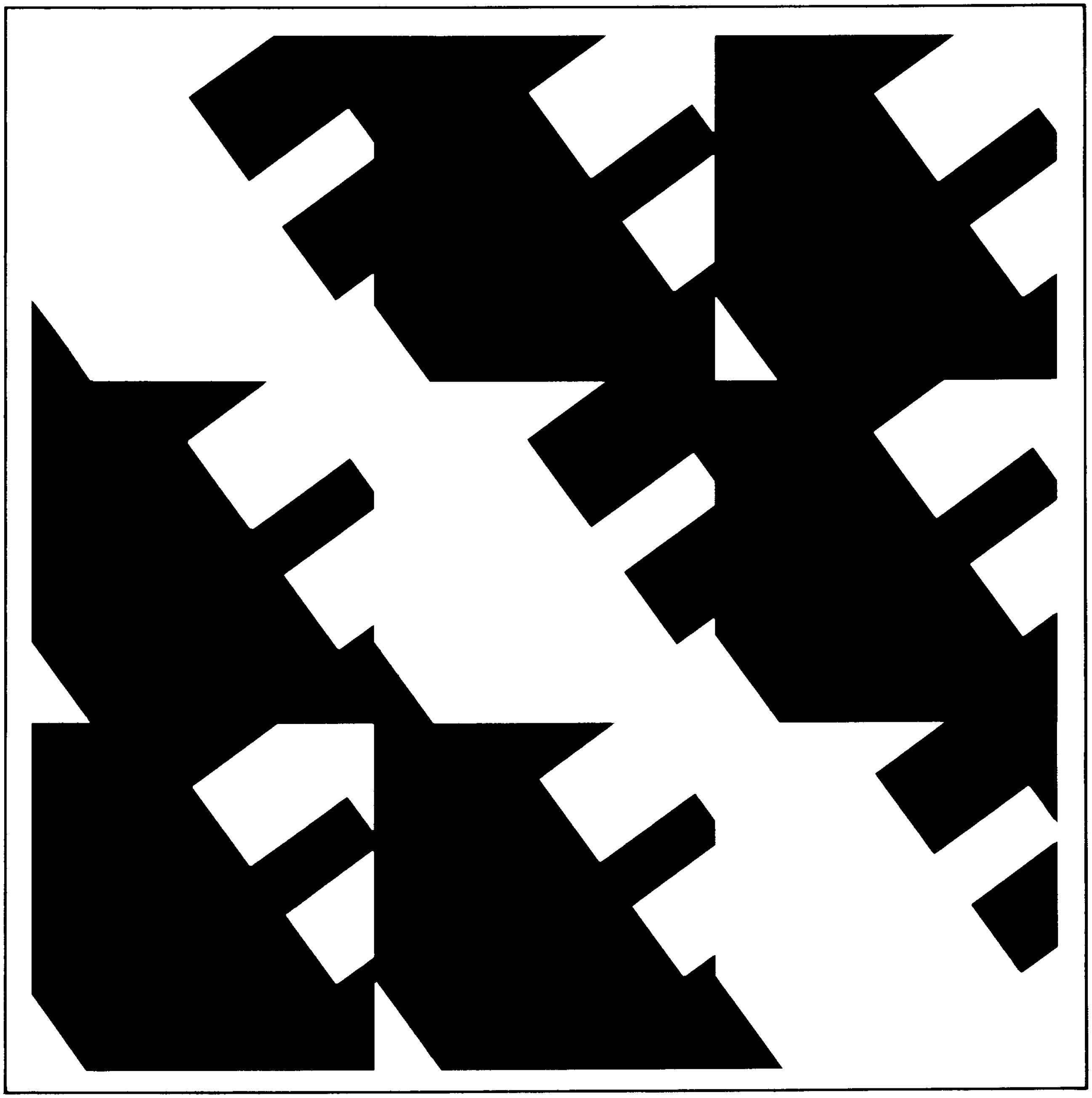
AMERICAN NATIONAL STANDARD

ANSI/IEEE Std 1030-1987

IEEE Guide for Specification of High-Voltage Direct-Current Systems Part I — Steady-State Performance



ANSI/IEEE Std 1030-1987

Published by The Institute of Electrical and Electronics Engineers, Inc 345 East 47th Street, New York, NY 10017, USA

May 12, 1988

SH11569

ANSI/IEEE
Std 1030-1987

An American National Standard

IEEE Guide for Specification of High-Voltage Direct-Current Systems

Part I
Steady-State Performance

Sponsor

Substation Committee and Transmission and
Distribution Committee of the
IEEE Power Engineering Society

Approved March 12, 1987

IEEE Standards Board

Approved September 11, 1987

American National Standards Institute

The Institute of Electrical and Electronics Engineers, Inc
345 East 47th Street, New York, NY 10017, USA

IEEE Standards documents are developed within the Technical Committees of the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Board. Members of the committees serve voluntarily and without compensation. They are not necessarily members of the Institute. The standards developed within IEEE represent a consensus of the broad expertise on the subject within the Institute as well as those activities outside of IEEE which have expressed an interest in participating in the development of the standard.

Use of an IEEE Standard is wholly voluntary. The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE Standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard. Every IEEE Standard is subjected to review at least once every five years for revision or reaffirmation. When a document is more than five years old, and has not been reaffirmed, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE Standard.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of all concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason IEEE and the members of its technical committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration.

Comments on standards and requests for interpretations should be addressed to:

Secretary, IEEE Standards Board
345 East 47th Street
New York, NY 10017
USA

IEEE Standards documents are adopted by the Institute of Electrical and Electronics Engineers without regard to whether their adoption may involve patents on articles, materials, or processes. Such adoption does not assume any liability to any patent owner, nor does it assume any obligation whatever to parties adopting the standards documents.

Foreword

(This Foreword is not a part of ANSI/IEEE Std 1030-1987, IEEE Guide for Specification of High-Voltage Direct-Current Systems, Part I — Steady-State Performance.)

This guide is based on a standard prepared by the International Electrotechnical Commission, (IEC), Document 22F, Performance of HVDC Systems, Part I, Steady-State Conditions. It was jointly sponsored by the DC Converter Stations Subcommittee of the IEEE Substation Committee and the Direct-Current Transmission Subcommittee of the IEEE Transmission and Distribution Committee.

The members of the IEEE DC Converter Stations Subcommittee that reviewed and approved this guide were as follows:

M. L. Holm, *Chairman*

Clifford C. Diemond, *Vice Chairman*

M. P. Bahrman
L. Bergstrom
J. P. Bowles
G. D. Breuer
J. A. Buchsbaum
A. F. Buelow
T. U. Cheng
R. E. Harrison
N. G. Hingorani*
G. Karady
A. E. Kilgour
E. Kolodziej
W. O. Kramer
P. C. S. Krishnayya
A. A. Leibold
P. Lips
W. F. Long
D. Mukhedkar
P. H. Nannery
J. Nelson
J. Paolozzi
J. Reeve
J. Sabath
J. Slapp
K. O. Sommer
C. F. Troesch
L. Vancers
T. W. Williams

*Past chairman

The members of the IEEE Direct-Current Transmission Subcommittee that reviewed and approved this guide were as follows:

S. Nilsson, *Chairman*

R. J. Piwko, *Secretary*

M. P. Bahrman
M. Baker
L. Bateman
L. Bergstrom
H. B. Biggs
J. P. Bowles
G. D. Breuer
C. C. Diemond
J. J. Dougherty
C. E. Grund
H. E. Harrison
D. P. Hartmann
N. G. Hingorani
G. Karady
A. E. Kilgour
P. C. S. Krishnayya
C. M. Lane, Jr
R. H. Lasseter
R. Lee
T. H. Lee
P. Lips
W. F. Long
M. F. McGranaghan
H. Martensson
E. A. Neal, Jr
R. V. Pohl
D. T. Poznaniak
F. F. Prabhakara
J. Reeve*
J. Slapp
E. C. Starr
M. Z. Tarnawecky
A. B. Turner
J. J. Vithayathil
D. A. Woodford

* Past chairman

The Joint Task Force of the Substation and the Transmission and Distribution Committees that prepared this guide had the following membership at the time it was submitted for approval:

Clifford C. Diemond, *Chairman*

John P. Bowles
G. D. Breuer
Dennis P. Carroll
C. E. Grund
R. E. Harrison
David P. Hartmann
N. G. Hingorani
George Karady
W. O. Kramer
P. C. S. Krishnayya
S. R. Lambert
E. V. Larsen
T. H. Lee
Michael Lebow
Peter Lips
Willis F. Long
David J. Melvold
A. J. Molnar
Stig Nilsson
T. L. Ong
John Reeve
E. C. Starr
M. Z. Tarnawecky
C. V. Thio

The IEEE Substation Committee that reviewed and approved this guide had the following membership:

J. Sabath, *Chairman*

C. J. Blattner, *Vice Chairman*

P. R. Nannery, *Secretary*

W. J. Ackerman
B. T. Afsher
J. D. Betz
W. R. Block
R. H. Bower
S. D. Brown
J. B. Cannon
J. W. Cheever
S. Cluts
E. F. Counsel
F. A. Denbrock
W. K. Dick
C. C. Diemond
P. R. Dolan
L. N. Ferguson
A. Haban
G. E. Heidenreich
N. G. Hingorani
J. E. Holladay
M. L. Holm
D. C. Johnson
E. F. Jones
G. Karady
H. P. Keil
D. F. Koenig
T. J. Kolenda
A. E. Kollar
L. W. Kurtz
D. Laird
L. M. Laskowski
K. P. Lau
A. A. Leibold
P. Lips
J. A. Maneatis
T. S. McLenahan
C. Minshew
J. T. Orrell
J. Paolozzi
S. G. Patel
R. J. Perina
T. A Pinkham
E. S. Raila
W. E. Richard
B. D. Russell
D. R. Schafer
K. O. Sommer
R. C. St. Clair
J. G. Sverak
W. K. Switzer
E. H. Taylor, Jr
H. M. Tucker
W. J. Wehling
B. W. Wray
R. M. Youngs
C. E. Zanzie

The Transmission and Distribution Committee that reviewed and approved this guide had the following membership:

D. D. Wilson, *Chairman*

V. L. Chartier, *Vice Chairman*

D. L. Nickel, *Secretary*

J. G. Anderson
J. W. Atman
P. L. Bellaschi
H. E. Brokenshire
K. H. Chakravarthi
M. Charest
A. A. Chase
W. H. Cole
F. A. Denbrock
C. C. Diemond
J. J. Dougherty
F. J. Ellert
J. C. Engimann
G. V. Fantozzi
W. S. Feero
C. M. Ferguson
L. H. Fink
W. G. Finney
R. W. Flugum
W. N. Fredenberg
D. A. Gillies
I. S. Grant
L. P. Hamilton
E. L. Harris
W. S. C. Henry
M. H. Hesse
J. W. Hipke
W. Janischewskj
J. G. Kappenmann
G. Karady
D. C. Keezer
A. E. Kilgour
K. W. Klein
F. W. Koch
N. Kolcio
P. C. S. Krishnayya
J. Lapp
W. F. Long
J. H. Mall
P. S. Maravuda
J. T. Morgan
F. D. Myers
J. L. Nicholls
G. B. Niles
S. L. Nilsson
H. G. Oswold
H. L. Patterson
T. A. Pinkham
C. K. Poarch
J. C. Poffenberger
J. Reeve
R. L. Retallack
F. A. M. Rizk
H. Rocamora
J. B. Roche
W. J. Ros
H. C. Seebald
M. Sforzini
D. F. Shankle
J. M. Silva
E. C. Starrory
W. E. Triplett
J. M. Van Name
S. S. Venkata
A. C. Westrom
H. B. White
F. S. Young

The following persons were on the balloting committee that approved this document for submission to the IEEE Standards Board.

Substations Committee

W. J. Ackerman
B. Y. Afshar
J. D. Betz
C. J. Blattner
W. R. Block
R. H. Bower
S. D. Brown
J. B. Cannon
J. W. Cheever
S. Cluts
E. F. Counsel
F. A. Denbrock
W. K. Dick
C. C. Diemond
P. R. Dolan
L. N. Ferguson
A. Haban
G. E. Heidenreich
N. G. Hingorani
J. E. Holladay
M. L. Holm
D. C. Johnson
E. F. Jones
G. Karady
R. P. Keil
D. F. Koenig
T. J. Kolenda
A. E. Kollar
W. O. Kramer
L. W. Kurtz
D. N. Laird
L. M. Laskowski
A. A. Leibold
P. Lips
J. A. Maneatis
T. S. McLenahan
C. Minshew
P. R. Nannery
T. L. Ong
J. T. Orrell
J. Paolozzi
S. G. Patel
R. J. Perina
T. A. Pinkham
E. S. Raila
W. E. Richard
B. D. Russell
J. Sabath
D. R. Schafer
K. O. Sommer
R. C. St. Clair
J. G. Sverak
W. K. Switzer
E. R. Taylor, Jr
H. M. Tucker
W. J. Wehling
B. W. Wray
R. M. Youngs
C. E. Zanzie

