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Guide to the specification and design evaluation of a.c. filters for HVDC systems

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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GUIDE TO THE SPECIFICATION AND DESIGN EVALUATION OF AC FILTERS FOR HVDC SYSTEMS

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IEC-PAS 62001 was submitted by the CIGRÉ (International Council on Large Electric Systems) and has been processed by subcommittee 22F: Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment.

The text of this PAS is based on the following document:	This PAS was approved for publication by the P-members of the committee concerned as indicated in the following document
Draft PAS	**Report on voting**
22F/97/NP	22F/102/RVN

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This PAS shall remain valid for an initial maximum period of three years starting from 2004-07. The validity may be extended for a single three-year period, following which it shall be revised to become another type of normative document or shall be withdrawn.

HOW TO USE THIS GUIDE

The principal purpose of this document is to give guidance to those responsible for:

- preparing the a.c. filtering aspects of Technical Specifications for HVDC projects,
- evaluating the proposed designs, and
- monitoring the subsequent project.

The main objective is to enable informed judgements to be made and future Technical Specifications to be written, such that the resulting a.c. filters are effective yet economical, and are not under- or over-designed.

The Guide has been written by a diverse group including engineers from various manufacturers, utilities and consultants, and the recommendations respect the interests of all parties.

This Guide can be used in different ways by different readers:

- The Guide provides sufficient instructional material so that it can be used as an introduction by those involved in HVDC technology for the first time. An initial reader can omit certain sections and concentrate on core aspects.
- An engineer preparing a Technical Specification can find the key points, which must be considered, highlighted throughout the Guide, and summarised in Section 16.
- The Guide emphasises aspects where the specified requirements can, perhaps unintentionally, have a significant impact on filter design and costs. A user issuing a Technical Specification should consider how these aspects apply to that Specification.
- For evaluating proposed designs and technically monitoring the project, a deeper understanding of many aspects will be required. This document contains guidance reflecting the accumulated knowledge of many HVDC projects, and so will be of value even to highly experienced users. It should help Customers to understand the reasons for differences among filter designs offered by Bidders.
- While making specific recommendations, it has also been necessary to provide a considerable amount of background material. Much of this information has never been brought together under one cover before, and so the Guide will provide a valuable source of reference.
- Additionally, the Guide also contains material which will be of relevance in power industry applications other than HVDC, for example in industrial filtering, switched capacitor applications and general power quality issues.

The Guide has been clearly set-out in sections, each covering specific aspects of a.c. filter design. For guidance on any particular subject, each section may be read individually. Cross-references to other sections are made where necessary.

The brief description below of the contents of each section is intended to assist the reader to use the Guide in the most appropriate way.

- For any reader, it is recommended to start with the short introductory Sections 1 and 2, which explain the justification for the production of this document and also discuss what a Technical Specification must attempt to achieve and the optional approaches regarding what should be included.

- Section 3 tackles the difficult and controversial problem of defining what harmonic distortion limits should be specified. This is a complex subject and one where it is difficult to make unambiguous recommendations, due to the vastly different local circumstances applying to different HVDC projects. The options and implications are covered in detail. However, a non-specialised reader need not go too deeply into this section before proceeding.
- In Section 4, various aspects of converter harmonic generation are discussed, concentrating on those points which could be defined in the Technical Specification, and making recommendations intended to avoid difficulties encountered in previous projects. This section contains essential introductory material.
- In Section 5, the impact of harmonic interaction across the converter is discussed. Recommendations are made as to how this phenomenon should be treated in the practical context of an HVDC project design.
- A brief review of many different a.c. filter configurations is given in Section 6, along with lists of advantages and disadvantages. As well as being of value as a reference, this information may be used in the evaluation of proposed filter solutions.
- The central question of how to calculate a.c. filter performance is treated in Section 7, which brings together various strands from other sections. The definition of a.c. system harmonic impedance is of crucial importance to the filter design, and this section shows the various options available and discusses the relative merits of each.
- The specification and design of a.c. filtering equipment is closely linked to the other main function of a.c. filters, which is to provide reactive compensation. The specified requirements on reactive compensation, and how these will influence the cost and complexity of the filter design, are covered in Section 8.
- Sections 9, 10 and 11 define how the steady-state rating, the transient rating, and the losses of a.c. filters are to be calculated, and what should be specified in this respect.
- Numerous aspects of valuable practical experience are brought together in Section 12, which discusses special areas of design not covered elsewhere in the document and what influence these aspects could have on a Specification. This section will be of value particularly to those with an in-depth knowledge of the subject
- Section 13 covers aspects of a.c. filter protection, providing sufficient information to enable an evaluation to be made of particular proposed protection schemes
- Sections 14 and 15 deal with the specialised areas of seismic design and audible noise, which in some instances can have a significant impact on the physical design, cost and layout of an a.c. filter installation.
- A summary of all the important parameters and requirements which must be specified by the Customer in a Technical Specification, is given in Section 16. This summary lists the key points which have been discussed in depth elsewhere in the Guide, and makes suitable cross-references.
- Section 17 contains a detailed description of what should be specified regarding the detailed design and testing of each item of filter equipment.
- Field measurements, and verification that the specified performance is achieved in service, are discussed in Section 18, which concentrates on those aspects which need to be clearly defined in the Technical Specification in order to avoid subsequent contractual conflict.
- Finally, the expected impacts of new technologies in the fields of HVDC converters and a.c. filters are discussed in Section 19.

