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

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

FOREWORD

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IEC TS 62001-3 has been prepared by subcommittee 22F: Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment. It is a Technical Specification.

This first edition cancels and replaces the first edition of IEC TR 62001-3 published in 2016. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to IEC TR 62001-3:2016:

a) added Clause 3 on terms and definitions;
b) added new Clause 4;
c) rearranged Clause 5, Clause 6 and Clause 7;
d) updated Bibliography.

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

Draft	Report on voting
22F/862/DTS	22F/869/RVDTS

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

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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 document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

– reconfirmed,
– withdrawn, or
– revised.

INTRODUCTION

IEC 62001 (all parts) deals with the specification and design evaluation of AC side harmonic performance and AC side filters for HVDC schemes. It is intended to be primarily for the use of the utilities and consultants who are responsible for issuing the specifications for new HVDC projects and evaluating designs proposed by prospective suppliers.

The IEC TR 62001 series is structured in five parts as follows.

IEC TR 62001-1 – 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.

IEC TS 62001-2 – Harmonic performance aspects

This part deals with telephone interference, current-based interference criteria, field measurements and compliance verification.

IEC TS 62001-3 – Modelling aspects

This part addresses modelling of three specific aspects of design: AC network impedance modelling, the treatment of pre-existing harmonics in performance and rating calculations, and harmonic interaction across converters (cross-modulation).

IEC TR 62001-4 – Equipment

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

IEC TR 62001-5 – AC side harmonics and appropriate harmonic limits for high-voltage direct current (HVDC) systems with voltage sourced converters (VSC)

This part addresses the AC side harmonic performance of voltage sourced converters (VSC).

1 Scope

This part of IEC 62001 provides in-depth consideration regarding three particularly important aspects of design, which are also mentioned elsewhere in other parts of the IEC 62001 series, which are: AC network impedance modelling, the treatment of pre-existing harmonics in performance and rating calculations, and harmonic interaction across converters (cross-modulation).

This document concentrates on passive AC filter technology and line-commutated high-voltage direct current (HVDC) converters, but much of the content is equally relevant to VSC converter technology. Where there is a distinction, this is indicated in the text.

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 specifically designed to be effective in the PLC and radio interference spectra.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

– IEC Electropedia: available at https://www.electropedia.org/

– ISO Online browsing platform: available at https://www.iso.org/obp

3.1
modelling
action of representing a physical situation to enable analysis

4 Overview of modelling

HVDC converter stations are large, complex and costly. Extensive simulations are required to ensure that the HVDC converter station acts as intended and to meet the requirements of the end customer. Such simulations can also be used to configure and adjust the parameters of the HVDC converter station to optimise and enhance the operation and performance.

To ensure that the simulations are realistic, it is important the models used are appropriate to the task in hand. For the purpose of this document, the focus on the modelling is in the frequency domain, although where time domain studies can be more appropriate, this is indicated. Modelling is discussed in many places throughout the various parts of the IEC 62001 series; however, this document focusses in-depth on a number of key aspects of modelling of the HVDC converter.

Clause 5 examines the connected AC system and the appropriate methods of modelling this for representation as a harmonic impedance.

Clause 6 considers the appropriate way to model the harmonic distortion already present in the AC system such that effect of the connection of the HVDC converter is modelled correctly in terms of the changes to the harmonic distortion at various points in the system and the rating of components.

Clause 7 considers the modelling of the active behaviour of the HVDC converter itself in terms of the harmonic inter-connection between the AC and DC sides of the converter, also referred to as cross-modulation.

5 AC network impedance modelling

5.1 General

IEC TR 62001-1 [1][1] and IEC TR 62001-4 [2] discuss the important influence of network harmonic impedance on both the performance and rating aspects of the AC filter design. For a customer, it is one of the most difficult aspects to specify, especially if the customer is not the owner of the network and has little direct knowledge of its composition and possible future development. The purpose of Clause 5 is to amplify the reasons why the correct specification of network harmonic impedance is crucial to an optimal design of AC filters and also to provide further detailed guidance as to its assessment.