Transmission and Distribution Committee

J. W. Atman
J. G. Anderson
P. L. Bellaschi
G. D. Breuer
R. E. Brokenshire
D. P. Carroll
K. R. Chakravarthi
M. Charest
V. L. Chartier
A. A. Chase
W. H. Cole
J. J. Dougherty
F. J. Ellert
J. C. Engimann
G. V. Fantozzi
W. E. Ferro
C. M. Ferguson
L. H. Fink
W. G. Finney
R. W. Flugum
W. N. Fredenberg
D. A. Gillies
W. M. Grady
I. S. Grant
C. E. Grund
L. F. Hamilton
E. L. Harris
R. E. Harrison
D. P. Hartmann
W. S. C. Henry
M. H. Hesse
J. W. Hipke
W. Janischewskj
J. G. Kappenmann
D. C. Keezer
A. E. Kilgour
K. W. Klein
F. W. Koch
N. Kolcio
P. C. S. Krishnayya
J. Lapp
E. V. Larsen
M. A. Lebow
R. F. Lee
W. F. Long
J. H. Mallory
P. S. Maravuda
D. J. Melvold
J. T. Morgan
F. D. Myers
J. L. Nicholls
D. L. Nickel
G. B. Niles
S. L. Nilsson
R. G. Oswold
R. L. Patterson
C. K. Poarch
J. C. Poffenberger
F. S. Prabhakara
J. Reeve
R. L. Retallack
F. A. M. Rizk
R. Rocamora
J. B. Roche
W. J. Ros
R. C. Seebald
M. Sforzini
D. F. Shankle
J. M. Silva
M. E. C. Starr
M. Z. Tarnawecky
C. V. Thio
W. E. Triplett
J. M. Van Name
S. S. Venkata
A. C. Westrom
H. B. White
D. D. Wilson
F. S. Young

Contents

FIGURES

TABLES

An American National Standard

IEEE Guide for Specification of High-Voltage Direct-Current Systems

Part I
Steady-State Performance

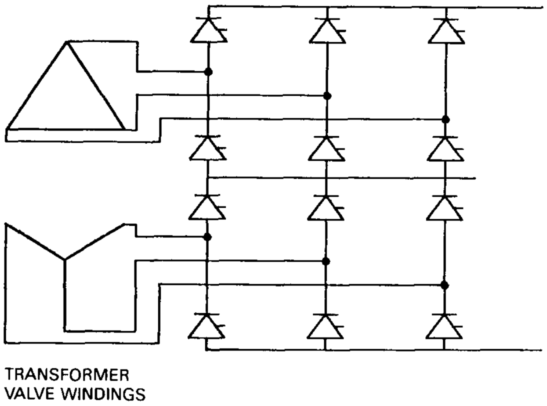
1. Scope and References

1.1 Scope. This guide provides general guidance on the steady-state performance requirements of high-voltage direct-current (HVDC) systems. It concerns the steady-state performance of two-terminal HVDC systems utilizing 12-pulse converter units consisting of three-phase bridge (double way) connections (see Fig 1). Excluded are multiterminal HVDC transmission systems. Both converters are assumed to use thyristor valves as the main semiconductor valves and to have power flow capability in both directions. No consideration is given herein to diode valves.

This guide, which covers steady-state performance, is accompanied by companion documents for dynamic and transient performance. All three aspects should be considered when preparing two-terminal HVDC system specifications.

The user is cautioned to be aware of the difference between system performance specifications and equipment design specifications for individual components of a system. While equipment specifications and testing requirements are not defined in this guide, attention is drawn to many of those that could directly affect performance specifications for the system. Also excluded from this guide are the matters of detailed seismic performance requirements. In addition, because there are many variations between different possible HVDC systems, this guide does not consider these in detail, consequently it should not be used directly as a specification for a specific project, but rather to provide the basis for an appropriate specification tailored to fit an actual system's requirements.

Fig 1
Twelve-Pulse Converter Unit



Frequently, performance specifications are prepared as a single package for both HVDC substations in a particular system. Alternatively, some parts of the HVDC system can be separately specified and purchased. In such cases due consideration should be given to coordination of such part with the overall HVDC system performance objectives and the interface of each with the system must be clearly defined. Data and parameters for such separate purchases must be obtained from one overall set of system studies. Typical of such parts, listed in the order of relative ease for separate treatment and interface definition are:

(1) DC line, electrode line, and earth electrode
(2) Telecommunication system
(3) Converter building, foundations, and other civil work
(4) Reactive power supply including ac shunt capacitor banks, shunt reactors, synchronous and static var compensators
(5) AC filters
(6) DC filters
(7) Auxiliary systems
(8) AC and dc switchgear
(9) DC reactors
(10) Converter transformers
(11) Surge arresters
(12) Valves and their ancillaries

(13) Control and protection systems

Items (12) and (13) are the most difficult to separate and separation of these two may be inadvisable.

1.2 References

[1] HVDC System Control for Damping of Subsynchronous Oscillations. EPRI EL-2708, Oct 1982.

[2] LARSON, E. V., PIWKO, R. J., and PATEL, H. S. The Effect of HVDC Systems on Turbine-Generator Torsional Vibrations — Focus on Solution and Impact on System Planning. 1981 American Power Conference Record.

[3] MORTENSEN, K., LARSON, E. V., and PIWKO, R. J. Field Tests and Analysis of Torsional Interaction Between the Coal Creek Turbine Generators and the CU HVDC System. *IEEE Transactions*, vol PAS-100, no 1, Jan 1981, p 336.

[4] HVDC Ground Electrode Design. International Engineering Company, Inc. *Electric Power Research Institute Report* EL-2020, Aug 1981.

[5] CIGRE, Protocol for Reporting the Operational Performance of HVDC Transmission Systems. 14-80 (WG 04) 14.

[6] ISO 1996/1-1982, Acoustics — Description and Measurement of Environmental Noise. Part 1: Basic Quantities and Procedures.

[7] Bell Telephone Systems (BTS) and Edison Electric Institute (EEI), C-Message Weighting.

[8] CCITT, International Telegraph and Telephone Consultive Committee, Psophometric Weighting.

[9] CCITT, American Telephone and Telegraph Company (AT&T) and the US Rural Electrification Administration (REA).

[10] CCITT Directives Concerning the Protection of Telecommunications Lines Against Harmful Effects from Electricity Lines, ITU 1983.

[11] PATTERSON, N. A. and FLETCHER, D. E. The Equivalent Disturbing Current Method for DC-Transmission Line Inductive Coordination Studies and DC-Filter Performance Specification. Montreal HVDC Conference, June 1984.

[12] CISPR Publication 16, International Special des Perturbations Radio Electriques.

[13] IEC Publication 146, Semiconductor Converters.

[14] ARRILLAGA, J. High-Voltage Direct-Current Transmission. London: Peter Perigrinus Ltd, 1983, pp 245.

[15] KIMBARK, E. W. Direct-Current Transmission. New York: Wiley-Interscience. 1971, pp 508.

2. Outline of Steady-State HVDC System Performance Specification

A complete steady-state performance specification for an HVDC system should consider the following items:

Section No	
3.	Types of HVDC systems
4.	Environment
5.	Rated power, voltage, and current
6.	Overload and equipment capability
7.	Minimum power transfer and no-load standby state
8.	AC system
9.	Reactive power
10.	DC line, electrode line and ground electrode
11.	Reliability
12.	Control and metering
13.	Telecommunication
14.	Auxiliary power supplies
15.	Audible noise
16.	Harmonic interference — ac
17.	Harmonic interference — dc
18.	Power line carrier interference
19.	Radio interference
20.	Losses
21.	Provision for expansion to the HVDC system.

The items listed above are covered in this guide. Equipment items are often separately specified and purchased. The dc line, electrode line and ground electrode (see Section 10) are included only because of their relationships with the HVDC substations.

For the purpose of this guide, a converter station is assumed to consist of one or more converter units installed in a single location together with buildings, reactors, filters, reactive power supply, control, monitoring, protective, measuring and auxiliary equipment. While there is no discussion of the ac switching substations in this guide, ac filters and var banks may be connected to an ac bus separate from the HVDC substation as discussed in Section 16.

3. Types of HVDC Systems

3.1 General. This part of the specification should include the following basic data:

(1) General information on the location of HVDC substations and the purpose of the project

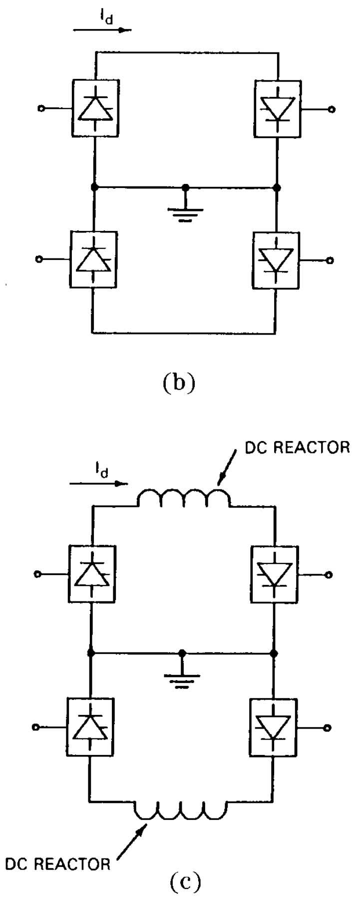
(2) Type of system needed, including a simple one-line diagram

(3) The number of 12-pulse converter units

(4) Pertinent information derived from the discussion in this section

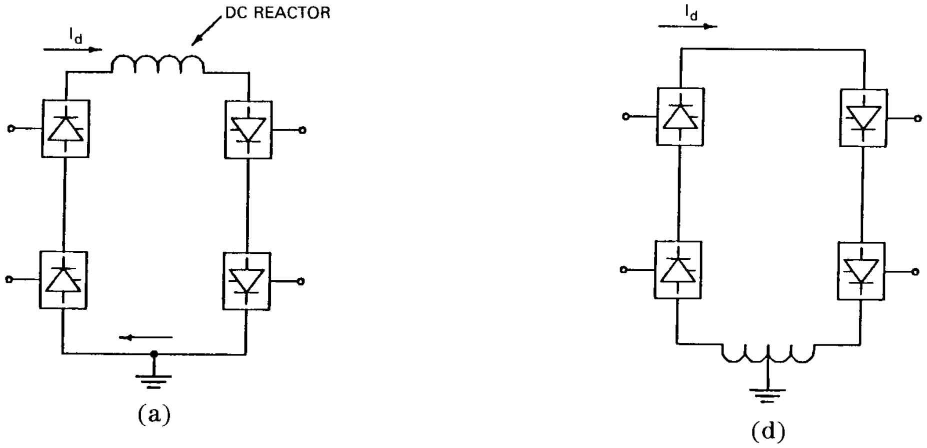
Generally, in studies of projects of the types discussed in this guide, economic considerations should take into account the capital costs, the cost of losses, and the other expected annual expenses.

3.2 HVDC Back-to-Back Ties (Fig 2). In this arrangement there is no dc transmission line and both converters are located at one site. The valves for both converters may be located in one valve hall, or even in one integrated structure. Similarly, many other items for the two converters, such as the control system, cooling equipment, and auxiliary system, may be located in one area or even integrated in layout into configurations common to the two converters. Circuit configurations may vary. Examples are given in Fig 2 (a), (b), (c), and (d). The performance and economics of these configurations differ and should be evaluated. DC filters are not needed.



(b)

(c)



(a)

(d)

(a) With one smoothing reactor and one dc system ground
(b) With one dc system ground and no smoothing reactors
(c) With one dc system ground and two smoothing reactors
(d) With one smoothing reactor, center point grounded

Fig 2
Examples of Back-to-Back HVDC Systems

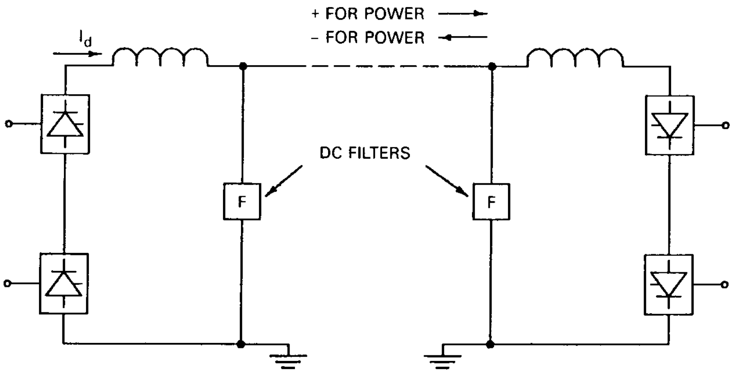


Fig 3
Monopolar Ground Return System

The voltage and current ratings for a given power rating should be optimized to achieve the lowest converter cost, including the evaluated cost of losses. As a rule then, with no line losses to consider, the voltage rating will be low and the current rating high in comparison with schemes that include overhead lines and cables. Ordinarily the user does not need to specify the direct voltage and current ratings, unless there are specific reasons to do so: for example, for compatibility with an already existing station or to provide for a future expansion. Economics dictate that each converter usually will be a 12-pulse converter unit. Where operating criteria require that loss of one converter unit will not cause loss of full power capability, large HVDC substations could be comprised of two or more back-to-back ties. For this, some of the equipment can be located in the same area or even physically integrated between the back-to-back ties for economic reasons.

