those higher harmonics, typically 10 %.

Such a method may have its shortcomings and can be perceived as arbitrary, but it provides a reasonable compromise as it

- allows for low order harmonics to be fully considered, which is important as these pre-existing harmonics are high in many AC system, and
- will not unduly penalise a filter design at characteristic harmonics, that is, it provides flexibility to allow for both sharply or broadly tuned branches.

A 10 % margin is of course arbitrary but it actually implies a reasonable design margin. To illustrate this, increasing a characteristic harmonic by 10 % is actually comparable with adding a pre-existing contribution of about 46 %, assuming quadratic summation of converter and pre-existing harmonics.

A numerical illustration of this method is given in Annex F.

5.8 Conclusions

The effects of pre-existing harmonic voltage distortion are crucially important in determining the performance and rating of the AC harmonic filters, and therefore their correct assessment and interpretation are vital. The customer and the network owner need to carefully specify these levels and clearly state how they shall be used. The technical specification also needs to state clearly how the converter and pre-existing harmonics should be summed for rating and, where relevant, performance evaluation.

The choice of values of pre-existing distortion set arbitrarily to levels equal to compatibility levels behind a resonant network impedance in the determination of filter rating may initially appear to be a robust methodology; it may however lead to levels of harmonic distortion at the AC filter busbar greater than those compatibility levels because of magnification effects. Alternative calculation approaches are described and assessed. Ultimately however, there is no perfect solution and an intelligent engineering approach is required by all parties, taking into account the particular circumstances of the project both in purely technical terms and also considering the economic factors and the consequences of risk.

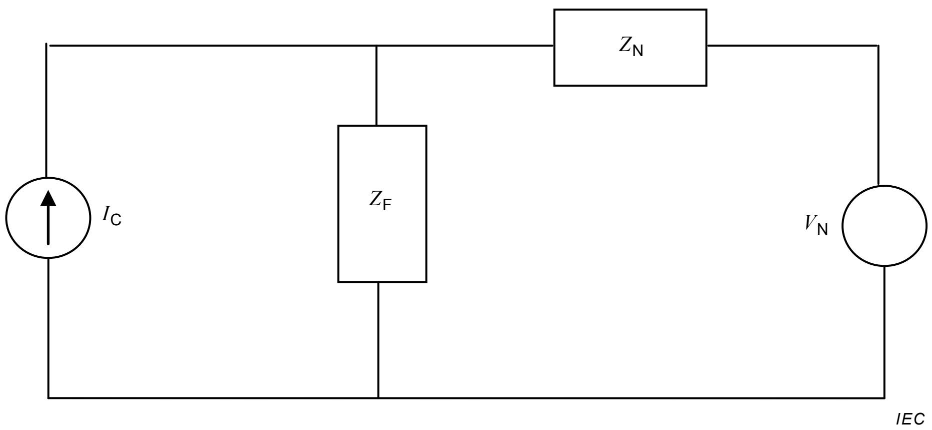
Annex A
(informative)

Location of worst-case network impedance

When discussing worst-case network impedances with regard to filter design, the question often arises of whether that worst-case impedance can occur within the bounding envelope, or whether it should lie on the perimeter. Proofs of this can be hard to find in the literature, and so the following is included here for reference.

From the equivalent circuit showed in Figure A.1, where the HVDC converter is represented by a harmonic current source and pre-existing distortion is represented as a voltage source behind the network harmonic impedance, this annex demonstrates that to obtain the maximum injected harmonic current into the filter (I_F), it is necessary and sufficient to only consider the perimeter of the network impedance envelope rather than the entire envelope.

A similar demonstration can be applied to determine the maximum voltage at the filter busbar (V_F) by using an admittance rather than an impedance envelope.



Key

I_C injected harmonic current from converter

Z_F filter harmonic impedance

Z_N AC network harmonic impedance

V_N pre-existing Thévenin harmonic voltage source

Figure A.1 – Equivalent circuit model for demonstration of worst-case resonance between AC filters and the network

The filter current I_F is given by:

$$I_F = I_C \cdot \frac{Z_N}{Z_F + Z_N} + \frac{V_N}{Z_N + Z_F} \tag{A.1}$$

Defining the term Z_H for mathematical convenience as:

$$Z_H = \frac{V_N}{I_C} \tag{A.2}$$

then:
$$I_F = I_C \cdot \frac{Z_N + Z_H}{Z_N + Z_F} \tag{A.3}$$

To maximize I_F and also V_F, $Z_N + Z_H$ is maximized and $Z_N + Z_F$ is minimized.

It can be demonstrated that the minimum distance between $-Z_F$ and Z_N corresponds to the minimum value of the denominator of the equation.

Since, to find the maximized calculated distortion, the phase angle of the voltage source and the phase angle of the current source are set to the worst values (arithmetic addition of the contributions of converter current and pre-existing distortion), Z_H has the same phase angle as Z_N in order to maximize the numerator of the equation. Then, Z_H being a constant, maximizing Z_N will maximize the numerator.

Figure A.2 shows the different vectors with a circle as an impedance envelope. Taking any network impedance with a constant impedance magnitude Z_N (dotted circle around the origin), it can be shown that the value inside the envelope which minimizes the distance between $-Z_F$ and Z_N lies on the perimeter. This will be also true for any Z_N value between the minimum R and the maximum R within the envelope and for any other envelope shape.

The methodology is equally applicable for AC harmonic filters that are electrically "distanced" from the impedance envelope, with an intervening impedance, for example for AC filters connected to the converter transformer tertiary winding and also for those applications including series connected AC harmonic filters.

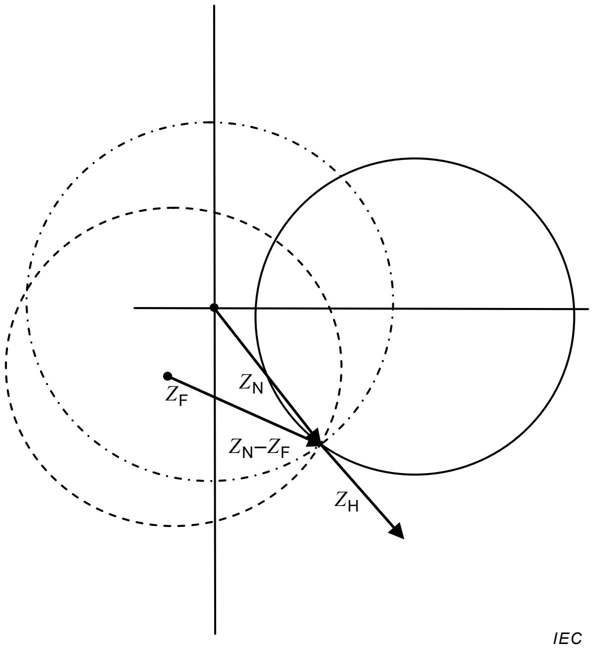


Figure A.2 – Diagram indicating vectors Z_F, Z_N and Z_H

An alternative algebraic demonstration is shown below:

Assuming that in the vector relation:

$$I_F = I_C \cdot \frac{Z_N + Z_H}{Z_N + Z_F} \tag{A.4}$$

The only variable quantity is Z_N, therefore it is possible to describe the maximum amplitude of I_F as:

$$\left|I_F\right| = \left|I_C \cdot \frac{Z_N + Z_H}{Z_N + Z_F}\right| = \left|\left|I_C\right| \cdot \frac{\left|Z_N + Z_H\right| \langle Z_N, Z_H \rangle}{\left|Z_N + Z_f\right| \langle Z_N, Z_f \rangle}\right| \quad \text{(A.5)}$$

Since the phase of I_F is unnecessary, we can rewrite:

$$\left|I_F\right| = \left|\left|I_C\right| \cdot \frac{\left|Z_N + Z_H\right|}{\left|Z_N + Z_F\right|}\right| \quad \text{(A.6)}$$

In all possible values for the sum of the vector Z_N and Z_H, the maximum amplitude is obtained when Z_N and Z_H are in phase, then

$$\left|Z_N + Z_H\right| = \left|Z_N\right| + \left|Z_H\right| \quad \text{(A.7)}$$

Remembering that Z_N is the only variable quantity, the variation of amplitude of I_F is described by:

$$\left|I_F\right| \propto \left|\frac{\left|Z_N\right|}{\left|Z_N + Z_F\right|} + \frac{\left|Z_H\right|}{\left|Z_N + Z_F\right|}\right| \quad \text{(A.8)}$$

Therefore, for a circle of Z_N radius around the origin, the maximum value of the first term is obtained when the sum of Z_N + Z_F is a minimum. It has already been demonstrated that this minimum value is obtained when Z_N is on the perimeter of the impedance envelope.

Annex B
(informative)

Accuracy of network component modelling at harmonic frequencies

B.1 General

Subclause 4.3.5 discusses the importance of correctly modelling and representing the frequency dependence of the various power network elements (overhead lines, cables, generators and transformers, etc.) for determining the resultant network harmonic impedance.

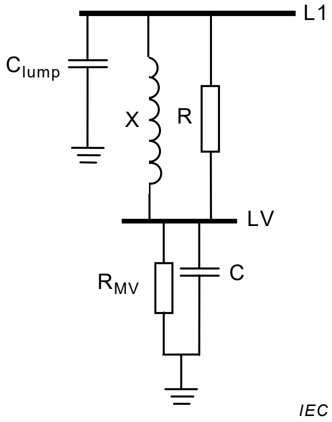
Numerous textbooks, papers and documents produced by CIGRE and IEEE propose different harmonic models for network components. References are included to a number of these. Various other variants are in use by different utilities, consultants and manufacturers. It is beyond the scope of this document to make a comprehensive review of these, or to compare their merits. It is apparent, however, that the origin of some formulae and recommendations have been lost over time and in repetition and it is not now possible to verify their justification.

This annex is therefore limited to giving some guidance on possible modelling techniques which are not widely covered in the literature and also indicating some areas of weakness in current practice.

B.2 Loads

In order to restrict the network model to a manageable size, loads are represented by equivalents located at suitable buses, as discussed in 4.3.5. The distribution load model may differ substantially between distribution networks using the "central delivery" concept, used in Europe and elsewhere, and the "local delivery" concept used in North America and in parts of Asia. In the central delivery concept, the MV network has limited extent and complexity, relatively large distribution transformers are used, and LV networks are extensive. In the local delivery concept, the MV network is extensive and reaches close to every consumer load. Small distribution transformers are used and the LV network is extremely limited.

Figure B.1 shows an example of a typical equivalent load network as used in the United Kingdom. Caution should be exercised regarding the applicability of such equivalent models on a generic and world wide basis as the method of connection of domestic consumers to their utility/distribution (MV) network can vary significantly country to country simply by virtue of the geographic constraints.



Key

L1	supply bus
LV	Low voltage load bus
C_{lump}	lumped capacitance
X	lumped transformer reactance
R	damping resistance
R_{mw}	resistive MW load
C	LV capacitance

Figure B.1 – Typical equivalent load network

In its simplistic form, the model includes lumped capacitance (C_{lump}), representing the total cable capacitance at the supply bus L1, a lumped transformer reactance (X) along with a damping resistance (R), representing all of the transformers between the supply bus and LV connected customers. The LV bus then is represented by a parallel combination of resistive MW load (R_{MW}) (predominately heating and lighting) and LV capacitance (C) to include power factor correction capacitance in the load and 400 V to 415 V cable capacitance. The choice of values for C_{lum}, X and C depend on the maximum permitted MW load as seen at the supply bus and topology of the network and load composition. The load composition and its degree of power factor correction will depend on whether the load is domestic, agricultural, commercial, commercial/domestic, industrial, lighting or traction, etc.

Where loads have a significant motor component, a series resistance and inductance can be added to the network of Figure B.1 in parallel with C and R_{MW}. Note that the real power flow into a motor at fundamental frequency does not constitute an equivalent resistance valid for harmonic modelling; a motor should be represented at harmonic frequencies by its subtransient reactance plus a resistive element equivalent to its losses.

