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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

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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:

a) expanded and supplemented Clause 6;
b) new Clause 4;
c) new Clause 5;
d) new annexes on the location of worst case network impedance;
e) accuracy of network component modelling at harmonic frequencies;
f) further guidance for the measurement of harmonic voltage distortion;
g) project experience of pre-existing harmonic issues;
h) worked examples showing impact of pre-existing distortion;
i) comparison of calculation methods.

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

Enquiry draft	Report on voting
22F/411/DTR	22F/415/RVC

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

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

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

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

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- withdrawn,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

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

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

INTRODUCTION

The IEC TR 62001 series is structured in four parts:

Part 1 – Overview

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

Part 2 – Performance

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

Part 3 – Modelling

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

Part 4 – Equipment

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

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

Part 3: Modelling

1 Scope

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

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

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

2 Normative references

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

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

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

3 Harmonic interaction across converters

3.1 General

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

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

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

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

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

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

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

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

3.2 Practical experience of problems

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

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

1 Numbers in square brackets refer to the Bibliography.

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

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

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

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

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

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

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

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

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

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

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

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

3.3 Indicators of where harmonic interaction is significant

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

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

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

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