3.3 Monopolar Ground Return HVDC System (Fig 3). Cost considerations often lead to adoption of a monopolar ground return system, particularly for cable transmission, which often is expensive. The monopolar ground return configuration might also be the first stage in development of a bipolar scheme. Monopolar arrangements may include one or more 12-pulse units in series or parallel at the ends of the HVDC transmission (Figs 4 and 5). More than one 12-pulse unit might be used:

(1) To ensure partial transmission capacity during converter unit outages

(2) To complete the project in stages

(3) Because of physical limitations of transformer transport

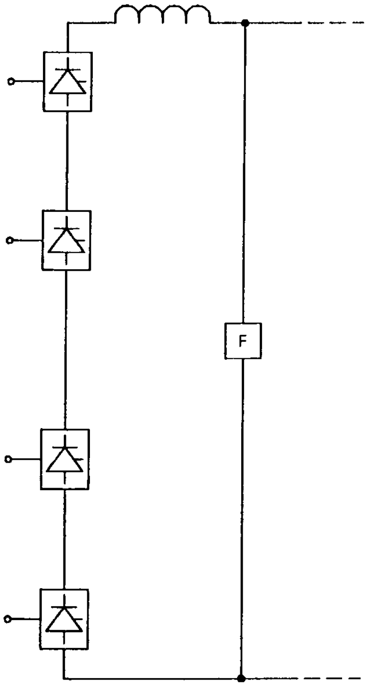


Fig 4
Two Twelve-Pulse Units in Series

This arrangement requires one or more dc reactors at each end of the HVDC overhead line or cable; these are usually located on the high-voltage side. However, the dc reactors may be located on the ground side when the resulting performance is acceptable. When the line is overhead, dc filters

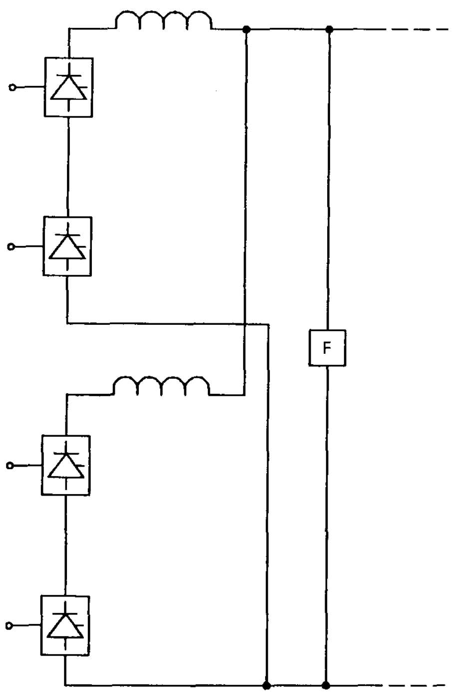


Fig 5
Two Twelve-Pulse Units in Parallel

are likely to be needed at each end (see Section 17). It also requires an electrode line and a continuously operable ground electrode at the two ends of the transmission. This involves consideration of issues such as possible interference with other underground or underwater metallic structures, and magnetic field effects.

3.4 Monopolar Metallic Return HVDC System (Fig 6). This configuration will generally be used:

(1) As the first stage in construction of a bipolar system and if long-term flow of ground current is not desirable during the interim period, or

(2) If the transmission line length is short enough to make it uneconomical and undesirable to build electrode lines and ground electrodes, or

(3) If the earth resistivity is high enough to impose an unacceptable economic penalty

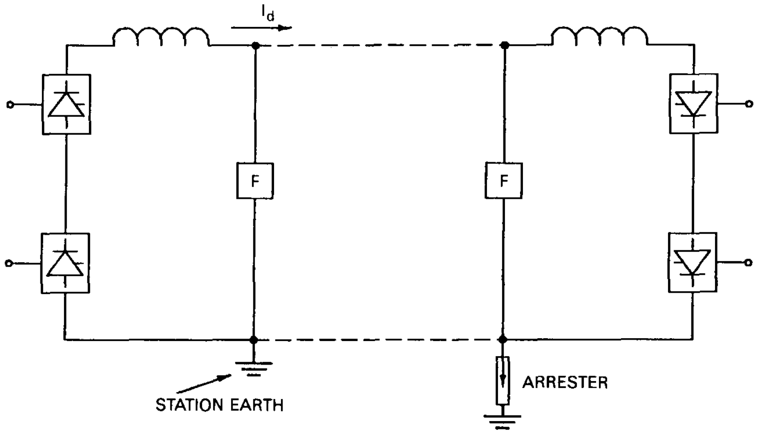
It utilizes one high-voltage and one low-voltage conductor. The neutral is tied at one of the two HVDC substations to its station ground or alternatively to the associated ground electrode. The other HVDC substation neutral is tied to its station ground either through a capacitor or an arrester, or both.

DC reactors are needed at both ends of the high-voltage conductor. However, the dc reactor may be located on the ground side when the resulting performance is acceptable. DC filters almost certainly will be needed if the dc line is overhead.

If this configuration is the first stage of a bipolar system, its neutral conductor could be insulated from the high voltage at this stage of development.

3.5 Bipolar HVDC System (Figs 7 and 8). This is the most commonly used arrangement when a dc transmission line connects two HVDC substations. Insofar as lightning performance of the line is concerned, it is effectively equivalent to a double circuit ac transmission. It reduces harmonic interference from the dc line as compared

Fig 6
Monopolar Metallic Return System



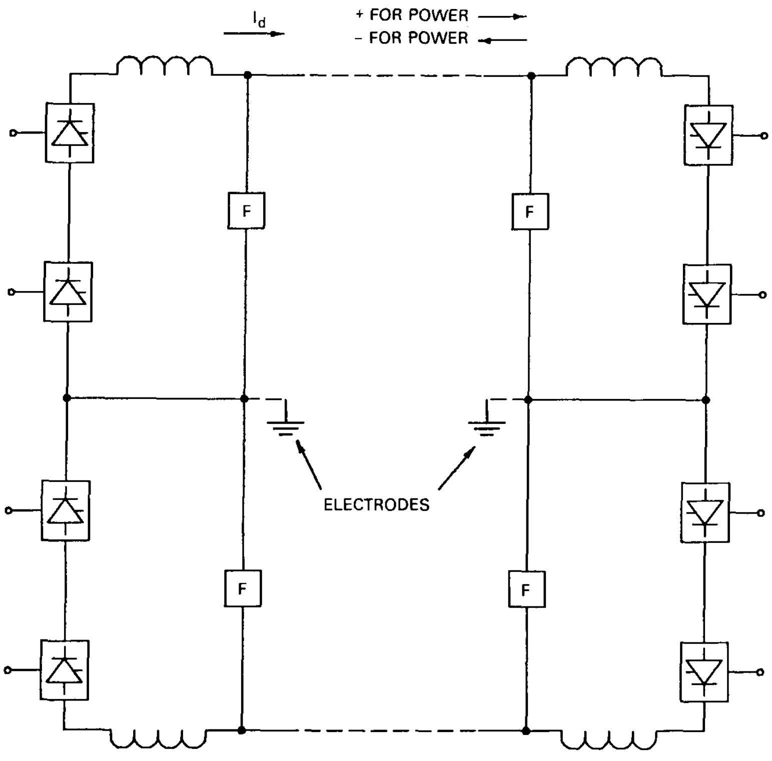


Fig 7
Bipolar System

with monopolar operation and it holds ground current flow to a small value. When combined, two monopolar ground return schemes give a bipolar scheme.

For power flow in one direction, one pole has positive polarity to ground and the other pole has negative polarity to ground. For power flow in the other direction the two poles reverse their polarities. When both poles are in operation, the imbalance current flow in the ground path can be held to a very low value.

This configuration offers the opportunity for a number of emergency operating modes. Consequently the requirements in 3.5.1 to 3.5.6 should be considered in the specifications.

3.5.1 During an outage of one HVDC transmission line pole, converter equipment of the other pole should be capable of continuous operation with ground return.

3.5.2 If long-term flow of ground current is undesirable and if the defective line pole still retains some less-than-normal voltage insulating capability, the bipolar system should be capable of operation in the monopolar metallic return mode (Fig 8). To switch into this emergency operating mode, the conductor of the off-pole is first connected in parallel with the ground path and then the ground path is interrupted to transfer the current to the metallic path (through the conductor of the off-pole). Load transfer without interruption requires a metallic return transfer breaker (MRTB) at one terminal of the dc transmission. When a short interruption of power flow is permitted, an MRTB is not necessary. The neutral equipment at the MRTB end of the HVDC transmission system must be insulated from ground for a somewhat higher voltage than at the other end of the system.

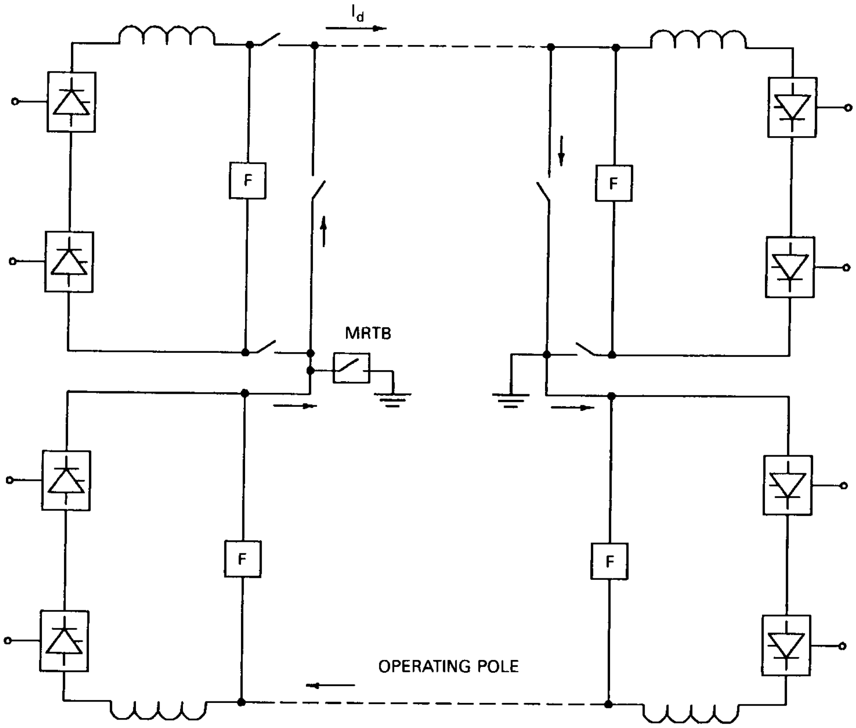


Fig 8
Metallic Return Operation of the Unfaulted Pole in a Bipolar System

3.5.3 During maintenance of the ground electrode(s) or the electrode line(s), operation of the bipolar system should be possible with the station neutral(s) connected to the station ground at one or both HVDC substations as long as the imbalance current between the two poles entering the station ground(s) is kept at a very low value. The imbalance current must be kept low to avoid saturation effects in the converter transformers and in other transformers located electrically nearby the converter station from flow of part of the imbalance current through the transformer neutrals. Under this arrangement when one transmission line or substation pole is lost, both poles should be blocked automatically.

3.5.4 In bipolar operation with both ground electrodes connected, the two poles of the HVDC system should be capable of operation with substantially different currents in each pole. This may be necessary if loss of cooling or some other unusual condition prevents operation of one pole with full-load current.

3.5.5 To provide for cases when the line insulation has been partially damaged, consideration should be given to design of the converters for continuous operation at reduced voltage with additional LTC range or more reactive compensation, so that either pole can be operated at reduced voltage (see also 7.3).

3.5.6 In the event of loss of one transmission pole line, the two converter poles can also be connected in parallel by using appropriate switches for polarity reversal in at least one station pole, thus enabling both poles to operate in the monopolar ground return mode. This, however, requires that the dc terminals of each 12-pulse group are insulated for the full-pole voltage and the ground electrode line and the ground electrode itself must be thermally capable of carrying a higher than nominal current.

A dc reactor is needed at each end of the transmission system in each pole, and if the HVDC system includes an overhead line, a dc filter would likely be needed. One 12-pulse unit per pole

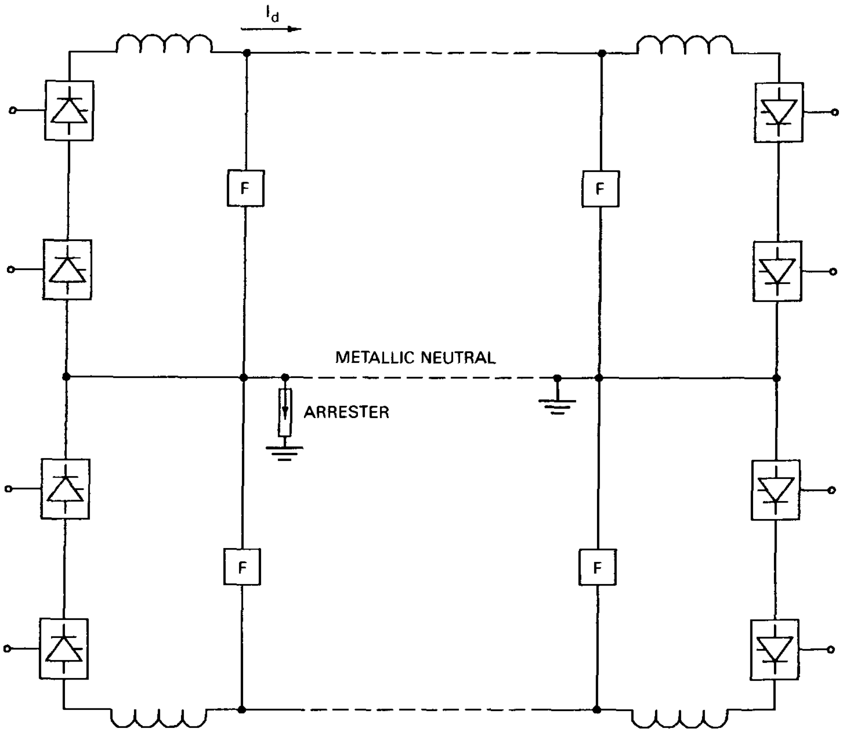


Fig 9
Bipolar Metallic Neutral System

is commonly used, however, large capacity systems or staged expansion may require 12-pulse units in series or parallel (see Figs 4 and 5).

3.6 Bipolar Metallic Neutral System (See Fig 9). When ground currents are not tolerable or when the distance between the HVDC system terminals is short or when a ground electrode is not feasible for any reason such as high earth resistivity, then the transmission line might be constructed with a third conductor to give a bipolar metallic neutral system. The third conductor carries imbalanced currents during bipolar operation. It also serves as the return path when one transmission line pole is out of service. This third conductor requires only low voltage insulation; however, and in this case, may also serve as a shield wire when the conductor is overhead. When it is fully insulated, it can serve as a spare conductor. If so, a separate shield wire may be required.

The neutral of one of the two HVDC substations could be grounded, while the neutral at the other end of the transmission would float or be tied to its station ground through an arrester, a capacitor, or both.

