



BSI Standards Publication

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

Part 3: Modelling

National foreword

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TECHNICAL REPORT



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

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS –
GUIDANCE TO THE SPECIFICATION AND
DESIGN EVALUATION OF AC FILTERS –****Part 3: Modelling****FOREWORD**

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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 62001-1:

- 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 date indicated on the IEC web site under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

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- withdrawn,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

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

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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 Chateaugay 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 11th and 13th harmonics creating a low impedance path in the 13th harmonic positive sequence network as well as the 11th harmonic negative sequence network. If the DC side impedance at the 12th harmonic is also small (as can occur on back-to-back schemes with small or no smoothing reactors), coupling can occur between the 11th and 13th networks of both AC systems. As a result of the coupling, 11th and 13th 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

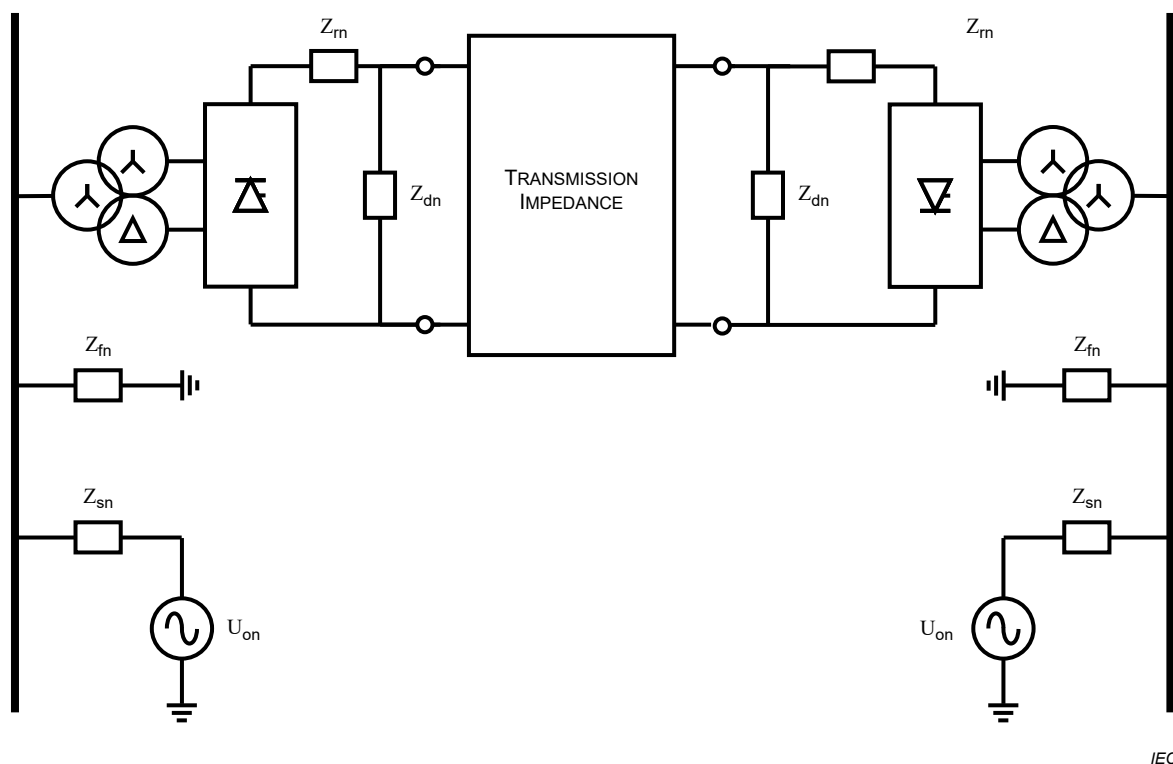
use of reduced models which attempt to de-couple the various elements and allow the design of the various groups of filters to be made independently.

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].



IEC

Key

U_{on}	AC system voltage
Z_{sn}	AC network harmonic impedance
Z_{fn}	AC harmonic filters
Z_{rm}	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 ($R_{sn} \pm j X_{sn}$) 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