The choice of supply bus voltage level to which to apply the use of an equivalent network depends on the proximity of that particular busbar to the busbar for which the network impedance is being assessed (which is typically the converter station AC busbar). For supply busbars close to the point of interest, it is usual practice to model the MV distribution network in greater detail in terms of representing specific voltage levels. For busbars remote from the point of interest, it is not normally necessary to represent all distribution voltage levels, and a more simplified equivalent at a higher voltage level will suffice. The more detailed the model becomes, i.e. in that further voltage levels are included, the more accurately the various actual load resonances will be represented. This will help to avoid the transformation of unrealistic series and parallel resonances between the various simple inductive and capacitive components within the equivalent load representation appearing at the transmission voltage level. The definition of whether a busbar is to be regarded as "remote" or "close" in terms of whether to represent the distribution network in detail or not may be determined by sensitivity calculations (i.e. comparing the effects in change of network impedance characteristic at the HVDC converter station busbar as a function of variation in load model complexity).

For example, take a network whose EHV voltage levels are 400 V and 275 kV with associated distribution voltage levels of 132 kV, 33 kV and 11 kV (typically, and as employed in the United Kingdom) and it is intended to calculate the network harmonic impedance at a particular 400 kV busbar (denoted as HVDC bus 1). The complete 400 kV, 275 kV network and the complete 132 kV distribution network in the vicinity of HVDC bus 1 would be modelled and down to the 33 kV level (or sometimes lower), including any 132 kV and 33 kV connected reactive compensation as discreet elements. The load model as shown in Figure B1 is then applied at each relevant 33 kV node (in this case L1 is thus at 33 kV level) with local capacitance in the form of either cable capacitance or power factor correction capacitance, and distribution transformers and loads being accurately represented (in terms of their effects on resonant frequencies, etc., as seen from HVDC bus 1). However, for 132 kV nodes electrically remote from HVDC bus 1, generally those not within the distribution network local to HVDC bus 1, it is considered sufficiently accurate to apply the Figure B.1 load models at 132 kV or even 275 kV (in which case L1 becomes 132 kV or 275 kV as applicable).

In North America, where the “local delivery” distribution design is almost universally applied, the MV distribution feeders are far too complex to feasibly model in detail for a transmission-oriented harmonic impedance analysis. It is usually deemed sufficient to model such distribution networks by an equivalent model connected to the MV terminals of the primary distribution substation transformer.

The load model previously shown in Figure B.1 can still be used to represent a typical ”local delivery” type of distribution network. However, the elements correspond to different parts of the network. When used with local delivery networks, the load model should be applied at the MV bus of each distribution substation. A series R-L should be placed in parallel with R_{MW} to represent the subtransient reactance and winding resistance (losses) of induction motors on load buses. R_{MW} should only represent the portion of the load that is resistive in nature, i.e. loads other than motors. C represents power factor correction applied directly at the loads. In North America, LV power factor compensation tends to be only present at larger commercial and industrial loads where reactive power demand is metered. Most power factor compensation is applied at the MV level on the feeders, or at the MV bus of the distribution substation, and is modelled by C_{lump} in Figure B.1. X represents the inductive reactance of the MV distribution feeders and the distribution transformers. R provides the appropriate frequency-dependent damping of this series impedance branch.

As a further example, resulting from a study recently performed in China relating to the assessment of harmonic voltage distortion for the planning of a 500 kV network, the aggregate load model [26] was employed. This arose because of the absence of detailed data regarding the network downstream of the 500 kV/220 kV transformers, other than simple planning load data. The results were somewhat surprising in that the total harmonic voltage distortion was as high as 20 % and in some instances reached 30 %, especially on the boundaries of the 500 kV network. This phenomenon was also verified using a further network calculation with the network downstream of the 220 kV busbars represented by simple load models – this too resulted in very high levels of THD. However, in practice, the measured values of THD on the actual 500 kV network was under 3 %. This implies that the load model in [26] should be used carefully, and as discussed above should not be applied to the nodes near the busbar concerned, because its resultant impedance is always inductive and increasing linearly with frequency, and will hence resonate with the remainder of the network under consideration at either one or several harmonic frequencies. The network downstream of each HV and MV distribution busbar network close to the point of interest should therefore be represented in as much detail as possible and presented if required as an envelope similar to Figure 6.

To conclude, the proposed employment of a universal and generic harmonic load model should not be undertaken without due consideration, especially when close to the busbar of concern because each downstream network is different and the load components (including their composition) are also quite different.

B.3 Transformers

B.3.1 Transformer reactance

The reactance of existing transformers should be accurately known because they are subjected to routine tests and measurements. The tolerance on the nominal reactance of a new transformer is typically ±7,5 % for two winding transformers with an impedance greater than 2,5 % on rating impedance and ± 10 % for autotransformers according to International Standards. The reactance of duplicate transformers produced by the same manufacturer should also not deviate more than 7,5 % for transformers and 10 % for autotransformers.

The transformer reactance varies also significantly with the tap position. [27] shows that, depending on winding arrangements, the reactance variation over the entire tap range can be very large, in the order of 40 % and more.

The transformer tap position will also affect the impedance of the network seen from either side of the transformer. That impedance varies with the square of the turns ratio. A typical tap changer range is ±15 %, which translates into a possible impedance error of around ±30 %. This error can obviously occur at both fundamental and harmonic frequencies. Programs employed to derive network harmonic impedance without performing a prior load flow or transferring the tap position from a load flow where the solution has been obtained may therefore introduce significant errors. The effect of neglecting to account for the correct transformer tap position is most significant for those transformers electrically close to the busbar of concern; the effect on network impedance of transformers remote from the busbar of concern is generally less so.

B.3.2 Transformer resistance

B.3.2.1 General

The variation of network component resistance with frequency is particularly important in determining the damping of the network at harmonic frequencies. Whilst certain data regarding this aspect in respect of overhead lines and cables exists, there is a noticeable lack of data with respect to transformers. Caution should be exercised in applying certain transformer resistance frequency-dependent models across the entire spectrum of harmonic frequencies to be studied (say n = 2 to 49) because they can often give insufficient damping at low order harmonics and excessive damping at high order harmonics or vice versa.

The transformer loss is also accurately measured during routine tests; however, it can vary significantly with the effects of frequency variation and temperature. Transformer losses also vary depending on when the transformer was constructed and the relative cost of energy losses compared to capital cost at that time.

B.3.2.2 Frequency variation

Reference [27] describes a recommended model for converter transformer losses. As illustrated in Figure B.2 below, however, it does not provide a suitable model for losses at harmonic frequencies.

Reference [28] gives an equation relating the losses to frequency for a converter transformer:

$$P_{\mathrm{n}} = I^2 R_{\mathrm{dc}} + P_{\mathrm{s}}[Wn^q + (1-W)n^p] \tag{B.1}$$

where

n is the harmonic order;

P_n is the load loss at n^{th} harmonic;

W is the winding stray loss as a fraction of the total stray loss at 60 Hz;

$1 - W$ is the other stray loss as a fraction of the total stray loss at 60 Hz;

P_s is the total stray loss at 60 Hz.

For the particular transformer analysed:

W = 0,25

q = 1,9

p = 1,4

[29] gives additional information regarding these parameters for normal (rather than converter) power transformers:

W varies between 0,25 and 0,38 depending on the tap position ([29], Table VI,

q = 2, winding eddies loss ratio of 0,694 ([29], Table II)

p = 1 or 1,4 (without and with magnetic tank shunts)

From normally available test reports, it is usually only possible to obtain the total fundamental frequency load loss and I^2R loss. Assuming a ratio of 75 % of I^2R loss to the total loss, we can obtain the extreme equivalent resistance R_n values (corresponding to load loss P_n at n^{th} harmonic) with the following sets of equation parameters:

Minimum R_n with W = 0,25, q = 1,9 and p = 1.

Maximum R_n with W = 0,38, q = 2 and p = 1,4.

Applying this to a notional 100 MVA transformer with a reactance of 12 % on rating and a tan ψ (X/R) of 32, we obtain the possible error compared with that derived from the recommended model according to [27]. From Figure B.2, the error can be seen to be quite significant throughout the complete range of interest.

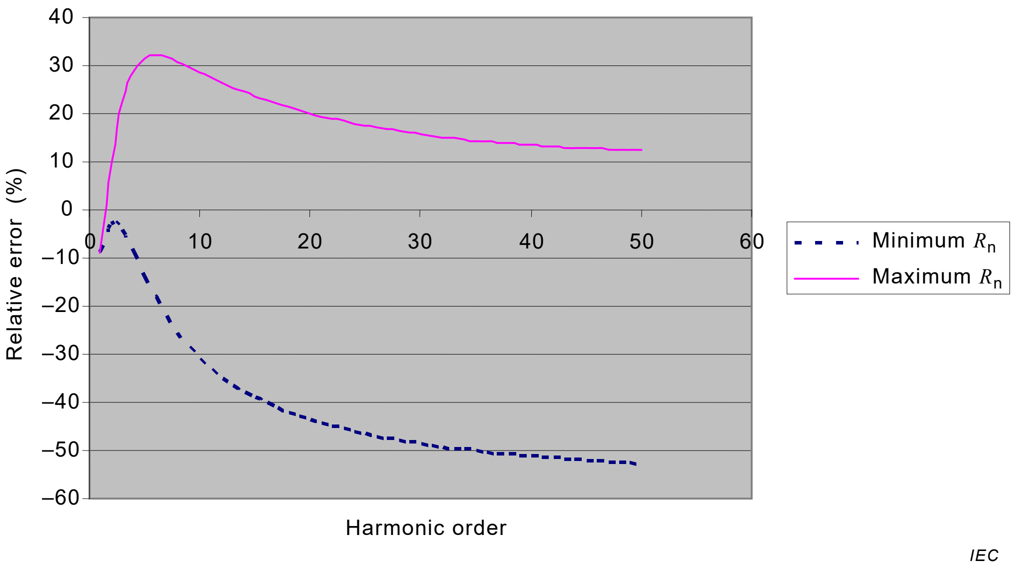


Figure B.2 – Relative error of equivalent load loss resistance R_n of using [28] compared with Electra 167 [27] model

As highlighted above, there is uncertainty regarding the provision of adequate and reliable data for transformer resistance variation as a function of harmonic frequency; it is therefore recommended that the variation of network harmonic impedance due to such effects is assessed firstly by assuming that there is no variation of transformer resistance with frequency (i.e. values set at fundamental frequency value) and secondly by varying the transformer resistance with harmonic frequency by the particular method chosen. Comparison of the results from the two methods (in particular the magnitude of the radius of major and minor impedance resonant loops) will then determine the sensitivity of the calculated network impedance to transformer damping at harmonic orders and hence the need or otherwise to refine the damping modelling techniques. It is often the case that transformers close to the busbar of interest have a more significant influence than those at a remote point.

B.3.2.3 Temperature variation

International standards (e.g. IEEE Std C57.12.90-1999) describe the variation of transformer loss with temperature:

$$P_{\mathrm{r}} = P_{\mathrm{rc}} \cdot \frac{T_{\mathrm{k}} + T}{T_{\mathrm{k}} + T_{\mathrm{m}}} \tag{B.2}$$

$$P_{\mathrm{s}} = P_{\mathrm{sc}} \cdot \frac{T_{\mathrm{k}} + T}{T_{\mathrm{k}} + T_{\mathrm{m}}} \tag{B.3}$$

where

P_{r} is the resistance loss at temperature T;

P_{s} is the stray loss at temperature T;

P_{rc} is the calculated resistance loss at temperature T_{m};

P_{sc} is the calculated stray loss at temperature T_{m};

T_{k} is 234,5 for copper;

T_{k} is 225 for aluminium.

Figure B.3 gives loss as function of temperature, according to the equations above. It can be observed that the temperature has a relatively low effect on resistance. As the temperature of each transformer is not known anyway, the loss value without temperature correction can be used without a significant impact on accuracy.