When the third conductor is fully insulated, the system can still be operated in the bipolar mode if one conductor becomes unavailable. Loss of one pole will require blocking of the other pole until the necessary switching has taken place for operation of the remaining sound portions of the HVDC transmission system. The neutrals at both terminals then should be connected to their local station grounds, and care should be taken to hold the imbalance current flow to very low values. A subsequent converter or line fault would require blocking of the bipole until further switching has taken place.

When one substation pole becomes unavailable, the system can be operated in monopolar metallic return mode by utilizing the other substation pole.

3.7 Two 12-Pulse Groups Per Pole. For a large bipole capacity, two 12-pulse units in series per pole may be considered. This means that when a forced or scheduled outage of a 12-pulse converter occurs, only 25% of capacity will be lost and the two poles can still operate with balanced current (without ground current). If sufficient overload capability is available, full power or almost full power can be transmitted. DC switches will be necessary to bypass and remove any 12-pulse group from operation. The cost of such an arrangement, compared to one 12-pulse group per pole for the same total rating, is expected to be greater.

3.8 Converter Transformer Arrangements. Each 12-pulse converter requires two three-phase transformer valve windings, one wye-connected and the other delta-connected. These are provided by either

(1) One three-phase transformer with two valve winding

(2) Two three-phase transformers, one connected wye-wye and the other wye-delta

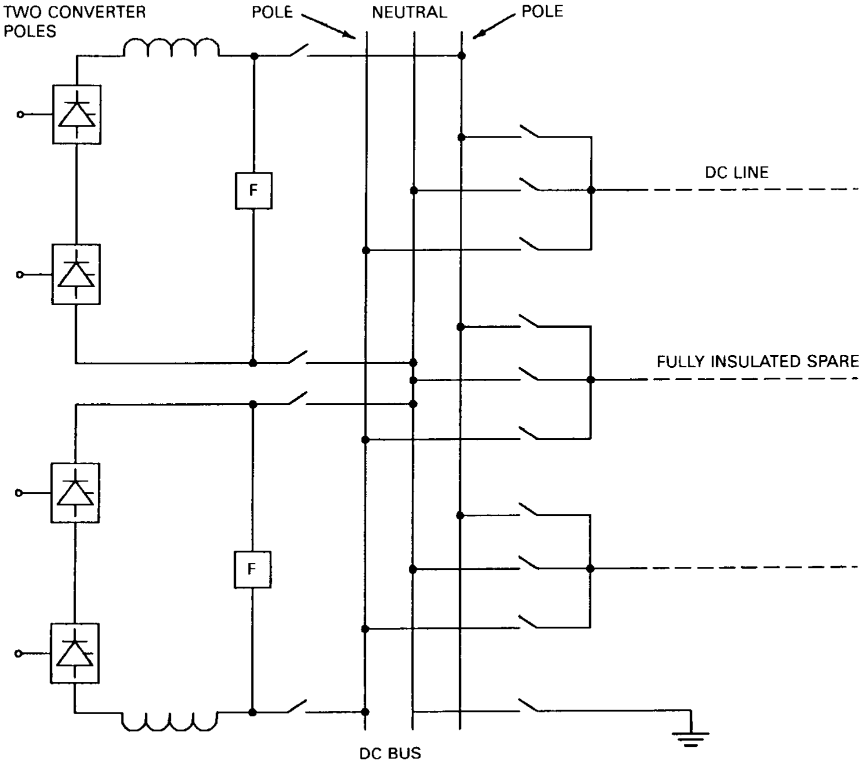
(3) Three single-phase transformers each with two valve windings, one for wye-connection and the other for delta-connection

(4) Six single-phase transformers, connected in two three-phase banks, one connected wye-wye and the other wye-delta

Depending on the HVDC system availability requirements, spare transformers may be needed at one or both ends even with identically connected ac system voltages and transformer tap ranges. Should the connected ac system voltages differ, separate spares will probably be needed at each terminal. Other considerations could include transportation constraints or the time for transport between the two terminals. These factors could diminish the justification for common spares for the two terminals.

Within a given terminal, however, since three-phase transformers are of different designs, spare considerations would indicate one spare of each

Fig 10
Direct-Current Switching of Line Conductors



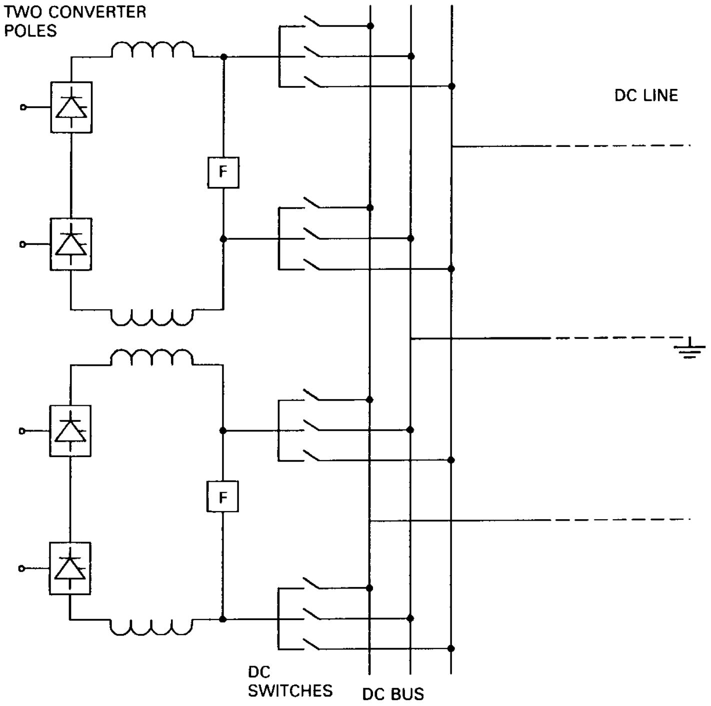


Fig 11
Direct-Current Switching of Converter Poles

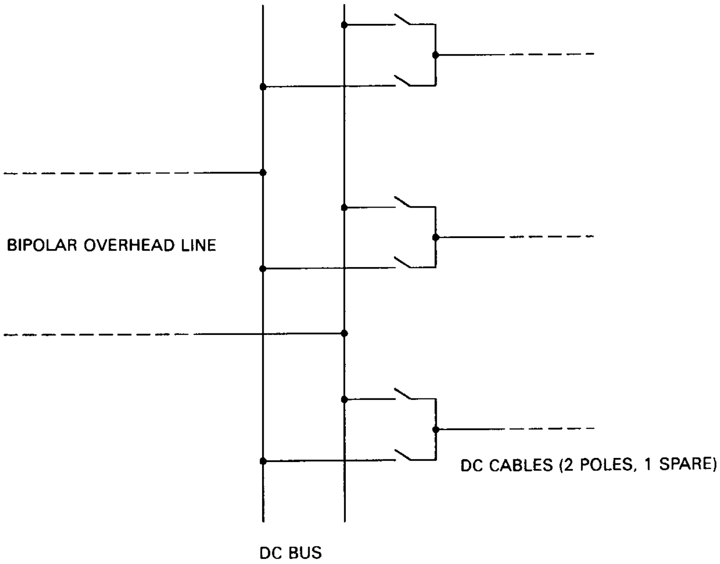


Fig 12
Direct-Current Switching — Overhead Line to Cable

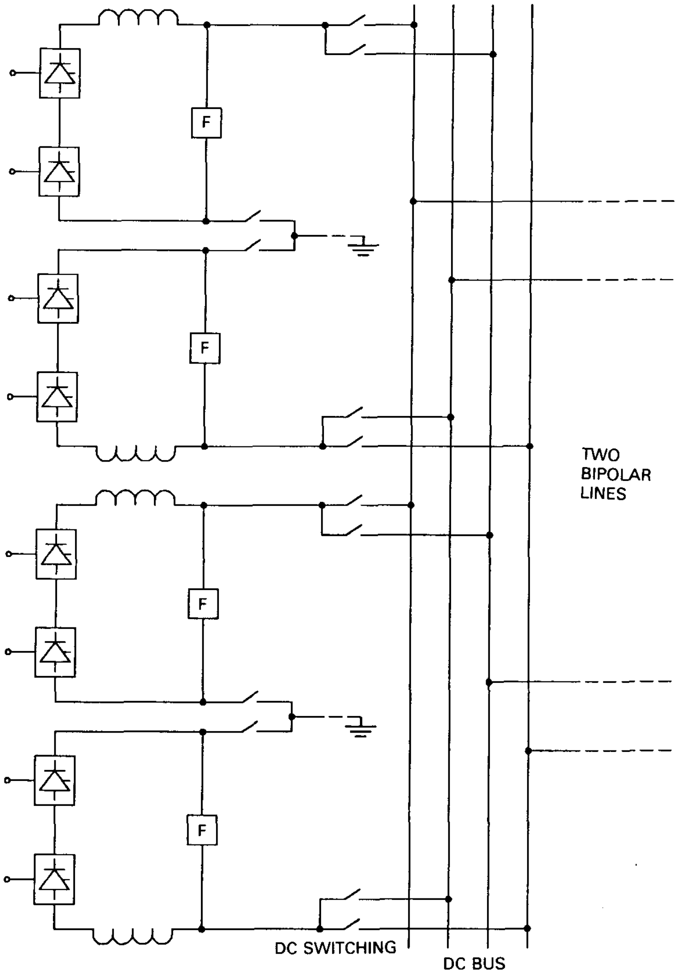


Fig 13
Direct-Current Switching — Two Bipolar Converters and Lines

design. Only one spare is required for the single phase, double-valve winding transformers since all three are identical. The second of the above options would suggest two spare transformers, one each for the wye and the delta-valve winding single-phase transformers at the terminal. However, a back-to-back terminal could require different spare transformers for the two sides of the terminal because of differences in the voltages of the two ac systems.

3.9 DC Switching Considerations. There are a number of possible dc switching arrangements intended to increase HVDC system availability.

Information on monopolar metallic return operation of a bipolar system is in 3.5.

For bipolar systems, dc switching may be provided (see Fig 10) so as to be able to use a transmission line pole for connection to any converter pole or to neutral. This arrangement is useful for a scheme involving cables, and where a fully insulated spare cable is available, or cables are connected in parallel. When the spare cable is switched from the neutral to a pole position, the neutrals at both terminals should be connected to their local station ground electrodes (see also 3.6). If one converter pole is out of service, then the cables can be paralleled to reduce line losses.

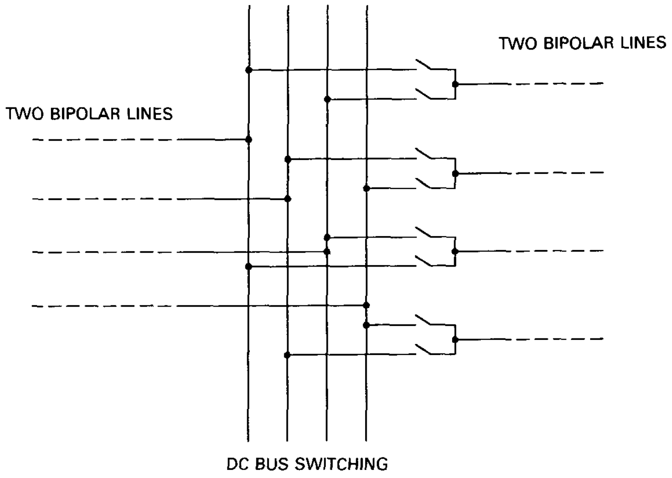


Fig 14
Direct-Current Switching — Intermediate

Generally, dc buses are fixed in relation to converters, with two pole buses and a neutral bus. This would preclude connection of the two converter poles in parallel.

However, when flexibility of connecting the two converter poles in parallel is needed, then provision for polarity reversal of at least one converter pole could be made and the dc terminal of each 12-pulse group of that converter pole also would need to be insulated for full line voltage. A possible switching arrangement is shown in Fig 11.

In the case of a dc line comprised of overhead line and cable sections a dc switching arrangement, such as in Fig 12, may be used at the junction of the overhead and cable sections.

For more than one bipolar line, paralleling of converter poles may be considered, to allow restoration of transmission capability (see Fig 13) for transmission line outages.

For long bipolar lines in parallel, intermediate switching such as in Fig 14 may be provided.

4. Environment

The information contained in Table 1 should be supplied for each HVDC substation.

Table 1
Location

Parameter	Units	Examples of Use and Comments
Height above sea level	m	For the design of air cooling systems and for air clearances
Outdoor air temperature	°C	The one-hour average maximum temperatures are given for rating purposes and the low temperatures for overload capability requirements. If the user intends to overload the equipment and accept a corresponding loss-of-life expectancy, this should be stated and the necessary information supplied. If preferred, curves showing how these parameters vary over the year could be provided on a monthly basis.
Maximum dry-bulb temperature	°C	Valve cooling, transformer and reactor design
Maximum wet-bulb temperature and maximum corresponding dry-bulb temperature	°C	Evaporative cooling system design and for valve hall relative humidity

Table 1 *(Continued)*
Location

Parameter	Units	Examples of Use and Comments
Maximum average dry-bulb temperature for a 24 h period	°C	Transformer and reactor design
Minimum average dry-bulb temperature for a 24 h period	°C	Transformer, reactor and disconnect switch design, and building heating needs—Capability for operation under low ambient temperature conditions
Minimum dry-bulb temperature	°C	Transformer, reactor and disconnect switch design, and building heating needs
Maximum and minimum indoor air temperatures and % relative humidities	°C	Usually determined by the valve designer for the valve hall and by the control designer for the control room
Indoor air temperatures and % relative humidities during maintenance and maximum transition time after shutdown	°C	Specified when indoor temperature extremes are too great for maintenance personnel
Maximum incident solar radiation		Building cooling, ratings of transformers, reactors, buses, etc
Horizontal surface	W/m^2	
Vertical surface	W/m^2	
Wind velocity		
Maximum continuous	m/s	Equipment support and building design
Maximum gust	m/s	Same
Maximum at minimum temperature ___ °C	m/s	Conductor, strain insulator, and tower design
Ice and snow loading		
Maximum ice thickness with no wind	mm	Equipment and structure design, for example, disconnect switch, conductor, etc
Maximum ice thickness with a maximum wind velocity of ___ m/s	mm	Same
Maximum snow load	N/m^2	Building design
Maximum depth of snow	mm	Equipment height above snow—hence ground level, for safety purposes
Rainfall		Building and site drainage
Annual average	mm	
Maximum in a 1 h period	mm	
Maximum in a 5 min period	mm	
Fog and contamination utility practice for insulator washing and greasing		To determine requirements for insulation and air-cooling system filter design, an estimated equivalent salt deposit density level should be specified for insulator design.
Lighting stroke density at the station and over the first 5 km-10 km of any overhead line as applicable	$strokes/km^2/(year)$ (substation) strokes/100 km/(year) (line)	Station lightning protection design
Seismic conditions		Equipment, structure and foundation design. Note that special seismic performance requirements may need to be specified for particular situations. These should be agreed to between the supplier and purchaser.