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

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

Specifications and design of the AC harmonic filters established at the tender stage normally form part of the later contract. If the customer decides to postpone the detailed network impedance study until execution of the contract, they should be aware of the following disadvantages and manage the risks.

– Received bids are possibly not based on the same assumptions, hence can be difficult to compare.
– Cost and space requirements of the AC filter scheme determined during the tender stage are possibly not sufficient.
– The contractor claims change/variation orders.
– The time needed for the final design stage is prolonged.

[1] Numbers in square brackets refer to the Bibliography.

There are some instances in which the methods for determining the network harmonic impedance described in [3] or in this document is inappropriate or require special consideration. Such situations include the following.

– Where a proposed HVDC scheme is to be connected in parallel with an existing scheme which is operating with adequately designed AC harmonic filters and there is a preference for the filters to be associated with the new scheme to have identical characteristics as the existing units, at least for the converter characteristic harmonics. In this case, any change in the definition of network harmonic impedance from that used for design of the original scheme will require careful consideration of the continuing viability of the existing filters and of the combined operation of the original and new filter designs. This topic is treated in depth in CIGRE Technical Brochure 798 [4].
– Where a proposed HVDC scheme will be connected to an AC network that is only operated in an "islanded" mode; that is a small and well-defined network for which it can be preferable to model the transmission lines, cables, transformers and generators, etc. explicitly rather than to employ impedance envelopes.

5.2 Implications of inaccurate definition of network impedance

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

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

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

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

5.3 Considerations for network modelling

5.3.1 General

IEC TR 62001-1 [1] gives references [5], [6] to various methods of deriving network harmonic impedance.

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

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

5.3.2 Project life expectancy and robustness of data

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

5.3.3 Network operating conditions

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

– System load/generation variation for a maximum demand day.

– System load/generation variation for a minimum demand day.

– System load/generation variation for intermediate demand day(s).

– Different AC system generation connection conditions, for example differing mixes and locations of hydro, nuclear, thermal, wind, solar and other HVDC links. Where nearby generation exists, it is generally recommended that the lowest practical levels of such generation are used for the various scenarios, in order to model the weakest system which for low orders generally gives the largest impedance envelopes.

– Status of reactive compensation plant, both dynamic and fixed (e.g. mechanically switched capacitors and reactors) types. In this respect, all possible combinations of shunt reactive compensation at or close to the converter station AC busbar are considered because, where more than one such device is connected, these are likely to interact, thereby forming differing resonance conditions.

– Similarly, where there is another HVDC link electrically close enough to have a significant impact on the network impedance, it is modelled explicitly, rather than being included as a lumped element within the network, with its associated AC filters being subjected to the effects of their detuning (due to changes in system frequency, ambient temperature, capacitor element failures, etc.) together with the variation in the number and types of filters which can be connected with varying load. See also [4].

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

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

The aim is to develop a network impedance characteristic which is valid for all reasonably possible system developments over the expected life of a project. Even mature networks do not usually have plans beyond the next 20 years to 25 years. It is possible that the network impedance definition therefore has to cover a period up to twice as long as the planning horizon. There is therefore some difficulty in how to cater for the years after the planning horizon and the resultant uncertainties. Some guidance is given in 5.5.4 and 5.5.5 on this topic.

5.3.4 Network impedances for performance and rating calculations

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

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

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

The resultant differences in the variation of network harmonic impedance when comparing "performance" and "rating" conditions can be significant, especially at higher order harmonics. This is discussed in 5.5.8.

5.3.5 Modelling of network components

The reader is directed to [5], [6], [7], [8] and [9] for methods of representing frequency dependent power system elements such as overhead transmission lines, cables, generators, transformers and inverter based resources (IBR) in determining the network harmonic impedance.

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

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