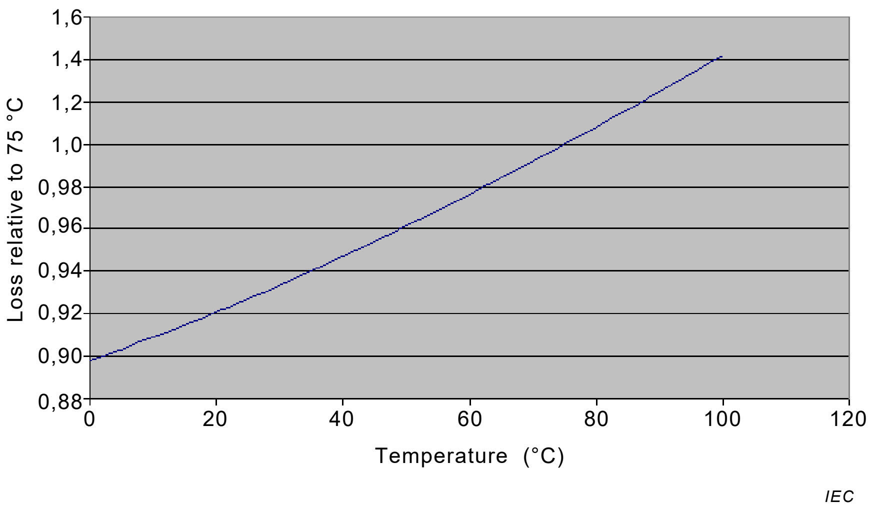


Figure B.3 – Effect of temperature on transformer load loss

B.4 Transmission lines

The damping introduced by transmission lines and cables can be highly influential in determining the overall damping of the network impedance envelope, and has been the subject of much discussion.

The following approach, which is employed in the UK and by some other utilities, applies the following formulae and correction factors for skin effect. These are based on research performed in the UK by CEGB and CERL during the 1970's and assume various standard conductors. They are offered for information only, as it was not possible to locate the original derivation of these formulae and therefore it is not possible to determine their relevance to different line, conductor and bundle types or more modern cables. The resistance at the nth harmonic, R_n , is given in terms of the fundamental frequency resistance R_1:

1) 400 kV or 275 kV lines

$$R_n = R_1\left(1{,}0 + \frac{3{,}45n^2}{192{,}0 + 2{,}77n^2}\right) \quad \text{for } 1{,}00 \le n < 4{,}21 \tag{B.4}$$

$$R_n = R_1(0{,}806 + 0{,}105n) \quad \text{for } 4{,}21 \le n < 7{,}76 \tag{B.5}$$

$$R_n = R_1(0{,}267 + 0{,}485\sqrt{n}) \quad \text{for } 7{,}76 \le n \tag{B.6}$$

2) 132 kV lines

$$R_n = R_1\left(1{,}0 + \frac{0{,}646n^2}{192{,}0 + 0{,}518n}\right) \tag{B.7}$$

3) 400 kV or 275 kV cables

$$R_n = R_1(0{,}198 + 0{,}794\sqrt{n}) \quad \text{for } n \ge 1{,}5 \tag{B.8}$$

4) 132 kV cables

$$R_n = R_1(0{,}187 + 0{,}532\sqrt{n}) \text{ for } n \ge 2{,}35 \tag{B.9}$$

A complication in modelling a 3-phase line with a single phase equivalent is to apply suitable frequency dependency of losses. Most models consider only the balanced mode (positive sequence) component of impedance. However, at harmonic frequencies, there is a significant conversion from positive to zero sequence along a transmission line [30]. The zero sequence impedance will generally have higher damping than the positive sequence, and its contribution to overall damping should ideally be taken into account.

Reference [30] also shows that, except for short lines, a multiphase matrix model should be used to obtain accurate results. The paper illustrates that, without representing the exact transposition of long lines, the accuracy of harmonic impedance above the 5^{th} harmonic is reduced. It also shows that for two long lines running in parallel, they should be represented including their mutual impedance, otherwise the error in impedance becomes significant even at lower than 5^{th} harmonic.

Another approach is to assess the frequency dependency of line losses by using the reduced impedance matrix Z (where $U_{X\ abc} = ZI_{X\ abc}$,) of a line and estimate the frequency dependency through the resistive values in the Z-matrix, taken as

- the average of diagonal elements $<r_{ii}>$, and
- the average of non-diagonal elements $<r_{ij}>$.

As an example, assume that line losses in the single phase equivalent are written as

$$R_1\left(\frac{f}{f_1}\right)^{\alpha}$$

where

R_1 is the fundamental frequency losses;

α describes the frequency dependency.

Then a higher value of α is derived from the Z-matrix than from the balanced mode components which is illustrated by Figure B.4. Figures B.4 and B.5 give the ratio between harmonic and fundamental frequency resistance as calculated for balanced mode components and as calculated as the averages described above. The line modelled is a 500 kV single circuit in delta configuration. To ensure that there is no modelling error in calculations, three different software programs are used for comparison with similar results.

For Figure B.4, a earth resistivity of 500 Ω – m is used. To illustrate that the earth resistivity has an impact, Figure B.5 gives the same calculated ratio as Figure B.4 but for varying values of earth resistivity. In the calculations, the permeability (μ_r) of shield wires and conductor cores are set to 1; this is pessimistic as a higher μ_r would result in a stronger frequency dependency of losses.

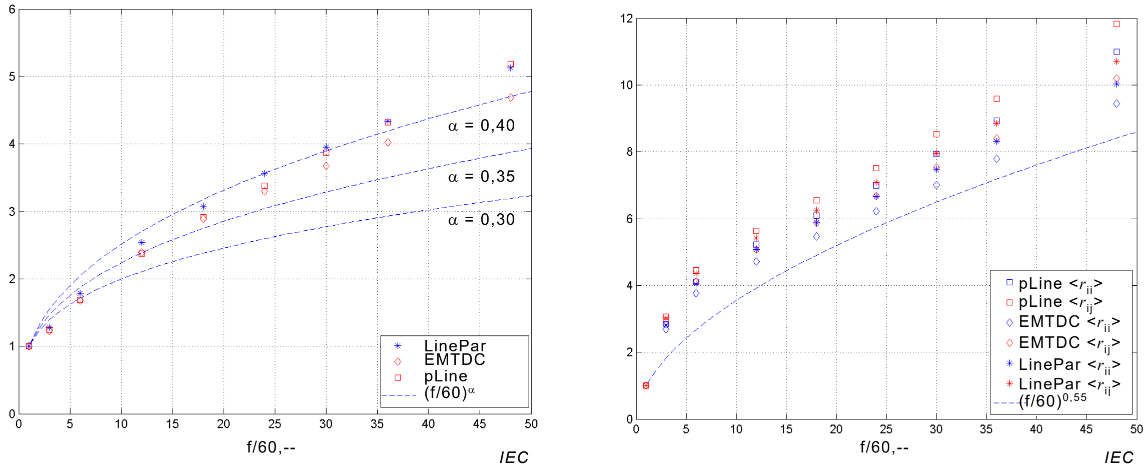


Figure B.4 – Ratio between harmonic and fundamental frequency resistance as calculated for balanced mode components and calculated from averages of reduced Z matrix resistance values

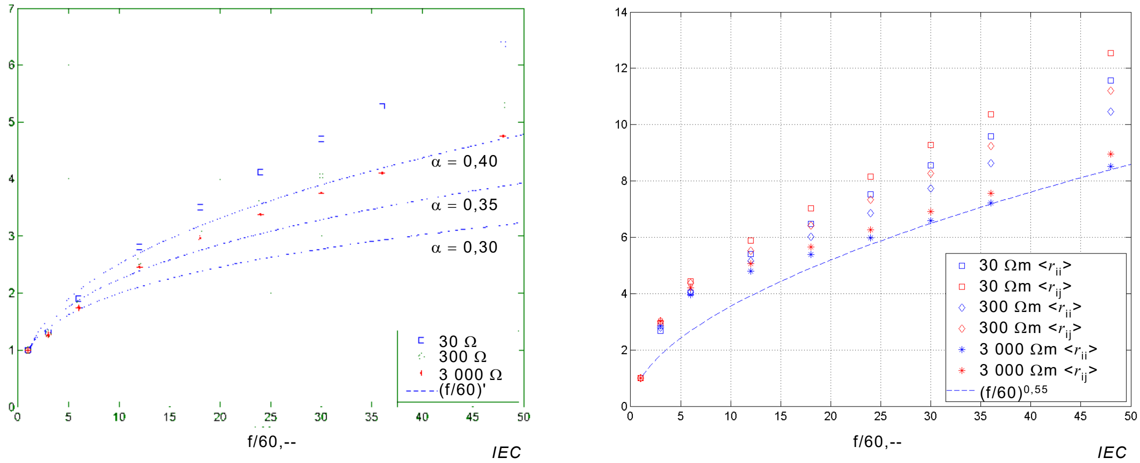


Figure B.5 – Ratio between harmonic and fundamental frequency resistance as calculated for balanced mode components and calculated from averages of reduced Z matrix resistance values, for varying earth resistivity

B.5 Synchronous machines

Reference [17] suggests that generators should be represented by their subtransient reactance and a series resistance equal to 0,1 X''_d. The reactance increases directly with n (harmonic order) and the resistance increases with $\sqrt{n}$. This model may not always be applicable as illustrated in Figure B.6 and Figure B.7, where it has been compared to values derived by a manufacturer for a salient pole hydro generator of 370 MVA.

Figure B.6 – Comparison of synchronous machine reactance between [4-1] recommendation and test measurements for a salient pole hydro generator of 370 MVA

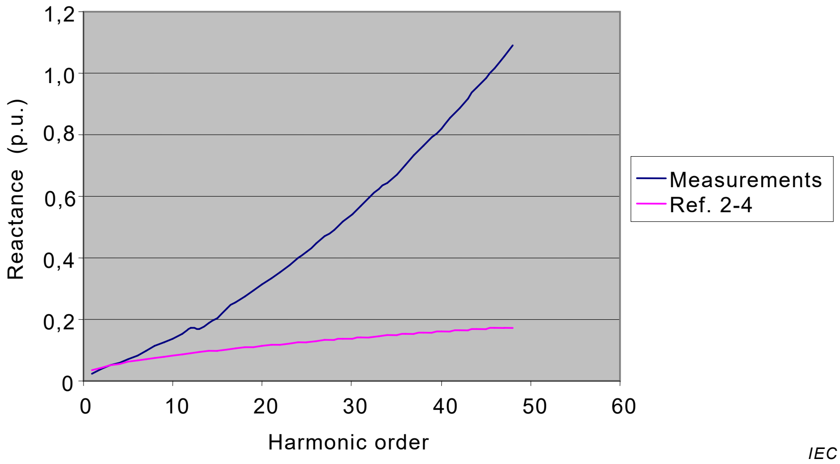


Figure B.7 – Comparison of synchronous machine resistance between [17] recommendation and test measurements for a salient pole hydro generator of 370 MVA

It can be observed that the reactance values are very close at the fundamental frequency but differ by 9 % at higher frequencies. In terms of the resistance values, however, the error at higher frequencies reaches 600 %, i.e. the [17] model greatly underestimates the damping. [25] proposes a resistance variation proportional to n^{α} where α is in the range of 0,5 to 1,5. The [17] model is on the lower end of the range and can be considered on the cautious side, but where there is a large generator installation close to the HVDC converter or busbar of concern, the generator manufacturer should be asked to provide more accurate values.

To model a machine as an impedance at a single frequency, as described above, is common practice even though it is a simplification. [31] shows that a generator cannot be modelled with complete accuracy by an impedance at a single frequency because of its time varying nature. When a machine is subjected to a harmonic disturbance at frequency $h\omega$, harmonic components of current are drawn at $h\omega$ and at the associated frequency, i.e. $(h \pm 2)\omega$. However, typically, detailed machine data is sparsely available and many software packages would not easily integrate such machine model which is why the simplification of a single impedance representation is generally accepted.

B.6 Modelling of resistance in harmonic analysis software

Variation of the resistance of the network components with frequency is often represented by sets of equations or even scattered resistance points obtained by tests. When representing this frequency dependent resistance variation, a common simplifying approach is to use the following equation:

$$R_{\mathrm{h}} = R_0 n^{\alpha} \tag{B.10}$$

where

R_{h} is the resistance at n^{th} order;

R_0 is the resistance at fundamental frequency;

α is a factor that varies for different network components.

Every network component may in fact have a different range of α that will depend on such factors as nominal voltage and power. In studies to determine harmonic impedance envelopes, it is a common simplifying approach to adopt one single value of α for each type of component – transmission lines, power transformers and synchronous machines.

However, because of its simplicity, this equation may

- overestimate damping at lower orders, for example third and fifth harmonics, which may result in an inadequate filter solution, and
- underestimate damping at higher order harmonics, which may result in unnecessary filters being provided.