Table 1 *(Continued)*
Location

Parameter	Units		Examples of Use and Comments
Maximum horizontal acceleration	m/s^2		
Frequency range of horizontal oscillations	Hz		
Maximum vertical acceleration	m/s^2		
Frequency range of vertical oscillations	Hz		
Duration of seismic event	cycles		
Cooling water available at the site (if used for secondary cooling)			Secondary cooling water may be used either for makeup and blowdown of evaporative coolers or for once-through cooling. Evaporative cooling towers can be a source of high humidity for the insulators and should be carefully located.
Source of water			Reservoir, well, etc
	Capability for rated power	Capability for low temperature	
Maximum continuous flow rate	m^3/s	m^3/s	Required for cooling system design
Maximum flow rate for a 24 h period	m^3/s	m^3/s	Required for cooling system design
Minimum continuous flow rate	m^3/s	m^3/s	Required for cooling system design
Minimum flow rate for a 24 h period	m^3/s	m^3/s	Required for cooling system design
Maximum 1 h average water temperature	°C		
Minimum 1 h average water temperature		°C	Required for cooling system design
Maximum allowable dump temperature	°C	°C	Required for cooling system design
ph level			Design of water treatment plant
Conductivity of water at 25 °C	μS		Design of water treatment plant
Type of dissolved solids			Design of water treatment plant
Quantity of dissolved solids	g/m^3		Design of water treatment plant
Type of undissolved solids			Design of water treatment plant
Quantity of dissolved and undissolved solids	g/m^3		Design of water treatment plant
Maximum earth resistivity at the HVDC substation	$\Omega \cdot m$		Station ground-grid design
Site soil condition depth of water table	m		Foundation design. Bore hold information (for example, rocks) and any special conditions such as maximum frost depth; foundation design.
Site accessibility			To determine installation and delivery costs
Weight and size limitation for transportation			Equipment design — especially transformers and dc reactors
Local profile limitations on equipment and buildings			Influence equipment, bus and building design
Environmental considerations			Audible noise limits, aesthetic requirements — architectural treatment, landscaping, etc

NOTE: Any special conditions not listed above, for example, pertinent regulations which might influence system performance should be given.

5. Rated Power, Voltage, and Current

5.1 Rated Power. Rated power is the active power the system should be able to transmit continuously without degradation of performance over the range of ambient conditions specified, with all equipment in service, but without the need to utilize redundant components, and the ac system voltage and frequency as well as converter firing and extinction angles being in their steady state range.

Because an HVDC system in general consists of three sections, that is, the two HVDC substations and the transmission line, each of which produces losses, the point of measurement of rated power should be specified.

5.1.1 HVDC Transmission Power Rating. Rated power of an HVDC system on a per pole basis is defined as the product of rated direct voltage times rated direct current.

For a given direct current, transmission line losses vary with ambient conditions, which are usually nonuniform along the length of the line. Therefore, rated power at the rectifier dc bus is customarily specified. If the required transmission capability is defined at some other location, that is, sending end ac bus, receiving end ac bus, or somewhere along the dc line, then the rated dc voltage should be defined and the rated direct current chosen through design optimization of the HVDC system.

Rated power and voltage at the inverter dc bus are derived from rectifier quantities, and line losses are usually based on defined conductor parameters and uniform conductor temperature assumptions along the line.

Long distance HVDC systems may be monopolar or bipolar. Rated power should be specified on a per pole basis stating the number of poles.

5.1.2 Back-to-Back Power Rating. In back-to-back configurations, there are no transmission lines. Therefore, the rated dc voltage and current are chosen generally through design optimization of the HVDC system. Moreover, rectifier and inverter are solidly connected at the dc side, operating as one unit. Rated power for such a system can therefore be specified as the real power drawn from or fed into the adjacent ac system bus.

5.1.3 Direction of Power Flow. When the same power rating is required in each direction, such as with system ties for power exchange, this should be stated.

Where power flow is primarily in one direction, such as with a HVDC system fed from remote generation, rated power may be specified only for that direction to minimize the inverter cost. A lower inherent transmission capability then must be accepted when power flow is reversed.

5.2 Rated Direct Voltage. The rated voltage is the mean value of the required direct voltage to transmit rated power at rated direct current. It is measured between the high-voltage bus at the line side of the dc reactor and the low-voltage bus at the HVDC substation, excluding the ground electrode line. The rated voltage is defined at nominal ac system voltage and nominal converter firing angle while operating at rated direct current.

For long distance HVDC transmission systems, rated voltage should be specified at the sending end. If the transmission line's voltage capability is higher than the rated voltage, then this should be stated. The rated voltage need not be specified for back-to-back ties as detailed under 5.1.2, unless there are specific reasons for doing so.

5.3 Rated Direct Current. Rated direct current is the mean value of the direct current the system must be able to transmit continuously for all ambient conditions specified and without time limitation. The rated current should not be specified for back-to-back ties as detailed under 5.1.2, unless there are specific reasons for doing so.

6. Overload and Equipment Capability

6.1 Overload. Overload in an HVDC substation usually refers to direct-current flow above its rated value. For this, consideration may be given to acceptable reduction in life expectancy of equipment (for example, due to thermal aging), use of redundancy, and low ambient temperatures.

Overload may be specified in terms of power. Voltage regulation in the converter including the transformer normally requires an increase in current somewhat more than an amount proportional to the increase in power. If rated voltage is to be maintained under overload conditions, then the following measures may be adopted, at additional cost:

6.1.1 The converter may be designed for a higher no-load voltage. This results in a higher MVA rating if overload is required over the full range of ac bus voltage.

NOTE: This may not be necessary, if overload is required only for the upper range of the steady-state ac system voltage.

6.1.2 The voltage rating of the converter valves, which is based on transformer no-load voltage, should be increased.

6.1.3 The on-load tap changer range should be increased if the converter firing angle is to be maintained at its nominal value. Alternatively, the converter may be designed for a higher nominal firing angle at rated power. This will increase reactive power consumption, harmonics and losses, and the internal stresses on valve components.

As a consequence, if rated direct voltage is to be maintained under overload conditions, oversizing of equipment will be necessary.

For a more economical design, an overcurrent rating may be specified, without regard for direct-voltage regulation. Basic converter equations then permit determination of the maximum current, beyond which further increase would be offset by excessive voltage regulation.

The required duration of HVDC substation overloading is most often determined by ac system needs, especially following contingencies in either the ac or dc system. In the case of an HVDC system with major generators near its rectifier, overload operation of the HVDC system can also be a viable alternative to generator unit tripping schemes following major system disturbances.

However, some constraints should be taken into account for the HVDC substation equipment. Thermal time constants range from one second to some hours, as described in 6.2. Longer duration overload requirements of high magnitude may therefore require an effectively increased rating of equipment and thus impose a cost penalty or a reduction of life expectancy. These factors should be weighed against system benefits when specifying overload.

NOTE: As an example, a practical value may be a 1.2 per unit overload for one hour, which should not result in loss-of-life expectancy of oil cooled transformers and reactors but the thyristor valve design could be affected. Also depending on the particular design, cooling redundancy may permit translation of the one-hour overload to continuous.

Other examples include oscillatory overloads as for modulation purposes at a frequency of up to 1 Hz and for durations of several seconds, or 5 s overloads to counteract temporary overvoltages or frequency changes.

The expected frequency of the overload cycles and the time intervals between cycles should be specified.

6.2 Equipment Capability. This concerns the ability of the HVDC substation equipment to permit transmission of greater than rated power without loss of equipment life expectancy. Operating conditions and the design criteria for individual components will affect this ability. Implications resulting from the latter are discussed in subsequent subclauses with respect to overload specifications.

Ambient temperature is an important factor. Power equipment should be designed to perform at rated loading under the most adverse ambient conditions specified. However, these conditions normally prevail for only limited time periods. At low ambient temperatures, some margin is available for increased capability, if the constraints listed in 6.2.3 can be overcome. This margin depends on the design chosen for the particular equipment and would differ for various HVDC substation components. A curve envelope of transmission capability versus ambient temperature can be specified along with the ac system conditions to be met. This should be specified in terms of wet bulb and dry bulb ambient temperatures.

6.2.1 Converter Valve Capability. The thermal time constant of the thyristor heat sink combination in a thyristor valve is rather small (several seconds up to a few minutes). Overloads following continuous operation at rated current and at maximum ambient temperatures will increase thyristor junction temperatures. This must be considered with respect to the specified fault suppression capability of the valve. Consequently, thyristor valve cooling should be designed so that safe operating temperatures are not exceeded even during specified overload operation.

Redundancy is provided as a general practice in the valve cooling circuit. Valves are designed so that the specified rating will be met under the most adverse ambient conditions and loss of thyristor cooling equipment redundancy. If additional capability is needed when redundant cooling is not provided, this should be explicitly specified.

On the other hand, with all redundant cooling equipment in service, extra thermal capability is available. The resulting greater-than-normal current capabilities depend on the thermal design of the valve and on the cooling system.

In view of the above, converter overload specification should state the magnitude and duration of overload, frequency of oscillatory overloads for modulation purposes, and the cooling equipment status to be assumed at maximum ambient temperatures.

6.2.2 Capability of Oil-Cooled Transformers and Reactors. The thermal time constant of transformer or reactor windings is approximately

15 min and ranges from one to some hours for their oil circuits, depending on the design.

Consequently, for short time overloads such as in the 5 s time range, oil-cooled equipment should not be the limiting factor for HVDC substation overloads. For overloads lasting longer than one hour, permitted loss-of-life expectancy should be specified. The expected frequency of occurrence of such overloads should also be given.

6.2.3 AC Harmonic Filter and Reactive Power Compensation Equipment Capability. HVDC substation overloads will usually generate harmonic currents greater than normally experienced when operating at rated load. These in turn increase harmonic loading, losses in filters, and harmonic interference levels. The specifications should state whether the required normal system rating interference performance also must be met under overload condition, or to what extent degradation of performance is permitted.

Also, since overload increases the converter reactive power consumption, the specifications should state how this is to be taken into account when designing reactive power compensation equipment. If additional reactive power is drawn from the system under HVDC substation overload conditions, excessive ac bus voltage regulation and a consequent reduction in power flow may take place. For this reason, the expected ac bus voltage under overload conditions should be specified.

6.2.4 Switchgear and Buswork Capability. Switchgear and buswork normally do not impose limits on HVDC substation overloads, unless paralleling of converters is planned. However, special attention should be paid to the overload capabilities of current transformers and bushings.

7. Minimum Power Transfer and No-Load Standby State

7.1 General. With HVDC converters, there is an inherent minimum limit on steady-state direct current. This is due to the fact that at some low level, the current becomes discontinuous and is the principal criterion for a minimum power limit.

7.2 Minimum Current. Since the direct-voltage output of a HVDC converter is made up of sections of the sinusoidal bus voltage, the dc-side current will have a ripple component. Should the instantaneous minimum of the dc-side current fall below a threshold at which the thyristor valves begin to turn off, a discontinuous mode of operation will be encountered. Discontinuous current should be avoided in steady-state operation, since high component stresses may appear in the converter units.

The ripple on the dc side will contain typically two major components due to:

(1) The characteristic harmonics (12, 24, 36, ...) and

(2) The 2^{nd} harmonic caused by any negative-sequence imbalance of the ac-bus voltage

One of the important ways for determining the size of the dc smoothing reactor and dc filter is to reduce both components of ripple so that the specified minimum average current can be maintained in steady-state without discontinuous operation. The ripple component due to characteristic harmonics is affected primarily by the smoothing reactor and transformer inductance and can be made smaller by increasing either of these parameters. The 2^{nd} harmonic component of ripple, however, is affected by the entire HVDC transmission network. Long-distance transmission lines usually have a resonant condition, which is close to 2^{nd} harmonic, and in many cases increasing smoothing inductance actually increases the total ripple, due to second-harmonic amplification. Hence, coordination of the smoothing inductance and dc filter capacitance at all converters is required to ensure attainment of a specified minimum average current on the dc side.

A HVDC specification should include a specified minimum dc current level. A value of 10% of rated current is commonly used, although some systems have requested as low as 5%. When determining a minimum current criterion, it should be recognized that its selection can have a major impact on the cost of the dc-side filtering equipment, and hence should be as high as the planned system operations will permit. Similarly, a value of negative-sequence imbalance on the ac voltage must be included in the specification, and should be realistic as the imbalance may have a significant impact on the cost of the equipment.

7.3 Reduced Direct-Voltage Operation. Under some contamination conditions, often in combination with unfavorable weather, operation of an overhead dc transmission line may not be possible at its rated voltage. However, the control system of the HVDC substation offers various means to achieve continuation of power flow at reduced transmission voltages.