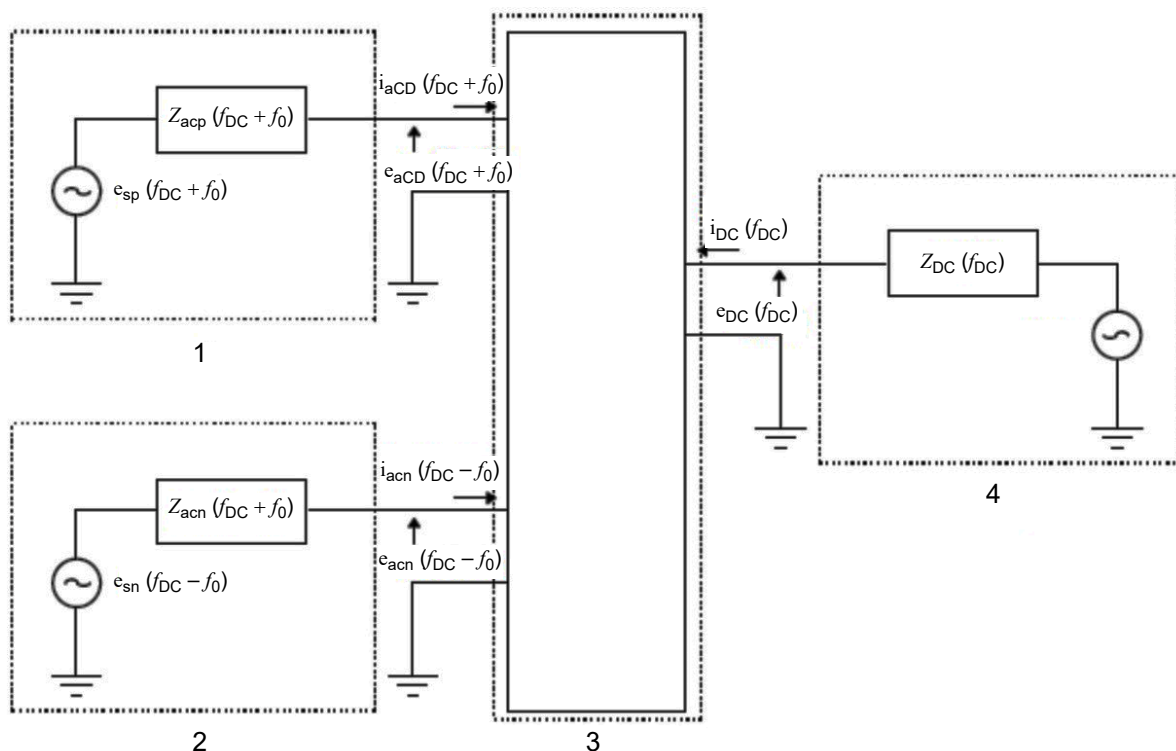
3.7.1 General

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.



IEC

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 2nd 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 12th 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 3rd 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 3rd harmonic positive sequence and negative sequence fundamental which tends to modulate the pre-existing NPS voltage. In the extreme case, the amount of 3rd harmonic current can almost double (and should be considered in the design of any 3rd 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 2nd, 5th and 8th harmonics being mainly negative sequence, and 4th, 7th and 10th harmonic being positive sequence may be reasonably valid. Any 3rd, 6th and 9th 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 3rd harmonic of positive sequence, and so it should not be assumed that all pre-existing 3rd 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 5th and 7th harmonic on the converter bus, with constant phase angle for 5th harmonic but varying phase angle for the 7th. 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.

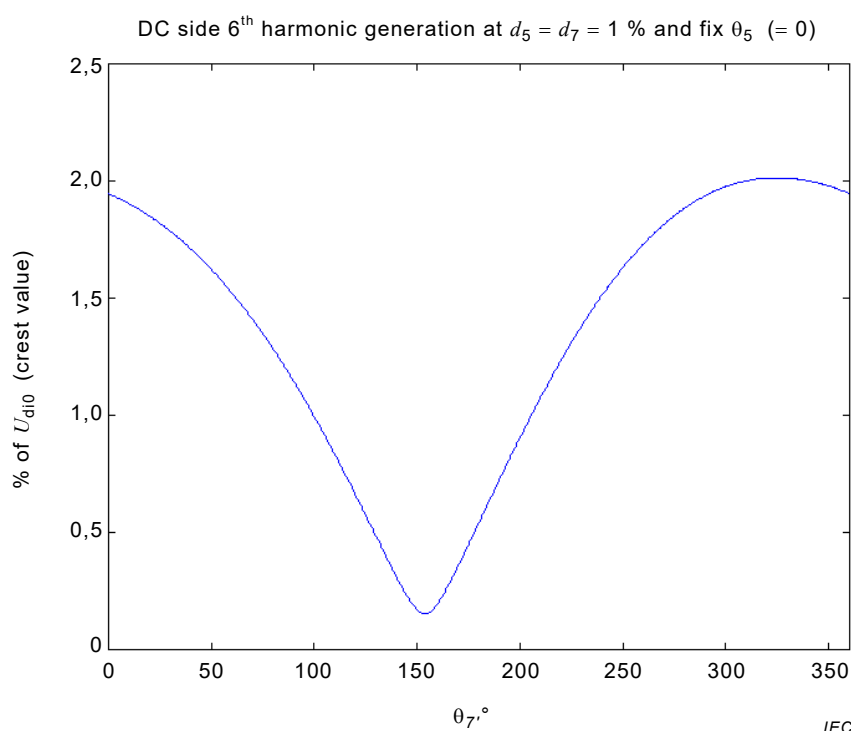


Figure 3 – DC side 6th harmonic voltage due to AC side 5th harmonic (fixed angle) and 7th harmonic (varying angle)

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, R_s , 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.

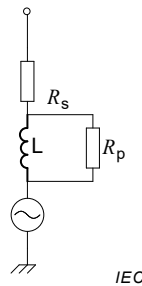


Figure 4 – Simple circuit used to represent AC network impedance at 5th and 7th harmonics

where:

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

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:

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

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 2nd 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 in limiting 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 5th and 7th 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.