An alternative approach adopted in Brazil [32] is to represent the frequency dependence of resistance by a five parameter equation, as shown below:

$$R_h = R_0(An^{\alpha} + Bn^{\beta} + C) \quad \text{(B.11)}$$

where A, B, C, α and β are constants that will vary for each network component of the network.

The following illustration is based on the modelling of theoretical frequency-dependent resistance as follows:

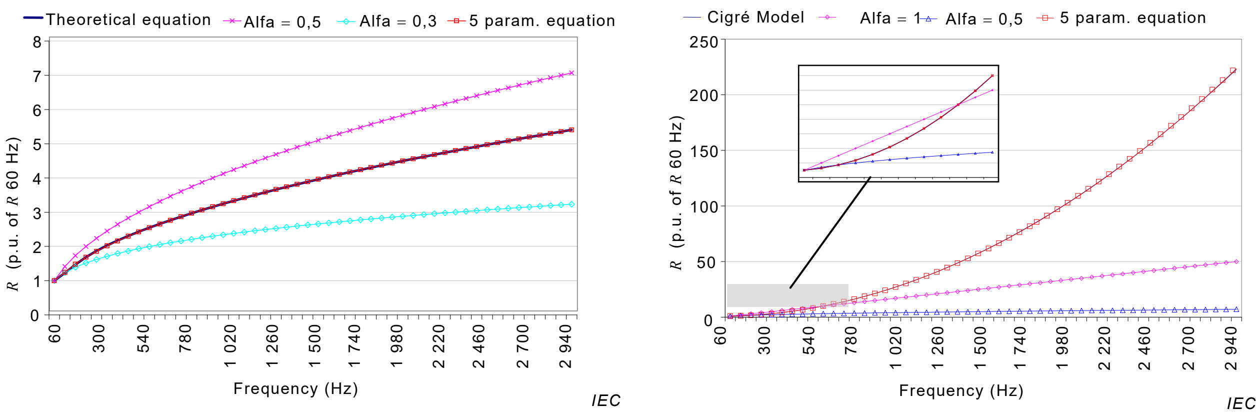
- transmission lines using Carson's equations for ground return and a Bessel function approximation for skin effect;
- the model proposed in [27] for a transformer of 100 MVA;
- for generators, resistance proportional to $n^{0,5}$.

Simple algorithms and commercial mathematical software were used to obtain the constants for Equation (B.11) that best fit the sets of points for each of the above components. Table B.1 shows examples of parameters adopted in [32] covering the range DC to 3 kHz.

Table B.1 – Constants for resistance adjustment – five parameter equations

Component	α	β	*A*	*B*	*C*
Transmission line	0,731 6	0,715 8	-1,243	1,549	0,6
Power transformers	1,909	1,5	0,143 1	-0,081 21	0,91
Generators	0,880 2	0,806 9	-0,822 2	1,37	0,6

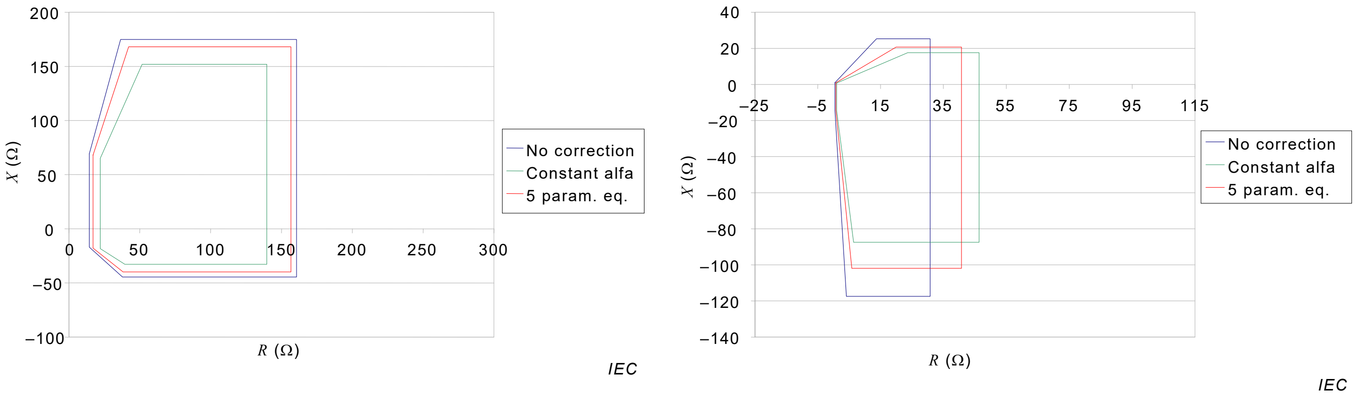
Figure B.8 shows comparisons of resistance variation for (a) a 500 kV, 300 km transmission line and (b) a 100 MVA power transformer, using different alphas in the simple formula, compared with the use of the five parameter equations.



(a) 500 kV, 300 km transmission line (b) 100 MVA power transformer

Figure B.8 – Comparison of different approximations for resistance variations

Examples of the effect of resistance corrections on harmonic impedance envelopes of the network are provided for 3rd (Figure B.9 (a)) and 13th harmonics (Figure B.9 (b)). The envelopes were obtained for Araraquara substation while performing studies for filters design for Rio Madeira HVDC converters. The polygons were obtained from tens of simulations for different contingencies and for an eight-year scenario. In order to compare the effect of different resistance representations on the filter design, three polygons were obtained for the following conditions: no resistance correction with frequency, resistances corrected with the simple α Equation (B.10) and resistances corrected with the five parameter equation.



(a) Network impedance at 3rd harmonics

(b) Network impedance at 13th harmonics

Figure B.9 – Network impedance for Araraquara substation

Annex C
(informative)

Further guidance for the measurement of harmonic voltage distortion

Dependent on the availability of suitable transducers, measurements of pre-existing harmonic voltage distortion should be undertaken, either at the point of HVDC link connection and/or at "remote" nodes. Many transmission systems exhibit considerable variations in the levels of pre-existing distortion due to variations of network load levels, generation patterns and system operating scenarios/outage conditions. The effects of reactive compensation plant (e.g. SVCs, MSCs) adjacent to the proposed HVDC link and their various operating modes can also have an influence. Extreme care is therefore undertaken to ensure that the measurements are conducted over sufficiently long periods to realistically encompass the various differing conditions. It is recommended for example that where the system load and generation pattern varies significantly throughout the year, and where it is practicable, measurements should be undertaken for one year on a continuous basis. If this is not practicable, then they should be conducted for at least one week, say four times in a year, to capture these variations as fully as practicable. However, it should be remembered that the survey covers only those points in time and may give no reliable information regarding future levels of distortion which will apply over the lifetime of the HVDC station. Where excessive levels of pre-existing distortion are found during the measurement period, an analysis should be undertaken to determine the cause, for example a particular large harmonic source, abnormal system operating condition, outage.

The choice of voltage measuring transducer and recording equipment requires special consideration to ensure that the required accuracy for harmonic voltage measurements is achieved. In respect of recording equipment, it is preferable that monitors achieving compliance with IEC 61000-4-7 Class A are employed. In respect of measuring transducers, the customer needs to be aware that the frequency response (i.e. actual ratio/nominal ratio) of the transducer employed may be far from linear. IEC TR 61869-103 reports the performance of existing instrument transformers as well as new technology transformers for their possible use in power quality measurements (including harmonics). Generally, there are three types of voltage transducer found in a transmission system, namely RC dividers, electromagnetic voltage transformers and capacitive voltage transformers. All of these are adequate for the purpose of measuring fundamental frequency voltage, typically for either protection, metering or system voltage control purposes. Not all of these, however, are suitable for accurate measurement of harmonic voltage distortion.

Whilst it may initially appear that an RC divider is ideal for such measurement purposes because of its near perfect frequency response, the effect of the secondary wiring, connections and burden can have a significant effect on its accuracy. It is also often overlooked that wound (magnetic) voltage transformers do not in fact have an adequate frequency response especially at high order harmonics. In general, the higher their primary voltage, the lower their first resonance occurs [14, 33]. It is unfortunate that for EHV voltages of the order of 400kV, such wound voltage transformers can exhibit a poor frequency response near key HVDC converter characteristic harmonic orders ($23^{rd}/25^{th}$) and can therefore give a misleading impression of the actual levels of pre-existing distortion and hence the available margin for the connection of the proposed converter station (although an inverse transfer function could be applied to the measured results as a correction). They do, however, provide a sufficiently accurate frequency response at the critical low order harmonics (3^{rd}, 5^{th} and 7^{th}) where there can be significant levels of pre-existing harmonic voltage distortion. Even at these low orders, capacitor voltage type transformers have a very poor frequency response and should not be expected to provide reliable results. However, recent developments in the field of power quality sensing devices that can be either fitted to new CVTs or even retrofitted to existing CVTs with minimal disturbance can provide a frequency response comparable to that of an RC divider [34] [35].

All measurements should ideally be taken on a three phase basis as it cannot be assumed that the harmonic distortion will be balanced over the three phases, especially for triplen order harmonics. If the harmonic analyser can perform measurements on the three phases simultaneously, it will be then possible to establish the positive, negative and zero phase sequence components of the pre-existing distortion.

It is recommended to compare the actual harmonic levels as measured with the planning levels by using one or more of the following indices (more than one index or more than one probability value – for example: 99 % and 95 % may be needed for planning levels in order to assess the impact of higher emission levels allowed for short periods of time such as during bursts or start up conditions). The basic standard to be used is IEC 61000-4-30.

- The 95 % probability daily value of $U_{\mathrm{h.vs}}$ (RMS value of individual harmonic components over "very short" 3 s periods);
- The 99 % probability weekly value of $U_{\mathrm{h.vs}}$ (RMS value of individual harmonic components over "short" 10 min periods);
- The 99 % probability weekly value of $U_{\mathrm{h.vs}}$

The planning levels for the first two indices may be the same. The planning level for the 99 % probability value of $U_{\mathrm{h.vs}}$ may exceed this by a factor (e.g. 1,25 to 2 times) to be specified by the system operator depending on the harmonic order and the system and load characteristics. It is worth noting that maximum values can be inflated by transients having rich harmonic contents that should not be considered. Such values should be removed from the measured data.

Further, when performing and assessing measurements to determine the effects of pre-existing distortion on the harmonic rating of AC filter components, and where the effects of pre-existing distortion are likely to be significant in comparison with those of converter generated harmonics (this is generally relevant for low order non-characteristic harmonic orders such as 3rd, 5th and 7th), because the various components comprising the AC filter have widely differing overvoltage or current versus time characteristics, it may be necessary to ensure that the time averaging characteristic chosen for the measurement of the relevant harmonic order(s) under consideration is appropriate for the filter component under consideration.

Annex D
(informative)

Project experience of pre-existing harmonic issues

D.1 General

The examples below are taken from experience with actual projects to indicate typical problems which have arisen due to high and increasing levels of pre-existing low-order harmonics.

D.2 Third harmonic overload of filters in a back-to-back system

A 500 MW HVDC back-to-back converter station was installed to inter-connect two 400 kV 50 Hz transmission systems, creating an asynchronous link. On each side of the station, there were multiple harmonic filters, of the following designs:

- 106 Mvar banks comprising 40 Mvar HP3 and 66 Mvar HP12/24 sub-banks;
- 106 Mvar banks HP12/24.

The level of pre-existing distortion for the purpose of filter equipment rating was defined in the customer's technical specification as equivalent to 20 % of the HVDC converter harmonic current. The performance limit for any individual harmonic was 1 %, with a THD of 2 % and an arithmetic total of 4 %.

During commissioning testing, the pre-existing distortion was measured prior to the first energization of the harmonic filters. The level of 3rd harmonic was found to be in excess of 1 %.

When the first filter was energised (HP3 + HP12/24), and before the HVDC converter was connected, the protection tripped the filter due to thermal overload of the HP3 filter resistor. This was due to the high levels of 3rd harmonic current from the system, which overloaded the filter resistor.

The 3rd harmonic current produced by an HVDC converter is predominantly due to the level of negative phase sequence (NPS) voltage on the AC network. However, the specified level of NPS voltage (1 %) resulted in a low level of injected 3rd harmonic current from the converter. Adding a 20 % allowance to this low current level did not adequately represent the duty actually imposed on the filter, by the over 1 % 3rd harmonic pre-existing voltage on the system. The resistor of the HP3 C-type filter was the component especially susceptible to 3rd harmonic overload.