One possibility is to move the transformer tap changer to the position resulting in the lowest ac voltage for the valves. In addition, a further decrease of transmission voltage can be achieved through operation at an increased firing angle. This requirement could mean a special valve design and thus increase valve costs. Furthermore, since operation at large firing angles causes an increased harmonic generation and reactive power consumption, operation at reduced direct voltage then may require a reduction of the direct current, if the filtering and compensation equipment are not rated for these conditions.

Other possibilities are to increase the tap changer range, or where the HVDC system is fed from an isolated power station, a reduction of ac-bus voltage can also be considered.

Practical values for reduced direct-voltage operation are at 70% to 80% rated voltage, perhaps at reduced current. It is reasonable to expect continuous operating capability at approximately rated current at 75% voltage with use of redundant cooling, provided that a somewhat higher harmonic interference level is acceptable; acceptability of this in turn depends on the expected frequency and duration of such operations.

Where two series-connected 12-pulse converter units are used, one might be switched off, resulting in a 50% voltage reduction, thus eliminating the necessity to operate at increased converter firing angle or reduced direct current.

To arrive at an economic design of the equipment, the ac voltage levels should be specified for any such expected reduced direct-voltage operations.

7.4 No-Load Standby State. In the no-load standby state, the HVDC substation should be ready for immediate pick-up of load in one second or less without the need for a lengthy start-up procedure. If such operations are planned, the status of various equipment should be specified to determine the no-load losses of the HVDC substation.

7.4.1 Converter Transformers — No-Load Standby. The converter transformers may remain energized or de-energized, depending on the user's policies with respect to the attendant losses. In the latter case, account should be taken of the time required for inrush currents to decay. Oil pumps and coolers should be in operation on a minimum level, as appropriate to the design of the transformers.

7.4.2 Converter Valves — No-Load Standby. The converter valves should be in the blocked condition. There will be small losses in the voltage grading circuits, if the converter transformers are energized. Primary, secondary, and valve hall cooling should be in operation at a sufficient level to permit immediate pickup of load.

7.4.3 AC Filters and Reactive Compensation — No-Load Standby. The ac filters and reactive compensation may be connected or disconnected depending on reactive power control strategy for the ac system. However, for the sake of no-load loss determinations, they should be considered disconnected.

7.4.4 DC Reactors and DC Filters — No-Load Standby. The dc reactors and dc filters should be connected. For dc reactors, pumps and coolers should be in operation on a minimum level, as appropriate to the design of the reactors.

7.4.5 Auxiliary Power System — No-Load Standby. The auxiliary power system should be fully operative and ready to pick up rated load, for example, all station service transformers energized, and battery chargers in operation.

7.4.6 Control and Protection — No-Load Standby. All control and protection circuits should be operative.

8. AC System

8.1 General. The following information should be given for ac systems at both ends of the HVDC transmission for each stage of development and for expected future changes.

The arrangement of the ac switchyard to which the converter units and filters are to be connected, including ac lines, should be described. This should also be done for the planned operating schemes of the switchyard.

Specific data should be made available for generators in the close vicinity, particularly if the major load for the generators is served through the rectifier. Often all data pertinent to load flow and short-circuit studies is also needed.

8.2 AC Voltage

8.2.1 Rated AC Voltage. Rated ac voltage is the rms phase-to-phase fundamental frequency voltage for which the system is designed and to which certain characteristics of the ac equipment are related, that is, ac switchgear, ac filters, reactive compensation equipment, and primary windings of converter transformers. Rated voltage may be used to define rated power of this ac equipment.

8.2.2 Steady-State Voltage Range. The steady-state voltage range is the range over which the HVDC system shall be able to transmit rated power and over which all performance requirements are to be met.

Any special performance requirements beyond the limits of the steady-state range should be specified. These may affect the design of main equipment, converter transformers, filters, auxiliary equipment, etc.

8.2.3 Negative Sequence Voltage. The negative sequence component of ac voltage calculated according to the method of symmetrical components is that balanced set of three-phase voltages whose maxima occur in the opposite order to that of the positive sequence voltages. It is generally expressed as a percentage of the rated voltage.

Although it is difficult to get an actual value of this parameter, the maximum to be used in determination of noncharacteristic harmonics of the ac and dc side currents should be specified. These harmonic currents and voltages are respectively used for the design of the ac filter and dc filter (see Sections 16 and 17).

8.3 Frequency

8.3.1 Rated Frequency. Frequency of the ac system should be specified to give the basis for rating of the ac equipment, converter transformer, and converter bridges and control.

The design of the dc filters is also influenced by the ac system frequency.

8.3.2 Steady-State Frequency Range. Steady-state frequency range is the range, in conjunction with the ac voltage steady-state range, over which the rated power may be transmitted and all performance requirements are to be met.

8.3.3 Short-Term Frequency Variation. Limits and duration of short-term frequency excursions for which system performance is required should be specified. This can be a sensitive parameter for ac and dc filter design. Filtering performance during such variations may be specified.

8.3.4 Frequency Variation During Emergency. During an emergency, the ac system frequency may reach extreme values for limited periods. These excursions and their expected durations should be specified. In this condition, the equipment should remain in service without damage but should not be required to meet the performance specified. For excursions beyond the specified operating frequency limits the equipment may be automatically disconnected.

8.4 System Impedance at Fundamental Frequency. For the purpose of analysis of commutation conditions in the converter the system impedance at its fundamental frequency should be stated. Maximum and minimum values of the subtransient impedance at the ac bus, without any filter or compensating equipment, are needed for such analysis.

Subtransient impedance is the positive sequence impedance of the ac system as determined by the subtransient reactance of synchronous machines, leakage reactance of induction machines, and positive sequence impedance of connecting lines.

8.5 System Impedance at Harmonic Frequencies. System impedance at all harmonic frequencies from the 2nd up to the 50th is needed for ac filter design and performance calculations.

This impedance may be calculated using the parameters of the lines, transformers, and generators up to five to eight buses from the HVDC substation. However, this impedance may change considerably under different load conditions and extension states of the system. Therefore, it is usually more convenient to use a R-X impedance diagram and to plot the envelope for the locus of the system harmonic impedance under expected system conditions.

In practice this diagram may take various forms such as a circular plot, limited by constant R/X ratio.

8.6 Positive and Zero-Sequence Surge Impedance. The positive and zero-sequence surge impedance is needed for all ac lines going into the station for evaluation of interference from converters in the carrier frequency band and for design of appropriate filters.

8.7 Other Sources of Harmonics. Other sources of harmonics electrically close to the HVDC substation should be identified. Their influence should be taken into account in ac filter and capacitor bank ratings. Generated harmonic currents should be stated from such sources as static reactive power compensators connected to the converter substation bus or to nearby ac substations.

8.8 Subsynchronous Torsional Interaction (SSTI). A HVDC terminal may interact unfavorably with torsional modes of vibration on electrically close turbine-generator units. Of particular concern are thermal generating plants, for which the turbine-generators typically have shaft torsional resonances in the frequency range of 5 Hz to 20 Hz. This interaction can be mitigated by proper HVDC system control design.

The HVDC specification should identify any generating units that may be affected. The ac system in the area should also be identified, and any viable contingencies that would result in greater coupling between the generator and the HVDC terminal. Series compensation, if used in the ac lines, must also be identified.

For ac systems without series compensation, the potential for interaction may be estimated by simple short-circuit calculations:

$$\mathrm{UIF_i} = \frac{\mathrm{MW_{HVDC}}}{\mathrm{MVA_{GENi}}}\left(1 - \frac{\overline{\mathrm{SC}}_\mathrm{i}}{\mathrm{SC}}\right)^2$$

where

$\mathrm{UIF_i}$ = unit interaction factor for generator i
$\mathrm{MW_{HVDC}}$ = MW rating of HVDC terminal
$\mathrm{MVA_{GENi}}$ = MVA rating of generator i
SC = short-circuit duty at HVDC station with generator i in-service
$\overline{\mathrm{SC}}_\mathrm{i}$ = short-circuit duty at HVDC station with generator i out-of-service

Experience suggests that interaction with any unit having a UIF greater than 0.1 for any viable contingency should be studied in detail.

The special HVDC control measures taken to mitigate unfavorable torsional interaction, should such exist, provide a function of permitting operation in conditions that would otherwise be unstable. Due to the potentially severe consequence of a torsional instability, a separate protective function to act for such unanticipated events is highly recommended. The most appropriate mode of protection is a function of the application. Existing systems where such protection has been applied have utilized relay equipment local to the generator, and have used a measure of shaft motion as an input signal. The protection should be considered for any units having a possible UIF above 0.1. Protective schemes that utilize a less direct measure of torsional instability may be possible in some applications, but would require extensive study to ensure security of the protective function (see [1], [2], and [3]).

9. Reactive Power

9.1 General. Line commutation of converter bridges, as used in HVDC systems, requires a consumption of reactive power in both rectifier and inverter operations. At full load, this consumption represents 50% to 60% of rated power for commonly used values of transformer impedance and firing or extinction angles.

At partial load, reactive power consumption can be varied according to ac system requirements by using an appropriate control strategy. With a control strategy often adopted, that is to maintain the delay angle α in the rectifier, or the extinction angle γ in the inverter, within narrow limits by means of the tap changer of the converter transformer the variation of reactive power versus real power is shown in Fig 15, curve (a), for constant direct voltage and constant extinction angle γ. As an alternate, a linear variation may be obtained, as shown in Fig 15, curve (b), which involves maintaining constant U_{do} by means of an increase of the delay angle α in the rectifier and extinction angle γ in the inverter, when the load is reduced.

If the direct current is kept constant and partial load is achieved by increasing the firing angle and thus reducing the direct voltage, reactive power consumption is increased at partial load according to Fig 15, curve (c). Characteristics between curves (a) and (c) can be implemented to meet specific ac system requirements. This capability can be of interest if such operation can reduce the number of switching operations of the shunt filter or shunt capacitor banks at dc loadings below the rated power.

Combined changes of the valve firing angle and the load tap changer of the converter transformer may be used to control the reactive power demand of a converter station. However, since this requires an increase of the firing angle it leads to an increased generation of harmonic currents and voltages and increased losses in the damping circuits of the valves.

Looked at in another way, filtering of ac is obtained through harmonic filters, which also generate reactive power. However, the fundamental frequency reactive power generated by the filters as determined by the ac filtering requirements at full load is generally less than the reactive power consumption of the converter bridges. Therefore, additional capacitor banks are usually provided to meet the total reactive power demand of the converter.

The net reactive power demand of the converter and filters, taking into account filtering considerations, may be controlled within certain limits, by switching of capacitor banks and also part of the filter banks, if needed. To define a suitable strategy of reactive power control, 9.2 should be specified.

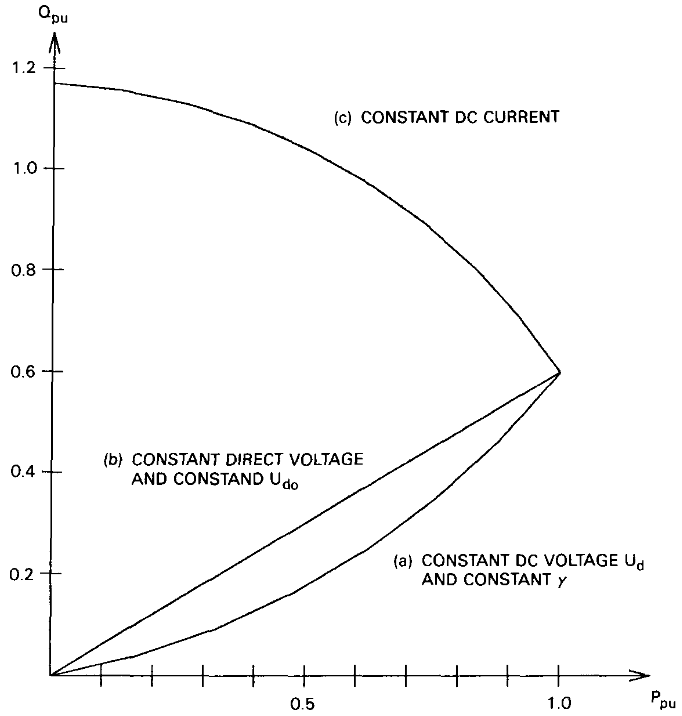


Fig 15
Variations of Reactive Power Q with Active Power P of a HVDC Converter

9.2 Converter Reactive Power Consumption. The reactive power consumption should be determined for the different operating conditions for the rectifier and inverter under partial load, full load, and overload conditions. The method of calculation and the parameters used in the calculations should also be specified.

The operating conditions to be considered include direction of power flow, monopolar ground return, monopolar metallic return, bipolar, and reduced direct-voltage operation over the specified range of steady-state ac bus voltage.

9.3 Reactive Power Balance With the AC System

9.3.1 To determine the reactive power sources to be installed, an overall balance of reactive power must be determined. Apart from the reactive power needs of the converters, consideration must be given to

(1) The power-factor range to be maintained in the ac lines for all operating conditions

(2) The operating voltage ranges under light and peak load conditions of the ac system

(3) Reactive power available from nearby generation

(4) Redundancy requirements

9.3.2 In case the rectifier is directly connected to a power station, the following points should also be considered:

(1) Generator capability over the maximum and minimum permissible operating voltage range

(2) Tap changer range available in the step-up transformer, and the tap to be used for each development stage

(3) Reactive power requirement of other loads

(4) Minimum permissible active power for the generators

(5) Self-excitation limit of the generators

(6) Minimum number of generators to be connected

9.4 Reactive Power Supply. The sources of reactive power supply to meet the total performance criteria should include the most economical combination of filters, shunt capacitors, shunt reactors, and synchronous and static var compensators. Part of the reactive power is supplied in the form of filters to meet required harmonic performance. Under light load conditions, the minimum size of available filter bank connected may lead to surplus reactive power and consequently excessive steady-state voltage. This may require provision of shunt reactors or use of converter capability to consume greater amounts of reactive power.