In some sections, detailed background material and equations have been set aside in small Appendices.

A substantial list of references is included, in Section 20.

1. INTRODUCTION AND OBJECTIVES

1.1 General

This document is a Guide to the specification and design evaluation of a.c. side harmonic performance and a.c. 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 Technical Specifications for new HVDC projects and evaluating designs proposed by prospective suppliers.

1.2 Definitions

The term “Technical Specification” or “Specification” used in this Guide is taken to mean the document which defines the overall system requirements for the a.c. filters and the a.c. system environment in which they have to operate. Such a document is normally issued by utilities to the prospective HVDC manufacturers. It also ensures the uniformity of proposals and sets guidelines for the evaluation of bids. The term as used here does not refer to the detailed engineering specifications relating to individual items of equipment, which are prepared by the HVDC manufacturer as a result of the filter design process.

The Technical Specification defines the technical basis for a contract between two parties, who in this Guide will be referred to as the “Customer” and the “Contractor”.

- The “Customer” is the organisation which is purchasing the HVDC converter station, including the a.c. filters. The term “Customer” is taken to cover similar terms which may be used in specifications, such as Owner, Client, Buyer, Utility, User, Employer and Purchaser, and also covers a Consultant representing the Customer.
- The “Contractor” has the overall responsibility for delivery of the HVDC converter station, including the a.c. filters, as a system, and may in turn contract one or more sub-suppliers of individual items of equipment. The term “Contractor” is taken to cover similar terms which may be used in specifications, such as Manufacturer, or Supplier.

Where the context clearly refers to the pre-contract stage of a project, the word “Bidder” has been used instead of “Contractor”, to indicate a prospective Contractor, or Tenderer.

1.3 Introduction

When installing an HVDC converter station in an a.c. system, the way in which it may affect the quality of power supply in that system is always an important issue. One of the main power quality topics is that of harmonic performance.

The a.c. side current of an HVDC converter has a highly non-sinusoidal waveform, and, if allowed to flow in the connected a.c. system, might produce unacceptable levels of distortion. A.C. side filters are therefore required as part of the total HVDC converter station, in order to reduce the harmonic distortion of the a.c. side current and voltage to acceptably low levels.

HVDC converters also consume substantial reactive power, a large proportion of which must normally be supplied locally within the converter station. Shunt connected a.c. filters appear as capacitive sources of reactive power at fundamental frequency, and normally in conventional HVDC schemes the a.c. filters are used to compensate most or all of the reactive consumption of the converter. Additional shunt capacitors and reactors may also be used to ensure that the desired reactive balance is maintained within specified limits under defined operational conditions.

The design of the a.c. filters therefore normally has to satisfy these two requirements of harmonic filtering and reactive power compensation, for various operational states and load levels. Optimisation of this design is the task of the a.c. filter designer, and the constraints under which the design is made are defined in the Technical Specification.

The a.c. filters form a substantial part of a conventional HVDC converter station. The fundamental reactive power rating of the a.c. filters (including shunt capacitors where applicable) at each converter station has

typically been in the range of 50% - 60% of the active power rating of the scheme. Together with the required switchyard equipment, the a.c. filters can occupy over half of the total land requirements of an HVDC scheme. The cost of manufacture, installation and commissioning of the a.c. filter equipment is significant, being typically in the approximate range of 10% of the total station costs. In addition, the filter design studies can be extensive and may have an impact on many other aspects of station design [Ref. 1-1, 1-2] and on the total project schedule. Once in operation, the a.c. filters will continue to have a major importance due to requirements for switching, maintenance, component spares, and reliability.