The solution to the problem was to switch in two of the filter banks type (HP3 + HP12/24). This reduced the 3rd harmonic current in each resistor by approximately half and hence the power dissipation by one quarter.

NOTE This indicates that the pre-existing harmonic was acting as a current source rather than a voltage source as is often assumed. This could be due to the network impedance being much greater than the filter impedance.

The disadvantage was the effect on reactive power balance at low operating power levels. As this was a back-to-back station, the converters could be operated at higher firing angles, hence reducing the DC voltage, to absorb the additional reactive power generated by the second filter. However, this increased the operating losses in the converter. When transmitted power was increased to the point where the second filter would have been switched in, the operation with increased reactive power could be relaxed and the station then operated in its normal designed mode.

This experience demonstrated that the former practice of increasing the level of converter harmonic currents, for example by 20 %, is unlikely to give a suitable representation of pre-existing harmonic distortion on the system, particularly at low order harmonics at which the converter harmonic generation, on which the 20 % margin is based, is relatively low.

D.3 Third and fifth harmonic overload of filters in a line transmission

At the inverter station of a 600 kV HVDC transmission system, constructed in the 1980's, 2 sub-banks of 3rd/5th harmonic filters were provided. These were deemed necessary both for the limitation of distortion due to the converter harmonic generation in steady-state, but also helped inverter recovery in transient situations [36] [37].

In the original rating of these filters, the only provision for pre-existing harmonics was the then usual addition of 10 % on the converter generated harmonics.

In the early years of operation, no significant problems were observed with these filters. During the 1990's, some overload warnings were noted during light load condition, and by the turn of the century overloads were common during all system operating conditions, leading sometimes to trips and even to damaged filter reactors. It became necessary to operate with both the filters always connected, which meant there was no redundancy or opportunity for maintenance.

Intensive studies were undertaken which proved that the overloads were due to a much-increased level of pre-existing harmonics in the area, which borders a mega-city with its high concentration of industry. It was therefore decided to install new 3rd/5th filters with a higher rating, designed to accommodate the levels of pre-existing harmonics being experienced and expected in the future. This project was executed around 2006 and has successfully eliminated such harmonic overload problems and has consequently increased the reliability of the HVDC transmission.

D.4 Overload of a DC side 6th harmonic filter

The converter station in question, part of a long HVDC line transmission, was designed in the late 1980's. The AC side filtering included 11/13th, HP24 and 3rd harmonic branches. The DC side filtering was complex and included 6th harmonic filtering.

By the early 2000's, problems began to be noted concerning overload and sometimes trip of the 6th harmonic filter on the DC side, and it was identified that this was due to the cross-modulation of 5th harmonic voltage on the AC bus. The high levels of 5th harmonic being observed were identified as being due to pre-existing harmonic sources in the network.

The determined solution was to convert two existing shunt capacitors to 5th harmonic filters. The specification for the conversion required that the 5th harmonic should be effectively mitigated, but also that other low order harmonics should not be unduly amplified, and uniquely for that project, that the new filters should provide a low impedance at frequencies above 2,8 kHz, similar to that already provided by the shunt capacitors to be converted, in order to mitigate issues with PLC systems.

Little data was available either on the actual levels of low order pre-existing harmonic distortion, or on the network impedance characteristics. The new filter design was therefore made with conservative assumptions for both the performance and for rating, where it was assumed that distortion levels equal to or greater than the IEC planning levels for individual harmonics could exist on the filter bus.

The required low impedance at high frequencies was achieved by using a 3rd order filter design, with a capacitor bypassing the lower voltage components of the filter, which gives an anti-resonance just above 5th harmonic and a decreasing capacitive impedance at higher frequencies.

Since installation of the new filters, the 5th harmonic voltage on the AC side has been mitigated to within the specified level, and the overload of the DC side 6th harmonic filters has been eliminated.

Annex E
(informative)

Worked examples showing impact of pre-existing distortion

E.1 General

The purpose of these worked examples is to demonstrate the impact of background harmonics on performance and equipment stresses, while varying network impedance parameters and using different methodologies. This may be valuable in giving a feel for the impact of the various factors involved and the magnitudes of the parameters concerned.

The first example illustrates the magnification effect, and how this can be very localized in an area of the network impedance range. The second example aims to illustrate the impact of network impedance. It demonstrates that factors governed by losses, here in terms of maximum impedance angle (Φ) and Z_{min}, will be critical for any design. The example also demonstrates that the extreme magnification of pre-existing distortion is very local, i.e. confined to a narrow and confined impedance area. That is, it emphasises preceding discussions on how critical a proper design criteria is, with respect to network impedance.

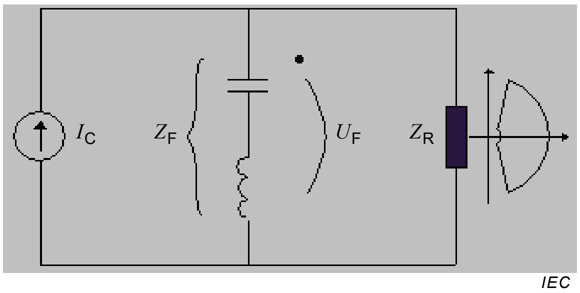
In both examples, the HVDC converter is modelled as a stiff current source, and pre-existing distortion is modelled by a voltage source behind a sector impedance, as illustrated by Figure E.1. With such models, the worst-case network impedance, which maximises filter bus voltage and equipment stresses, will be given by

- the network impedance which minimises the sum of filter (Y_{F}) and network (Y_{R}) admittance, for the converter harmonics, and
- the network impedance which minimises the sum of filter (Z_{F}) and network (Z_{R}) impedance, for pre-existing harmonics.

This is visualised, for converter harmonics, by Figure E.2.

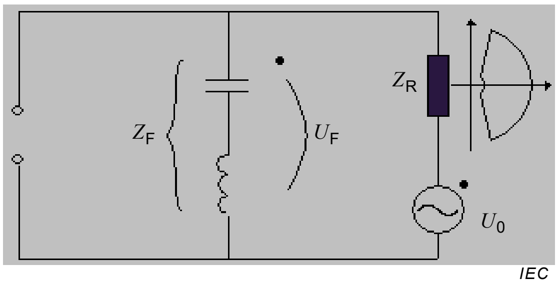
To add the harmonic contributions, thus calculated using two different network impedances, is conservative but is quite often used as it saves computation effort. It also has the advantage that the known source (converter) contributions are taken fully into account.

Converter Harmonic(s)



$$U_F = I_C \frac{1}{Y_F + Y_R}$$

Pre-existing Harmonic(s)



$$U_F = U_0 \frac{Z_F}{Z_F + Z_R}$$

Figure E.1 – Harmonic models for converter and for pre-existing distortion

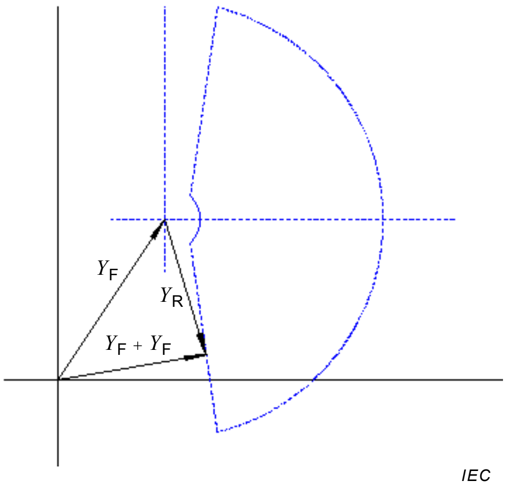


Figure E.2 – Geometrical visualisation of selecting worst-case impedance for converter harmonics

E.2 Pre-existing distortions

E.2.1 Example 1 – Illustration of magnification

For this example, the pre-existing distortion is modelled by a voltage source of 1 % at each of 5th, 7th, 11th, 13th 23rd and 25th harmonics (THD = 2,4 %) applied behind a sector impedance.

The filter design is a simplified scheme, as shown in Figure E.3, not entirely representative for a typical HVDC scheme but sufficient for demonstration purposes, with branches having both high and low q-factors.

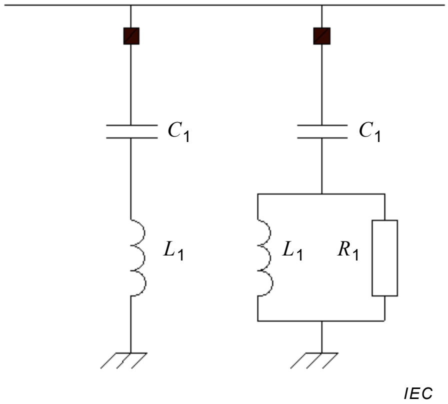


Figure E.3 – Simple filter scheme to illustrate magnification

Table E.1 – Parameters of elements of a simplified filter scheme shown in Figure E.3

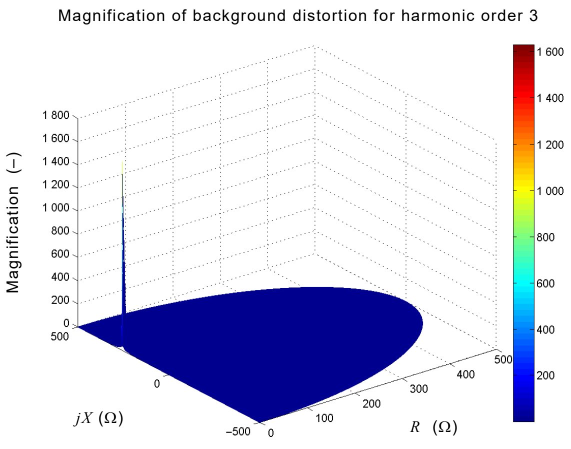
Branch	**BP11**	**HP24**
Q, **Mvar** $_{3ph}$	100	100
h_0, **--**	10,95	24
q**-factor**	200[a]	5
C_1, **uF**	1,973	1,986
L_1, **mH**	42,83	8,857
R_1, **Ω**	--	334
[a] q-factor of reactor at tuning frequency.		

In calculating bus voltage and current distortions, the following system data is considered.

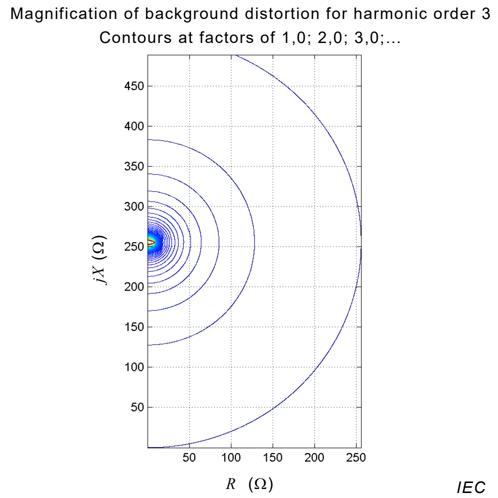
- Fundamental frequency 50 hz ± 0,1 Hz.
- System voltage 400 kV ± 20 kV.
- Detuning is modelled through explicit frequency variations and component tolerances.
  – The BP11 branch is tuneable, and a capacitance variation between -2,1 % and 1,2 % is considered (dielectric temperature variation and element failures). The reactor is assumed to have taps with a maximum tap step of 0,5 %, and a tuning error of 0,3 % (i.e. half a tap step).
  – The HP24 branch is non-tuneable, and a capacitance variation of -4,1 % and 3,2 % is considered (manufacturing tolerances added). For the reactor, a manufacturing tolerance of ± 2 % is considered.

The 3-D plots in Figure E.4 below show voltage magnification of pre-existing harmonics, $\frac{Z_F}{Z_F + Z_N}$, as mapped over the Z_N plane, taken as Real(Z_N) > 0, for a few selected harmonics.