Shunt capacitor banks are the most economical source for the required remaining reactive power. Synchronous and static var compensators should be considered only if there is a dynamic voltage or stability problem (beyond the scope of this guide). There may be additional requirements associated with the adjacent ac systems.

9.5 Maximum Size of Switchable Reactive Power Sources. Filters and capacitor banks may be divided into small switchable banks. The size of switchable banks depends on

(1) Voltage control requirements over the whole operating range from no-load to full-load and overload

(2) Acceptable regulation step per switching operation. It should be noted that the regulating effect from switching shunt capacitor banks can be modulated with the help of converter control

(3) Frequency of Switching

When considering combinations of filters and shunt capacitors with synchronous compensators, the filters and shunt capacitors should be limited in size to avoid self-excitation of the synchronous machines.

NOTE: Partial or complete load rejection can result in intolerable fundamental frequency overvoltages due to the continued energization of the reactive power compensation.

10. DC Line, Electrode Line, and Ground Electrode

10.1 General. This section identifies those characteristics of the dc line, the ground electrode, and the electrode line that are relevant to the specification of the steady-state performance of the converter, including power-line carrier performance requirements and the design thereof. It does not provide the information that must be specified for the design of the dc line, electrode lines, or electrodes themselves.

Key performance specification data for the dc line and the ground electrode will have already been determined. Precision in showing these data is not necessary, since small changes in these parameters can be easily accommodated during the converter design stage, provided the designer is advised regarding them in a timely manner.

10.2 Overhead Line(s)

10.2.1 General. The total length of the line should be given, including details concerning any overhead and cable sections. Information should be provided regarding any right-of-way joint uses. Particulars of all communications and power-line crossings and parallelisms need to be given to enable assessment to be made of possible electrical interactions and interference.

For bipole and multipole lines, information on the spacings between poles and bipoles along the complete route is needed.

10.2.2 Electrical Parameters. The following data should be provided to the HVDC system designer:

(1) *Resistance.* Maximum positive and zero-sequence dc values at minimum load, full load, maximum overload with due consideration to the ambient conditions, (temperature, radiation, and wind speed) prevailing during the load conditions under consideration and curves of frequency dependence up to 100 kHz for full load

(2) *Capacitance.* Positive and zero-sequence capacitance, C_1 and C_0, curve of frequency dependence up to 100 kHz for these

(3) *Inductance.* Positive and zero-sequence inductance, L_1 and L_0, curve of frequency dependence up to 100 kHz for these.

10.2.3 Alternative Physical Data. When the information in 10.2.2 is not available, as an alternative the necessary data to enable its calculation could be given. To calculate these parameters the following data are required:

(1) Conductor size, type, geometry (including the shield wire)

(2) Tower outlines, spacing and sag profiles

(3) Soil resistivity along the route

(4) Tower footing resistances

(5) When carrier is to be used, the worst-case maximum conductor surface gradients to permit calculation of corona effects

(6) Critical impulse flashover level of insulation

10.2.4 Lightning Shielding. It is highly recommended that the dc line be adequately shielded from direct lightning strokes for at least the first

10 km from the HVDC substation and for the tower footing resistances of the dc line to be sufficiently low, for example, 10 Ω to 25 Ω or less.

10.2.5 Self and Mutual Impedance Alternative. As a third alternative, in place of sequence components, the information could be provided in the form of self and mutual impedances between conductors and earth.

10.3 Insulated Cable Line(s)

10.3.1 General. Length of sections or total length should be given as appropriate. Any restrictions on service conditions imposed by the cable supplier should be stated. Examples of such restrictions might include

(1) Limitations on polarity reversal
(2) Limitations on discharge rate
(3) Limiting voltage and current ripple level
(4) Limitations on overvoltages and overcurrents

10.3.2 Electrical Parameters

(1) DC resistance of conductor, maximum value at full load and at maximum overload
(2) Conductor resistance frequency dependence up to 5 kHz
(3) Cable sheath resistance and frequency dependence up to 5 kHz
(4) Inductance and frequency dependence up to 20 kHz
(5) Capacitance of conductor to sheath
(6) Capacitance of sheath to ground (armor)
(7) Surge impedance of cable conductor-to-sheath
(8) Attenuation characteristics up to 50 kHz

10.4 Electrode Line. To evaluate possible transformer saturation effects due to direct current flowing by way of the station grounding system and grounded transformer neutrals, the electrode line length, and the length of any part of it that is on the dc line towers should be given.

The electrode line resistance — maximum value and ambient temperature assumptions should be given.

10.5 Ground Electrode. The maximum resistance of the ground electrode relative to remote earth should be provided. Note that this resistance may increase with time, environmental changes or load conditions (see [4]).

11. Reliability

11.1 General. The reliability of an HVDC system is a measure of its ability to transmit a defined energy within a defined time under specified system and environmental conditions.

The purpose and scope of this section is to give direction for writing specifications and evaluating reliability. This section discusses reliability calculations during the acceptance period of a HVDC system. See [5], which describes a reporting procedure for specific failures and overall availability of HVDC systems in operation. Its scope is different from this guide.

Terms and definitions applicable to the reliability of HVDC systems are discussed below. With regard to reliability performance two elements should be considered:

(1) Energy availability
(2) Number of forced outages

In 11.2 through 11.8, various types of outages and methods of calculating the two elements of reliability are defined.

NOTE: To ensure adequate reliability for a HVDC system, care should be exercised in reliability specifications for all of the system elements, particularly if major elements, such as telecommunication links, var compensation, switchgear, and auxiliaries, are obtained from a source other than the HVDC substation supplier. The telecommunications between HVDC substations can play an important reliability role, depending upon the design of the control and protection equipment.

11.2 Outage. An outage of the HVDC system is an event when the transmission capability falls below a defined base power level P_B (see 11.4). This may be caused by defects of components or parts of the equipment, human errors, switching out of equipment for maintenance and repair, switching out caused by any operation of protection equipment, including undesired operations, etc. Consideration should be given to define which of these or other causes are to be included in the availability calculations and annual number of forced outages. When a certain defect does not lead to reduction of transmission capability to below the base power level P_B, then such an event should not count as an outage. An outage should be included in the calculations, either as a forced outage or a scheduled outage (11.2.2 and 11.2.4, respectively).

11.2.1 Partial Outage. An outage when the transmission capability falls below the base power level P_B, but remains greater than zero.

11.2.2 Forced Outage. An outage that cannot be deferred and that exceeds a specified time period.

11.2.3 Outage and Repair Time. It is important to define how the time of outage and repair/replacement of each major equipment item is calculated taking into account the actual time taken, available manpower, spares, and tools.

11.2.4 Scheduled Outage. An outage, partial or full, necessary for the maintenance, tests, measurements, and other work, which is planned beforehand or can be deferred for a convenient time that should not be less than a specified period. It is important to define how the time of scheduled outage is calculated in relation to the actual time taken and available manpower. The permitted time interval for scheduled outages of the transmission system or any part of it should also be defined. Predetermined outage time periods are usually scheduled for routine maintenance once per year, each comprised of one or more working shifts. Time per shift and shifts per day and per week should also be specified.

Depending upon the value and complexity, the failure rates, and the ability to repair a component, some parts of converter equipment may have different maintenance periods, that is, six-month intervals, yearly, or three to five years.

The number of scheduled outages and the outage time intervals per year are determined largely by: maintenance and repair facilities for the HVDC equipment; availability of trained personnel; test and monitoring facilities for rapid identification of faults and malfunctions in the system; auxiliary tools and installations for dismantling and reassembling of heavy or complex components and the type, number, and complexity of spare parts available on site or from the supplier.

The built-in thyristor redundancy should be based on the expected thyristor failure rate and planned maintenance intervals. In most cases, faulty thyristors can be replaced during scheduled outage times.

11.3 Period Hours, *PH*. Period hours (*PH*) are the number of calendar hours in the period in consideration. In a full year there are 8760 period hours, *PH*.

11.4 Base Power Level (P_B). The power level is taken as base capability for availability calculations. Continuous operation under normal conditions must be possible at this power level. There may be more than one base power level P_B, for example, rated power level, 50% of rated power level, and continuous overload capability.

11.5 Energy Unavailability, *EU*. This is a measure of energy that could not have been transmitted due to outages.

Energy unavailability consists of forced energy unavailability, *FEU* and scheduled energy unavailability, *SEU*.

$EU = FEU + SEU$, %

For reliability studies, it is essential to distinguish between the effects of line faults on monopolar and multipolar (bipolar) transmission systems.

In a monopolar system, a line fault causes a complete collapse of the transmission. In a bipolar system for most cases, a line fault only affects one pole of the transmission system, so that line faults would in general reduce energy transmission by 50%. However, if the remaining transmission line pole is designed for some degree of overcurrent capability and if the converter groups in the HVDC substation can be connected in parallel, then more than 50% of the energy may be transmitted after necessary switching for paralleling the converters has been performed.

In the case of a fault in a converter unit the affected unit may have to be switched out. The percentage loss of transmission capacity is given by the number of converter groups taken out of service related to the total number of converter units.

There may be other contingencies, such as partial loss of filters and faulted ground electrode line. Their impact on availability should be defined.

11.5.1 Forced Energy Unavailability, *FEU*. This is a measure of the energy that could not have been transmitted due to forced outages:

$$FEU = \sum_{i=1}^{n} \left(\frac{P_f}{P_B} \cdot \frac{OD}{PH} \right)_i \cdot 100, \quad \%$$

where

P_f = reduction of transmission capability from the base power level, P_B, due to forced outages

OD = outage duration expressed in hours, calculated according to an agreed procedure

n = number of forced outages during the period hours, *PH*

11.5.2 Scheduled Energy Unavailability, *SEU*. This is a measure of the energy that could not have been transmitted due to scheduled outages:

$$SEU = \sum_{i=1}^{m} \left(\frac{P_S}{P_B} \cdot \frac{OD}{PH} \right)_i \cdot 100, \quad \%$$

where

P_S = reduction of transmission capability from the base power level, P_B, due to scheduled outages

m = number of scheduled outages during period hours, PH

11.6 Energy Availability, *EA*. This is a measure of the energy that could have been transmitted by an HVDC system:

$EA = 100 - EU, \quad \%$

11.7 Maximum Permitted Number of Forced Outages. Not all the forced outages should be counted. For this accounting, a forced outage occurring within the converter station limits is an outage that cannot be deferred, which exceeds the specified time limit and for which the fraction loss of the power capability exceeds a specified level. The normal power capability often is taken as the same value specified for the system performance after successful recovery (usually to 80%-90% of the power being transmitted before occurrence of the fault). The maximum permitted number of such forced outages for period hours *PH* should be defined.

11.8 Statistical Probability of Outages

11.8.1 Component Faults. In addition to the availability of the overall system, reliability of some individual components may also be considered.

Every component in the system can be characterized by its failure rate λ. It is wise to distinguish between statistical failures (random outages) and failures at the end of the component's lifetime (for example, outages of luminescent diodes because of aging). To stock spare parts, good practice differentiates between these two kinds of failures, since at the end of lifetime all of the concerned components should have been replaced.

11.8.2 External Faults. The expected number of ac system faults, their probability, and their duration, which may detrimentally influence the behavior of a HVDC system, should be stated. The probability of the occurrence of such faults should be considered when stating the permitted number of HVDC system forced outages.

12. Control and Metering

12.1 Control Objectives. It should be recognized that a HVDC system is highly controllable, and therefore, the advantages of a HVDC system very much depend on the utilization of this controllability in ensuring maximum flexibility, reliability, and adaptability for different system requirements.

The objective of such a control system should be to provide efficient operation and maximum flexibility of power control in magnitude, rate of change, and direction without compromising the safety of the equipment, while maintaining the maximum independence of each pole and overall reliability of the dc transmission. The control system should be suitable for high-speed response so that it can effectively respond to disturbances in the ac and dc systems. Long-distance transmission requires a high-speed telecommunication system for the most effective operation. However, the HVDC system should be operable without telecommunication and for this case the performance should be maximized to the extent possible.

In addition to the conventional control functions, the control system should minimize reactive power consumption during normal conditions. It also should be adaptable for

(1) Increased and controlled var consumption, if necessary, to control the ac voltage
(2) Frequency control
(3) Active power modulation
(4) Combined active and reactive power modulation
(5) Subsynchronous resonance (SSR) damping
(6) Remote operation

12.2 Control Structure. The various control circuits of a HVDC substation are generally structured in a hierarchical manner. They normally operate automatically. For HVDC transmission systems, a telecommunication link is needed to coordinate between rectifier and inverter. The various levels in the usual control hierarchy are described in 12.2.1 through 12.5, starting with the lowest level (see Fig 16).

12.2.1 Converter Unit Control. The converter unit control is essentially an open-loop control. Its outputs are the firing pulses to the individual valves in a 12-pulse converter unit. These are synchronized to the ac system voltage. The input is the delay angle α, or angle of advance β as provided by the next higher level in the hierarchy.

There are two main types of converter unit firing control principles that have been used for HVDC: equal delay angle control and equidistant firing control.

Equal delay angle control is a method of timing the valve control pulses so that the delay angles of the valves in the converter unit are essentially equal, regardless of imbalances in the ac system voltages.