It is therefore important that the way in which the requirements for the a.c. filters are specified is such as to allow the design to be optimised in terms of all the above factors, while fulfilling the essential functions of disturbance mitigation and reactive power compensation.

The scope of this Guide covers a.c. 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.

1.4 Past experience

In practice, there have been few problems of harmonic disturbance from HVDC schemes and few problems relating to a.c. filter equipment in operation. Section 12 discusses some application problems, while analyses of some filter reactor failures may be found in Ref. 1-3. Further information on experience with existing a.c. filter schemes is available through the “HVDC Users’ Group”.

This past experience indicates that designs in general have been at least adequate. However, it is not obvious to what extent this satisfactory experience might indicate that a.c. filters in some instances may have been over-designed, and that a more economical design might have been possible.

One of the fundamental problems in specifying a.c. filters is that some of the essential design data is not readily available. The harmonic impedance of the a.c. system is of paramount importance to the design, and yet is difficult to measure or calculate for all operational conditions, both at present and during the future operational life of the scheme. The level of existing harmonic distortion to be considered is another factor which is difficult to measure or predict, as is the extent to which existing or future telecommunication systems may be affected by harmonic currents flowing in the a.c. network. The tolerance to harmonics of existing and future equipment such as motors and electronic loads, connected to the power system itself, is also difficult to evaluate.

Other factors affecting the filter design have, in the past, been difficult to calculate accurately with the available tools. Most prominent of these is the effect of the harmonic interaction between the a.c. and d.c. sides of the converter which, while well understood in theory, has been difficult to incorporate consistently into the design process.

One important aspect of the filtering scheme is the eventual ease of operation. Complex switching schemes with several different types and sizes of a.c. filter bank may fulfil rigorous requirements on performance and reactive power exchange, but the practical consequences and costs of lifetime operation should also be considered.

Historically, there has been a wide variation in the content and requirements of Technical Specifications of a.c. filters for different HVDC projects. There have developed several near-standard types of specification, associated with certain utilities and consultants, but even these are adapted to suit individual projects.

1.5 Objectives

In preparing this Guide, CIGRÉ Working Group 14.30 has attempted to:

- examine previous a.c. filter specifications and consider relative merits,
- consider field experience and draw conclusions,
- review results of previous and current CIGRÉ work on voltage and current limits, on a.c. system modelling, and on a.c./d.c. harmonic interaction and consider how the recommendations resulting from this work can usefully be incorporated in future specifications for HVDC projects,
- take note of other relevant work in CIGRÉ and the IEEE,
- examine how particular aspects of specification can have a significant influence on the design and costs,
- look forward to the likely impact of new technologies, both in the HVDC field and in related areas such as telephone technology,
- make recommendations based on all of the above,
- provide information to facilitate reasoned decisions in the preparation of future Technical Specifications and the evaluation of prospective designs.

In doing so, the Working Group sought to bring together the experience, and consider the interests, of all sectors of the HVDC community and to produce a Guide which, while primarily intended for the use of utilities and consultants, will be of interest to all parties.

1.6 Approach

The Guide attempts to review all possible aspects to be covered in a specification and the subsequent design evaluation, and to give a more detailed analysis of critical or contentious points.

The technical background to each subject area is described briefly, and reference made to further sources of information, in order to provide the background and context for the decisions to be made.

Where it is possible to make clear recommendations, these are given in the Guide. In other instances, where there may be different ways to approach some aspect, then the different approaches and their consequences are described. The intention in such instances is to enhance awareness of the implications of different possible approaches.

The Guide gives a comprehensive treatment of most aspects of the subject. This does not imply that a Technical Specification needs to mention all the aspects included in this Guide. In some circumstances a simple and open Specification may be preferable. However, while preparing any Specification, those responsible should at least be aware of, and consider, all the points discussed in this Guide. In the eventual design evaluation phase, most of the material included in this Guide will be of relevance.

New technologies which are currently being introduced into HVDC systems will, where applied, substantially alter many aspects of a.c. filter design. Foremost of these are the series compensated converter, the automatically continuously tuned reactor, and active filters.

To introduce throughout this Guide the radically different approaches which such new technologies require, would have led to a clumsy presentation. Instead, the bulk of the Guide concentrates on the “conventional” a.c. filter technology and current-source line-commutated HVDC converters. Discussion of the changes entailed by new technologies is treated exclusively in Section 19. Other unusual applications, such as series filters, which use conventional technology but are only employed in very specific circumstances, are discussed in Section 12.