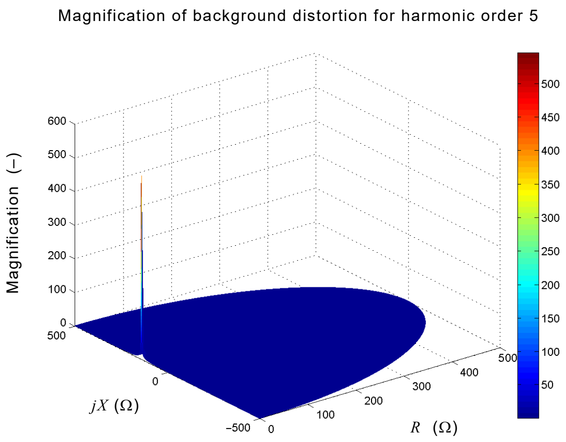
The magnification is very local, which is further demonstrated by additional close-up contour plots. The extreme magnification factor, in particular for the lower order harmonics, is unrealistically high as the impedance angle of Z_N is allowed to reach ±90° at the same time as the filter branches are virtually lossless at these harmonics.



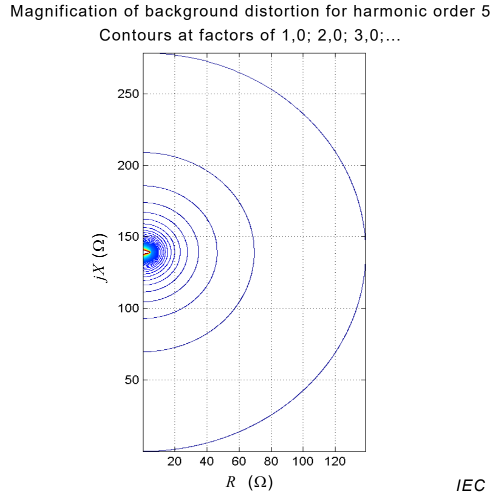
IEC



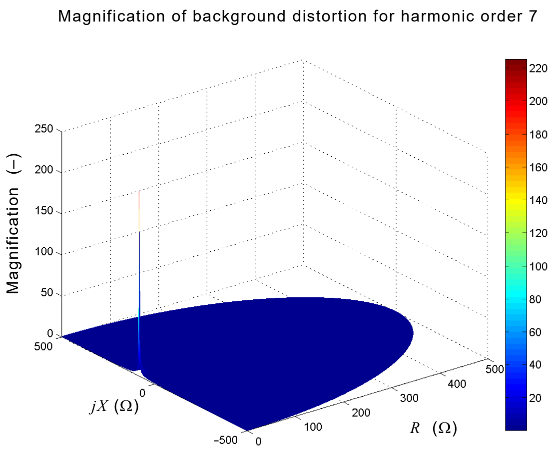
IEC



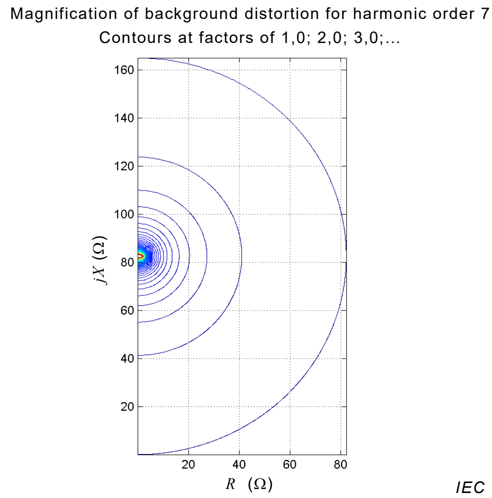
IEC



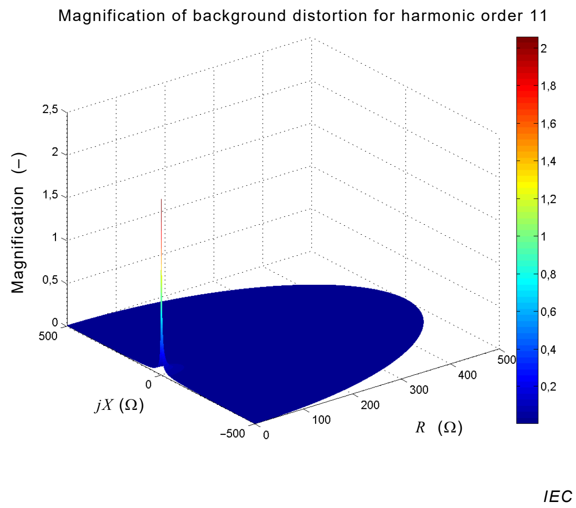
IEC

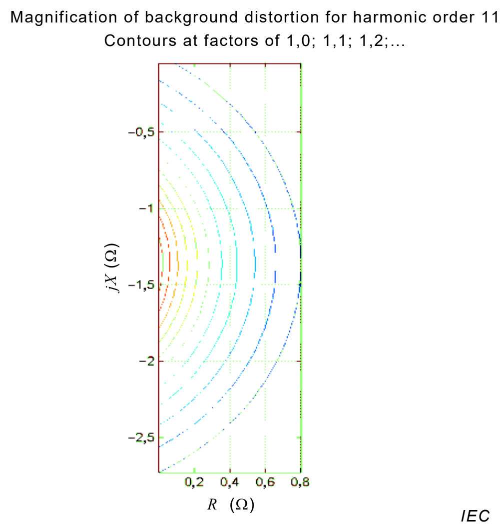


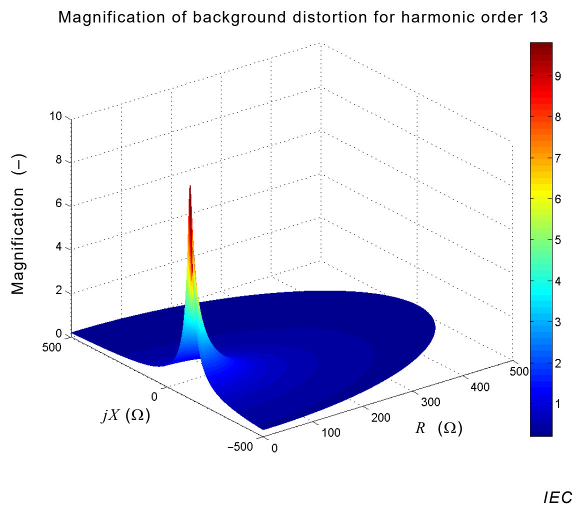
IEC

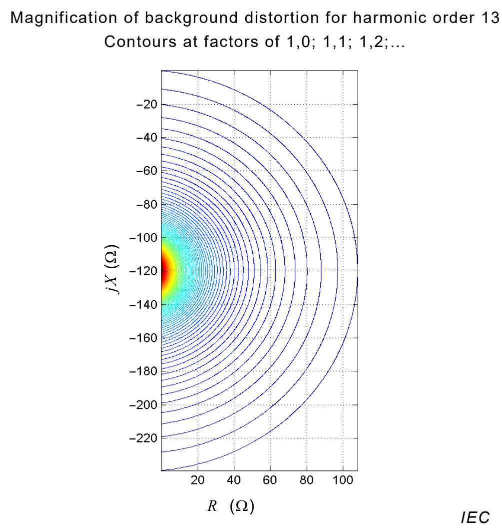


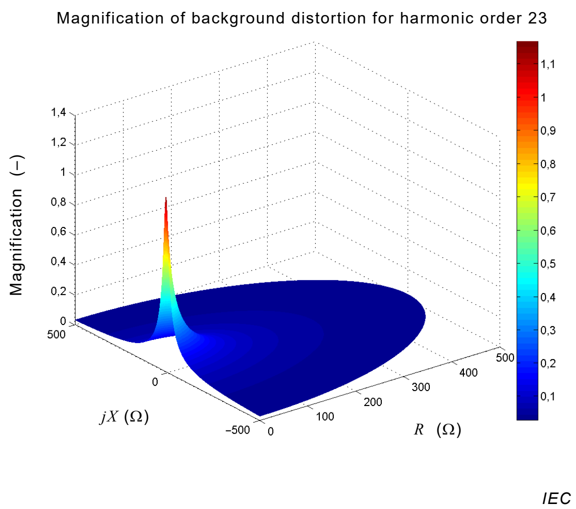
IEC

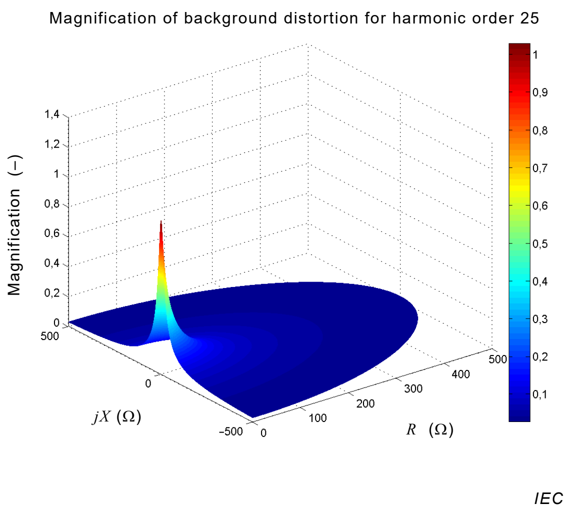

Magnification of background distortion for harmonic order 11
Magnification (–)
jX (Ω)
R (Ω)
IEC


Magnification of background distortion for harmonic order 11
Contours at factors of 1,0; 1,1; 1,2;...
jX (Ω)
R (Ω)
IEC


Magnification of background distortion for harmonic order 13
Magnification (–)
jX (Ω)
R (Ω)
IEC


Magnification of background distortion for harmonic order 13
Contours at factors of 1,0; 1,1; 1,2;...
jX (Ω)
R (Ω)
IEC


Magnification of background distortion for harmonic order 23
Magnification (–)
jX (Ω)
R (Ω)
IEC


Magnification of background distortion for harmonic order 25
Magnification (–)
jX (Ω)
R (Ω)
IEC

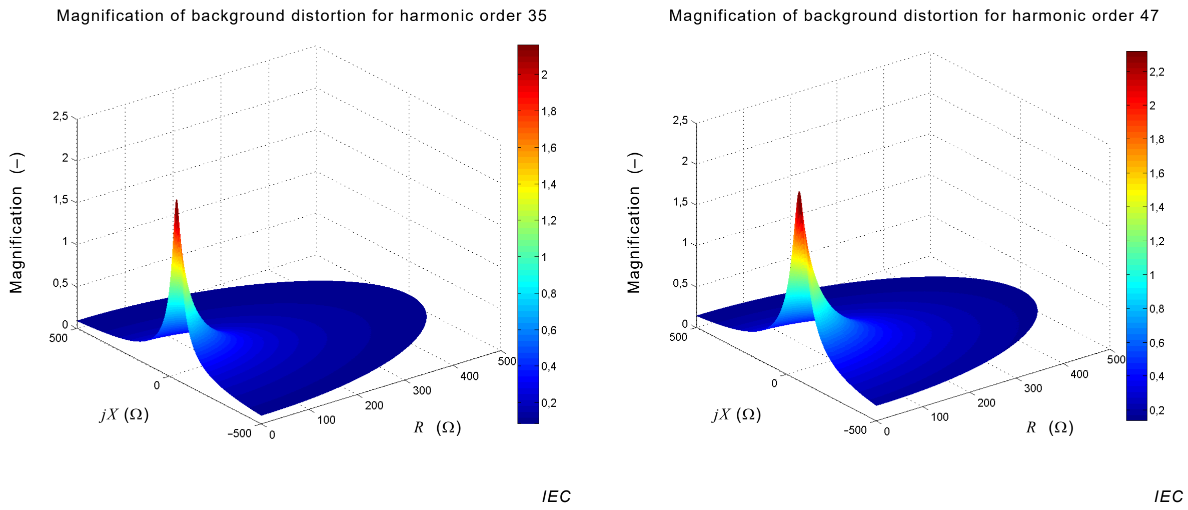


Figure E.4 – Plots illustrating magnification of various pre-existing harmonics

E.2.2 Impact of network impedance parameters

The following numerical example is intended to illustrate the impact of different network impedance parameters. An arbitrary impedance sector is selected, defined by:

- Z_{min} (variable);
- Z_{max} (1000 Ω);
- $\pm\,\Phi$ (variable).

Again for this example, the pre-existing distortion is modelled by a voltage source of 1 % at each of 5th, 7th, 11th, 13th 23rd and 25th harmonics (THD = 2,4 %) applied behind a sector impedance.

For the pre-existing harmonics, 5th, 7th , 11th , 13th , 23rd and 25th , Tables E.1 and E.2 summarize the voltage and current distortion on the network side of the filter, in p.u. of 400 kV and 440 MW load respectively, that is, $I_1 = 440MW \div \left(\sqrt{3}\ 400kV\right) \approx 0{,}6kA$. The cases shown are calculated with

- Z_{min} = 1 Ω and varying Φ (Table E.2), and
- Φ = ± 85° and varying Z_{min} (Table E.3).

Table E.2 – Voltage and current distortion for Z_{min} = 1 Ω and varying Φ

Φ	±85°		±75°		±65°		±55°		±45°	
	U_{PCC}	I_{LINE}	U_{PCC}	I_{LINE}	U_{PCC}	I_{LINE}	U_{PCC}	I_{LINE}	U_{PCC}	I_{LINE}
h\THD	**18,1 %**	**448,8 %**	**7,0 %**	**373,2 %**	**4,7 %**	**325,9 %**	**3,7 %**	**291,3 %**	**3,1 %**	**264,5 %**
5	11,8 %	29,8 %	4,0 %	10,5 %	2,5 %	6,4 %	1,8 %	4,8 %	1,5 %	3,9 %
7	11,5 %	48,7 %	4,0 %	17,5 %	2,5 %	10,8 %	1,8 %	8,0 %	1,5 %	6,5 %
11	3,2 %	444,0 %	2,1 %	370,0 %	1,7 %	322,8 %	1,4 %	288,2 %	1,2 %	261,4 %
13	6,4 %	22,9 %	3,2 %	9,3 %	2,1 %	6,4 %	1,7 %	5,0 %	1,4 %	4,2 %
23	1,4 %	28,1 %	1,.2 %	26,9 %	1,1 %	25,9 %	1,1 %	25,6 %	1,0 %	25,3 %
25	1,0 %	28,1 %	1,0 %	27,3 %	1,0 %	27,0 %	1,0 %	26,7 %	1,0 %	26,4 %

Table E.3 – Voltage and current distortion for Φ = ±85° and varying Z_{min}

Z_{min}	2 Ω		4 Ω		8 Ω		16 Ω		32 Ω	
	U_{PCC}	I_{LINE}	U_{PCC}	I_{LINE}	U_{PCC}	I_{LINE}	U_{PCC}	I_{LINE}	U_{PCC}	I_{LINE}
h\THD	**18,1 %**	**428,3 %**	**17,9 %**	**332,2 %**	**17,8 %**	**120,1 %**	**17,8 %**	**75,8 %**	**17,7 %**	**66,1 %**
5	11,8 %	29,8 %	11,8 %	31,6 %	11,8 %	31,6 %	11,8 %	31,6 %	11,8 %	29,7 %
7	11,5 %	48,6 %	11,5 %	52,0 %	11,5 %	52,0 %	11,5 %	52,0 %	11,5 %	48,4 %
11	3,2 %	422,0 %	1,9 %	324,4 %	0,6 %	95,7 %	0,2 %	32,2 %	0,1 %	13,0 %
13	6,4 %	23,9 %	6,4 %	11,6 %	6,4 %	11,6 %	6,4 %	11,6 %	6,4 %	24,8 %
23	1,4 %	28,1 %	1,4 %	29,1 %	1,4 %	27,1 %	1,3 %	20,5 %	0,7 %	15,4 %
25	1,0 %	27,9 %	1,0 %	26,6 %	0,9 %	26,2 %	0,7 %	21,4 %	0,4 %	10,9 %

Annex F
(informative)

Comparison of calculation methods

F.1 General

The aim of this annex is to illustrate numerically the impact of the different methods for taking into account pre-existing distortion when rating equipment. The methods considered are as follows, applying pre-existing distortion:

Method 1 as source voltages behind a worst network impedance;

Method 2 as source voltages directly on the filter bus as in 5.7.2;

Method 3 limiting the filter bus harmonic voltage to a maximum level for filter rating (MLFR) as in 5.7.3;

Method 4 limiting total source distortion to the THD level, as in 5.7.4;

Method 5 limiting explicit representation of pre-existing distortion to below the 10^{th} harmonic, and adding 10 % to converter harmonics for all the remaining harmonics above 10^{th}, as in 5.7.5.

In addition, a reference set of converter generated harmonic stresses is calculated for comparison.

The preconditions are identical for all cases. It is assumed that the scheme has a rated power of about 600 MW connected to a 50 Hz, 400 kV system with a short circuit level of between 1 500 MVA and 15 000 MVA.

The AC network harmonic impedance envelope is defined by the sector shown in Figure F.1 where:

- $\sqrt{n} \times Z_{\text{min 50}} \le Z_{\text{n}} \le n \times Z_{\text{ma50}}$ where n is the harmonic order and Z_{max50} and Z_{min50} are the maximum and minimum network impedances at fundamental frequency, evaluated from minimum and maximum short circuit power respectively.
- the phase angles are: $\begin{matrix} 0° & & 80° & & 2\ldots4 \\ -75° & \le \varphi_{\text{n}} \le & 75° & \text{for } n = & 5\ldots10 \\ -70° & & 70° & & 11\ldots50 \end{matrix}$

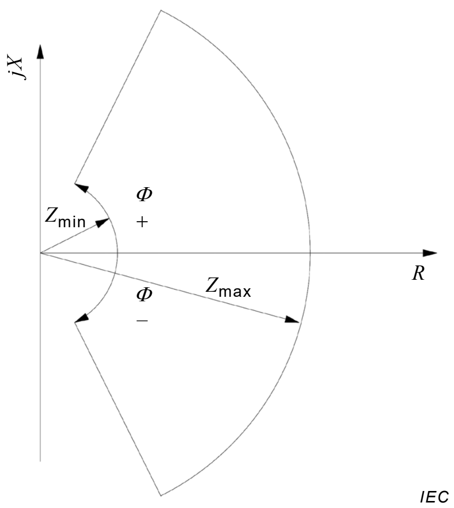


Figure F.1 – Network impedance sector used in example

For the example, it is assumed that the complete filter design consists of two identical filter banks, but in the calculations only a single filter bank is considered to be connected, consisting of a double-tuned 11/13th bandpass branch and a high-pass 24th harmonic branch. No low-order filter, such as an HP3, is provided. The filter is detailed in Figure F.2. In the calculations, the following is further assumed.

- Fundamental frequency 50 Hz ± 0,1 Hz.
- System voltage 400 kV ± 20 kV.
- Detuning is modelled through explicit frequency variations and component tolerances.
  – The BP1113 branch is tuneable, and a capacitance variation between -2,1 % and 1,2 % is considered (dielectric temperature variation and element failures). The reactor is assumed to have taps with a maximum tap step of 0,5 %, and a tuning error of 0,3 % (i.e. half a tap step).
  – The HP24 branch is non-tuneable, and a capacitance variation of -4,1 % and 3,2 % is considered (manufacturing tolerances added). For the reactor, a manufacturing tolerance of ± 2 % is considered.

The pre-existing harmonic distortion is arbitrarily taken as the IEC planning levels, see Figure F.3.

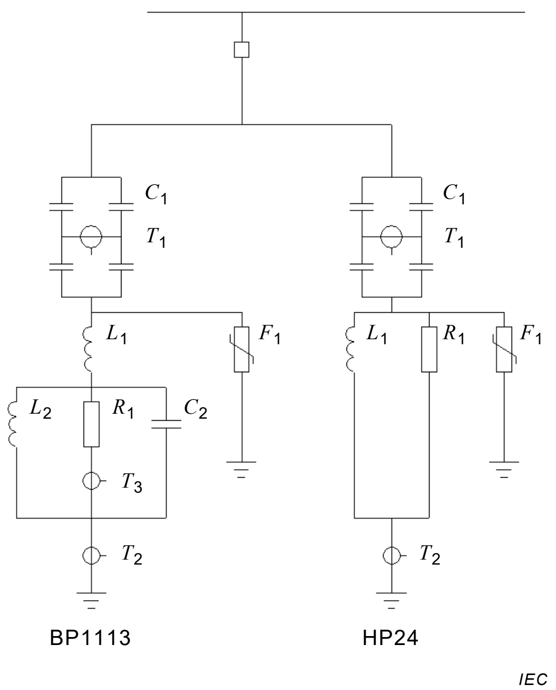


Figure F.2 – Assumed filter scheme for examples of different methods of calculation

Table F.1 – Parameters of components of filters shown in Figure F.2

Branch	**BP1113**	**HP24**
Q, Mvar $_{3ph}$	43	47
h_0, --	11 and 13	24
C_1, uF	0,85	0,94
L_1, mH	84,2	18,7
C_2, uF	30,4	--
L_2, mH	2,3	--
R_1, Ω	250	250

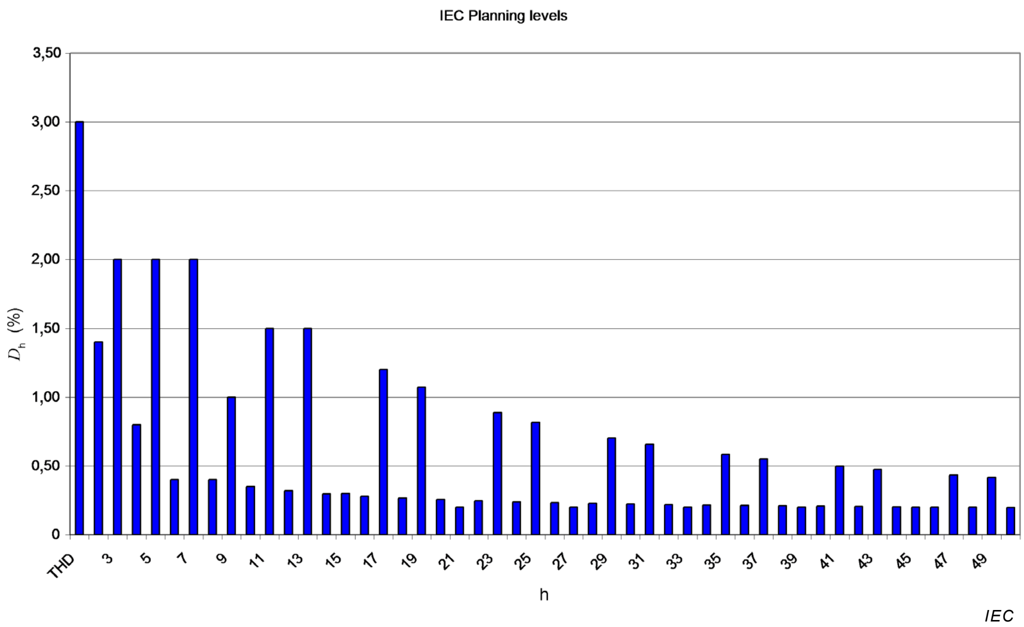


Figure F.3 – IEC planning levels used for source voltages in the study

In assessing equipment stresses for the different methods, calculated stresses are determined as indicated in the tables for each method as RSS, qRSS or SUM, which are defined as:

- root-sum-square values (RSS), for example $I = \sqrt{\sum I_h^2}$;
- quasi-root-sum square values (qRSS), for example $U = U_k + \sqrt{\sum_{h \neq k} U_h^2}$ where U_k is the maximum individual harmonic;
- arithmetic sum values (SUM), for example $U = \sum U_h$.

Table F.2 summarises the results. The converter generated stresses are given both excluding and including fundamental frequency stresses, whereas the pre-existing distortion cases (Methods 1 to 5) only contain harmonic stresses. As the table demonstrates, the harmonic stresses due to pre-existing distortion for most methods exceed or are comparable to the converter generated stresses. That is, for the assumptions made here, the impact of pre-existing distortion would be dominant for component stresses. That would not be expected nor representative for the general experience of HVDC plants in service. These examples therefore emphasise that preconditions should be selected with care. The example also demonstrates that the selected method used in determining stresses will be critical and directly decisive.

From Table F.2, it can be seen that the impact of the various methods on the separate components is significantly different, depending on the dominant harmonics responsible for the particular component stresses, and how these are affected by the applicable rating method.

No low order (3rd or 5th/7th) filters have been included here, but if they had been, then the impact of low order stresses on these would be dominant and a different pattern of stress reduction by the various methods would be seen.

F.2 Reference case – Converter generated harmonics only

This calculation is provided as a reference case to show the stresses calculated for the converter operating at 600 MW transfer with a single filter bank in service. The calculated THD is about 1,9 %. The fundamental frequency components are excluded. Equipment stresses are summarised in Table F.2.

Table F.2 – Component rating calculated using different calculation methods

		Method 1	**Method 2**	**Method 3**	**Method 4**	**Method 5**	**Converter harmonics only**	**Converter including funda-mental**	
BP1113									
U C1	kV	74	157	63	64	50	36	246	$\sqrt{\Sigma U_h^2}$
	kV	223	269	170	120	134	61	299	ΣU_h
I C1 and L1	A	194	487	180	182	96	106	120	$\sqrt{\Sigma I_h^2}$
I C2	A	1 000	2 780	999	1 000	129	573	573	
I L2	A	1 030	2 890	1 020	1 030	211	606	609	
I R1	A	35	98	35	35	6	21	21	
HP24									
U C1	kV	36	16	24	28	35	5	243	$\sqrt{\Sigma U_h^2}$
	kV	140	82	104	62	90	20	261	ΣU_h
I C1	A	96	80	80	72	64	25	77	$\sqrt{\Sigma I_h^2}$
I L1	A	89	70	71	69	63	22	76	
I R1	A	36	39	35	23	11	12	12	

Method 1: as source voltages behind a worst network impedance

Method 2: as source voltages directly on the filter bus as in 5.7.2

Method 3: limiting the filter bus harmonic voltage to a maximum level for filter rating (MLFR) as in 5.7.3

Method 4: limiting total source distortion to the THD level, as in 5.7.4

Method 5: limiting explicit representation of pre-existing distortion to below the 10th harmonic, and adding 10 % to converter harmonics for all the remaining harmonics above 10th, as in 5.7.5

F.3 Method 1 – Source voltages behind impedance sector

With the source voltages located behind the sector impedances, Method 1 gives a THD at the converter bus of about 14,4 % (dominated by 5th and 7th harmonic). Equipment stresses are summarised in Table F.2.

F.4 Method 2 – Source voltages at filter bus (see 5.7.2)

With the source voltages located directly on the filter bus, Method 2 gives a THD at the converter bus of about 5,6 %. Equipment stresses are summarised in Table F.2.

F.5 Method 3 – Limiting the filter bus harmonic voltage to a maximum level for filter rating (MLFR) (see 5.7.3)

The maximum levels of distortion at the filter bus to be considered as realistic for filter rating (the MLFR) are here selected as 2 times IEC planning levels for all harmonics except characteristic harmonics where a maximum level of 1,2 times is used, based on the concept that effective filtering is present at these frequencies. These are arbitrary levels selected for illustration – they may be chosen as higher or lower as appropriate to a given project.

Table F.3 illustrates the methodology, using the current as calculated for BP1113 filter HV capacitor. The second column gives the calculated filter bus distortion for the worst-case impedance and the third the MLFR harmonic distortion limits. The fourth gives the calculated current corresponding to the raw calculated distortion and the fifth gives the current as corrected by MLFR.

Table F.3 – Rating calculations using Method 3 – for BP1113 C1

BP1113 I C1	$D_{\text{h Calc}}$	$D_{\text{h limit}}$	$I_{\text{h Calc}}$	$I_{\text{h Corrected}}$
$\sqrt{\Sigma I_h^2}$			193,62	179,23
2	1,82 %	2,80 %	2,37	2,37
3	4,21 %	4,00 %	8,53	***8,11***
4	4,57 %	1,60 %	13,06	***4,57***
5	7,66 %	4,00 %	29,45	***15,38***
6	1,52 %	0,80 %	7,77	***4,08***
7	7,55 %	4,00 %	51,47	***27,26***
8	1,50 %	0,80 %	14,03	***7,51***
9	3,68 %	2,00 %	51,08	***27,73***
10	1,24 %	0,70 %	30,50	***17,25***
11	1,11 %	1,80 %	139,44	139,44
12	0,30 %	0,64 %	4,16	4,16
13	1,00 %	1,80 %	96,82	96,82
14	0,60 %	0,59 %	22,99	***22,62***
15	0,41 %	0,60 %	8,51	8,51
…	…	…	…	…

Clearly, the impact of the MLFR method in reducing stresses (see Table F.2) is greatest where the dominant harmonics for a particular component are not the sharply-filtered 11th and 13th harmonics, where the calculated voltage level was anyway not high enough to be limited by the application of this method.

F.6 Method 4 – Limiting total source distortion to the THD level (see 5.7.4)

This recognizes that if, for example, IEC planning levels are taken as the pre-existing source voltage, the quadratic sum of the individual harmonics exceeds the allowable maximum THD. In this method, the individual harmonic contributions are therefore limited such that the specified THD is not exceeded. This is done such that a different set of individual harmonics may be selected for each filter component, depending on which harmonics give the highest stresses for that particular component.

As an example to illustrate the method, Table F.4 and Table F.5 show this calculation procedure for the current in the BP1113 C2 capacitor and the HP24 R1 resistor respectively. Two components are shown to illustrate that a different set of harmonics is chosen for each component, depending on the sensitivity of the loading of that component to each harmonic.

As a first step, the raw calculated harmonic stresses for the given component (C2 or R1) are sorted in descending order, as shown in column I_{Calc}. Then, using this order, harmonics stresses are added up starting with the largest harmonic contribution and adding successively smaller harmonic contributions, also adding the individual source voltages until the chosen THD limit for the harmonic source is reached. The other (arbitrarily) selected limits on maximum limits for individual groups of harmonics are also respected while performing these additions, as follows:

- THD of the corresponding source voltage is limited to ≤ 3,0 % ($\text{THD}_{\text{Total}}$);
- contribution of 3rd, 5th and 7th harmonic is max. 70 % of THD, i.e. ≤ 2,1 % ($\text{THD}_{3,5,7}$);
- contribution of harmonics ≥ 15 is max. 50 % of THD, i.e. ≤ 1,5 % ($\text{THD}_{\geq 15}$).

The resulting harmonic stresses are given by $I_{\text{Corrected}}$.

For information, the voltage levels at the filter bus are also given ($D_{\text{Filter Bus Corrected}}$).

For the HP24 R1 resistor, this method has a significant impact on the rating. Table F.4 shows that the rating current is not dominated by just a few large harmonics, but is composed of many fairly equal harmonics. A large proportion of the more dominant ones are higher frequency non-characteristics, which are probably not realistic, and these are limited by the $h \geq 15$ criterion. The limitation on h 3,5,7 contributions is also enforced, and finally the THD = 3 % limit cuts off remaining harmonic contributions. Harmonics 25, 5, and 13 being reduced proportionally at each of these limits respectively to maintain the contributions from those groups within their respective limits. The total current is reduced from 35,27 to 23,25 A, a reduction in power rating of 56 %.

However, Table F.5 shows that the mitigating influence of this method on the calculated current rating of the BP1113 C2 capacitor is negligible. The current in this component is mainly composed of 11th and 13th harmonics, which are not limited by this algorithm as their total does not exceed THD and as they are not covered by the other arbitrary limits. The only limitation which is applied here is when the total reached 3 %, when the 7th harmonic is reduced accordingly to limit the total to 3 %. All subsequent harmonic contributions are then neglected, but this makes an almost insignificant difference to the total.

In both these cases, the resulting voltage distortion on the converter bus is still unrealistically high, both for some individual harmonics and for THD, which implies that Method 3 could be applied in addition to Method 4 to derive an overall more realistic rating for these components.

Tables showing the calculated stresses for all components are shown further below, and these are summarized in Table F.2.

Table F.4 – Rating calculations using Method 3 – for HP24 R1

HP24 I R1	D_{Source}	$D_{\text{h=3,5,7}}$	$D_{\text{h}^{3}15}$	D_{Others}	THD_{Total}	I_{calc} A	$I_{\text{corrected}}$ A	$D_{\text{Filter Bus Corrected}}$
19	1,07 %		1,07 %		1,07 %	13,33	13,33	1,28 %
23	0,89 %		0,89 %		1,39 %	13,02	13,02	0,80 %
25	0,82 %		0,56 %		1,50 %	11,16	7,62	0,43 %
17	1,20 %					11,10		
29	0,70 %					8,87		
31	0,66 %					8,40		
35	0,58 %					7,37		
37	0,55 %					6,87		
7	2,00 %	2,00 %			2,50 %	6,68	6,68	7,53 %
41	0,50 %					6,00		
9	1,00 %			1,00 %	2,69 %	5,64	5,64	3,67 %
43	0,47 %					5,62		
47	0,43 %					4,97		
49	0,42 %					4,69		
22	0,25 %					3,66		
20	0,26 %					3,48		
24	0,24 %					3,40		
5	2,00 %	0,64 %			2,77 %	3,34	1,07	2,45 %
26	0,23 %					3,05		
18	0,27 %					2,92		
21	0,20 %					2,91		
30	0,22 %					2,84		
28	0,23 %					2,84		
32	0,22 %					2,80		
34	0,22 %					2,74		
36	0,21 %					2,67		
38	0,21 %					2,60		
14	0,30 %			0,30 %	2,78 %	2,59	2,59	0,58 %
33	0,20 %					2,55		
40	0,21 %					2,52		
27	0,.20 %					2,51		
39	0,20 %					2,45		
42	0,21 %					2,45		
44	0,20 %					2,39		
10	0,35 %			0,35 %	2,81 %	2,38	2,38	1,22 %
45	0,20 %					2,33		
46	0,20 %					2,32		
48	0,20 %					2,27		
50	0,20 %					2,21		
16	0,28 %					1,92		
8	0,40 %			0,40 %	2,83 %	1,77	1,.77	1,49 %
15	0,30 %					1,77		
13	1,50 %			0,98 %	3,00 %	1,58	1,04	0,28 %
4	0,80 %					1,26		
12	0,32 %					1,03		
6	0,40 %					0,97		
11	1,50 %					0,94		
3	2,00 %					0,67		
2	1,40 %					0,12		
	THD	**2,10 %**	**1,50 %**	**1,53 %**	**3,00 %**			**9,10 %**
	$\sqrt{\Sigma I_h^2}$					**35,27**	**22,35**	

Table F.5 – Rating calculations using Method 4 – for BP1113 C1

BP1113 I C2	D_{Source}	$D_{\text{h=3,5,7}}$	$D_{\text{h}\geq 15}$	D_{Others}	THD_{Total}	I_{calc} **A**	$I_{\text{corrected}}$ **A**	$D_{\text{Filter Bus Corrected}}$
13	1,50 %			1,50 %	1,50 %	790,18	790,18	1,00 %
11	1,50 %			1,50 %	2,12 %	593,03	593,03	1,11 %
14	0,30 %			0,30 %	2,14 %	95,23	95,23	0,60 %
12	0,32 %			0,32 %	2,17 %	83,08	83,08	0,30 %
10	0,35 %			0,35 %	2,19 %	61,93	61,93	1,24 %
9	1,00 %			1,00 %	2,41 %	60,70	60,70	3,68 %
17	1,20 %		1,20 %		2,69 %	34,48	34,48	1,44 %
7	2,00 %	1,32 %			3,00 %	25,19	16,66	4,99 %
15	0,30 %					25,12		
19	1,07 %					18,82		
…						…		
	THD	**1,32 %**	**1,20 %**	**2,41 %**	**3,00 %**			**6,69 %**
	$\sqrt{\Sigma I_h^2}$					**1 001,38**	**1 000,51**	

F.7 Method 5 – Pre-existing harmonics considered only up to the 10th, with 10 % margin on converter generation for remainder (see 5.7.5)

Stresses were calculated considering explicitly the pre-existing harmonics up to the 10th harmonic using the voltage source/worst network approach, and then adding 10 % of converter generated harmonic stresses for all higher harmonics (as in 5.7.5). The results are listed in Table F.2.

The impact on the characteristic harmonics is clearly much lower than with any of the methods involving a voltage source/worst network approach at these harmonics. It is arguable whether this is sufficiently conservative at these harmonics.

No limitation on pre-existing harmonics is applied even though the corresponding calculated THD level at the filter bus is unrealistically high at 14 % (compare to Method 1).

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