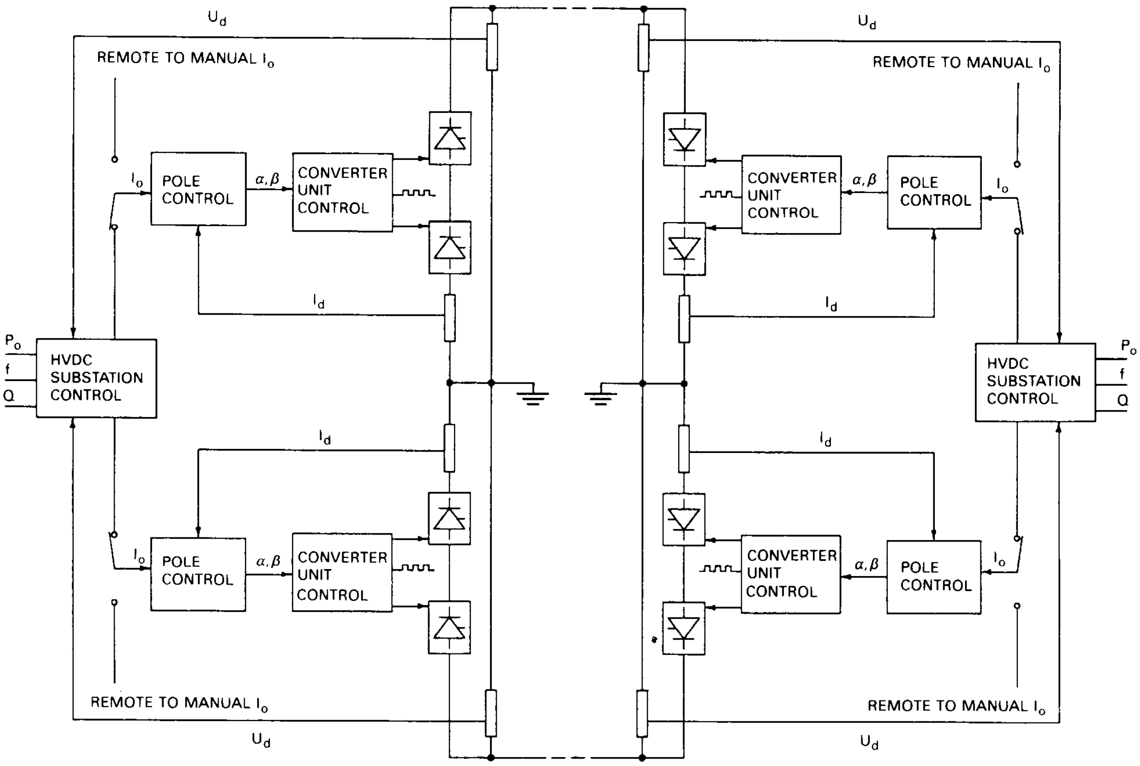


Fig 16
Control Hierarchy

Equidistant firing control is a method of timing the valve control pulses so that they are essentially equidistant in time, regardless of imbalances or distortion in the ac system voltages.

The functional requirements of the converter firing control are:

(1) Operation with lowest possible consumption of reactive power, that is, with the smallest possible delay angle α and extinction angle γ.

(2) Operation down to low values (that is, 2-3) of the ratio between the short-circuit capacity of the ac network and the transmitted dc power.

(3) That the permitted deviation from equidistant firing is normally indicated as $\pm\Delta°$, that is, each firing during conditions specified is to occur $30° \pm \Delta°$, after the preceding firing (for a 12-pulse converter unit). It should be noted that $\Delta°$ may vary for different converter modes of operation, that is, operation with minimum α, current control, or commutation margin angle control.

Deviation from equidistant firing gives rise to noncharacteristic harmonics transferred to the ac network and to the dc line. A typical permitted maximum value of $\Delta°$ is 0.2°, assuming that the ac system voltage and impedances are balanced.

(4) Deviation between the set current order and the actual current is dependent upon the tolerance of the current control system and the current sensor. Typically, the total tolerance is less than one percent at rated current.

12.2.2 Pole Control. Pole control provides the reference value for all series connected converter units per pole as applicable.

Pole control is a closed-loop control and includes the basic control functions that are required for stable operation of the HVDC system.

Generally, each substation pole is provided with a pole control (see Fig 16) that controls the dc voltage output of the converter by determining the firing instant of the valves. The pole control senses the difference between the order and response and adjusts the converter dc output voltage accordingly. If the current order in the rectifier is larger than the current response, the firing

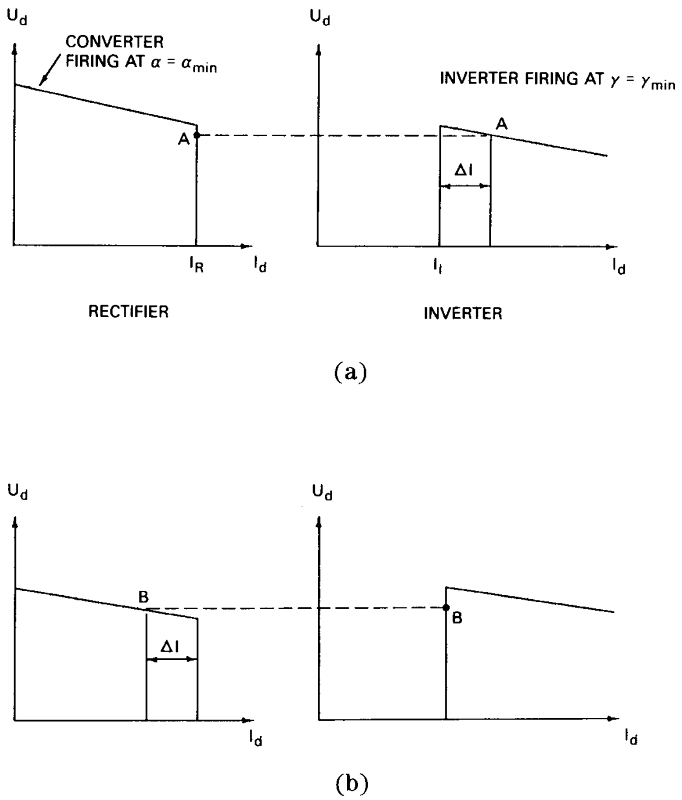


Fig 17
Converter Voltage-Current Characteristic
(a) Normal Operation — Rectifier Controls the Current
(b) Inverter Controls the Current

control increases the direct voltage by decreasing the delay angle, thus increasing the direct current. The direct voltage will be increased until the current response equals the current order or the maximum voltage is reached when firing at minimum delay angle, that is, the minimum voltage across the valve to be able to fire it. On the other hand, if the current response is larger than the current order, the direct voltage is correspondingly decreased. This action is limited when the converter operation has been changed from rectification to inversion and firing is given the least permitted margin of commutation, to ensure safe valve recovery.

The voltage-current characteristics of a rectifier and inverter are shown in Fig 17(a) and (b).

Normally, the maximum voltage limit in the inverter is lower than that of the rectifier and the current is controlled by the rectifier. That is, the inverter maintains the voltage, and the rectifier adjusts its voltage until the current becomes equal to the order input, and a stable working point A is established [see Fig 17(a)].

If the inverter voltage limit is larger than the rectifier voltage limit, the inverter controls the current and the rectifier maintains a maximum voltage, for which a stable working point B could be established [see Fig 17(b)].

As noted, the rectifier usually controls the current and the dc voltage is determined by the inverter. The inverter current order equals the rectifier current order less the *current margin* ($\Delta I = I_R - I_I$) See Fig 17(a). The inverter is forced to fire at the lowest allowed angle of advance β, keeping the margin of commutation constant at $\gamma_{\min}$, to establish the voltage on the dc line. In some systems the inverter is controlled so as to keep the dc line voltage constant. In this case the margin angle is allowed to increase above $\gamma_{\min}$.

For long-distance transmission the direct voltage is usually kept constant within close limits by appropriate control of the inverter end transformer tap changer.

The delay angle in the rectifier is kept within a narrow band (nominal $\alpha \pm \Delta\alpha$) by means of adjustment of the tap changers of the converter transformers. Direct-current voltage variation by changing the delay angle by $\Delta\alpha$ normally corresponds to one tap changer step. Alternatively the converter no-load direct voltage may be kept constant by means of adjustment of the tap changer.

Reduced dc voltage may be needed, for example, at times of reduced voltage withstand of the dc line after damage to the insulation. This can be accomplished in the rectifier, and in the inverter, primarily by tap change in the converter transformer, secondarily by adjustment of the delay angle, and thirdly by switching off one series-connected converter group, if any.

12.2.3 HVDC Substation Control. The HVDC substation control is a closed-loop control. It includes

(1) Coordination of current orders between the two ends by way of the telecommunication link, usually on a per pole basis

(2) Power control

(3) Coordination between the poles of a HVDC substation (if there is more than one pole)

(4) More sophisticated control strategies

Examples of the more sophisticated control strategies are described below.

(a) The reactive power consumption of a HVDC substation is dependent upon the firing angle and the direct-current flow. Thus, the dc link can be used for control of reactive power or for voltage control in the ac network.

(b) The HVDC substation control can be coordinated with the control external to the HVDC substation, for example, the turbine governor of a generator station. The HVDC substation can also be provided with controls to avoid subsynchronous torsional shaft resonance (SSR) of a turbine-generator.

(c) Pole balance control can be specified to minimize ground electrode line current (equal to the imbalance current between two poles of a bipolar HVDC transmission) to avoid corrosion problems from ground current flow through other metallic underground structures. A typical imbalance current limit between the two poles of a bipolar system without balance control might be 3% of rated current.

Specifications should describe which control strategies are intended to be used and in which priority they should be operable under expected operating and ac system conditions.

The power control tolerance is dependent upon the accuracy of the voltage divider, the current sensor, and the resolution of the power order. A typical tolerance value is approximately 1.5% at rated power.

12.2.4 Master Control. Master control is usually integrated into the HVDC substation control. However, if more than one HVDC substation is connected to the same ac bus, the master control is a separate level above substation control and generally would include more sophisticated control strategies. It would interface with the ac system and coordinate the various substations. Master control can also be provided remotely, for example, at a dispatch or power system control center (PSCC). For this case, telecommunications should be provided for the PSCC to the HVDC substation.

12.3 Control Order Settings.

Both converters of a HVDC system are most often equipped with identical control equipment since most HVDC systems are designed to transmit power in both directions.

Only the dc substation control at one location can be in the lead at one time. Generally, the setting of the substation control order and rate of change are provided manually at the lead station. The changes in order are then transmitted to the other substation(s) for execution, by way of the telecommunication media. Capability for setting of the lead station control order can also be transferred to a remote location, for example, to a PSCC.

In the current control mode, the current order can be set manually in both stations, if voice communication is available for coordination purposes. Current control can also be provided remotely, for example, at a PSCC.

Switching from power to current control mode may be ordered automatically after failure of the telecommunication channel or by command from the substation control.

The resolution in power order setting may be specified (typically 10 MW at a rated power of 1000 MW). Its rate of change may also be specified (for example, between 1 MW/min and 99 MW/min in steps of 1 MW/min).

Change in power direction is normally initiated from the lead station, but could also be ordered automatically, if emergency reversal is called for, for example, after a disturbance in one of the ac networks.

12.4 Current Limits. Various limits can be applied to the current order. The main purpose of these is to optimize the permissible current with respect to main circuit components and cooling conditions. Examples of such limits are:

(1) Overload of limited duration—permits overload for a fixed duration per 24 h period, for example, to take account of transformer temperature-rise limitations

(2) Winter overload—permits overload when valve cooling conditions are favorable during low-ambient temperature periods.

(3) Dynamic overload—permits overload for short times based on transient thermal properties of thyristors and their coolers

(4) Other current limitations—because of loading limits for generators connected to the rectifier substation or for operation with reduced dc voltage; or other system dynamic performance requirements

(5) Minimum current—normally 0.05 pu-0.1 pu

The limited current order can be transmitted between the two substations and synchronizing equipment ensures that the two substations at any particular time will be given identical current orders.

12.5 Reactive Power Consumption. The reactive power consumption of a converter substation of a HVDC transmission is dependent upon the firing angle and the direct-current flow. Thus the dc link can be used for control of reactive power or for voltage control in the ac network.

12.6 Control Circuit Redundancy. Control circuits in HVDC substations are normally structured so that failure or malfunction of one circuit does not result in complete loss of transmission. In addition, redundant control circuits may be provided to minimize partial HVDC system outages.

12.7 Metering. Metering items of interest in a HVDC system are as follows:

(1) DC current
(2) DC voltage and polarity
(3) DC power and direction
(4) Reactive power consumed by the converters
(5) Net reactive power including var banks and filters
(6) AC current
(7) AC voltage
(8) AC power
(9) Energy
(10) Ground current
(11) Delay angle
(12) Margin angle
(13) Tap changer positions

A decision should be made as to which of these metering items are required, whether measurements should be made on a per hole basis, and their accuracies, types, and location(s) of instruments for display.

13. Telecommunication

13.1 Types of Telecommunication Links. Alternative types of telecommunication can be used for control and operation of a HVDC transmission. This listing ranges from the lower to higher performance grades of telecommunications:

(1) Telephone
(2) Telemetry
(3) Power-line carrier (PLC)
(4) Microwave
(5) Radio link
(6) Optical telecommunication

The types of telecommunication systems to be used should be specified. More than one system may be used. None of these is required for back-to-back systems.

13.2 Telephone and Telemetry. A public telephone network or telemetry is one alternative of HVDC transmission control especially where redundancy is a requirement, or it may be used even as a link for continuous operation. The basic need is a voice communication channel between the stations for the correct timing and coordination of measures to be taken in the stations during operational changes. However, for the operation of the HVDC transmission from a power system control center (PSCC) when HVDC substations are unmanned and to make use of the inherent HVDC system speed of response for control of transmitted power, a higher grade telecommunication system is needed (see 13.3, 13.4, and 13.5).

13.3 Power-Line Carrier (PLC). PLC is one means of telecommunication for a HVDC transmission with overhead lines; however, its capabilities may be insufficient to meet the requirements of high-speed modulation control.

For a HVDC cable system, the transmission capacity of a PLC over the cable will be reduced for longer cable distances. The approximate cable distance limit is 150 km for one duplex PLC channel.

When allocating frequencies for a PLC system that utilizes the dc line for its carrier signal transmission, account should be taken of frequency coördination with other PLC systems of interconnected ac networks to avoid interference.

PLC over the dc line might well use a higher carrier frequency close to the HVDC substations to achieve a satisfactory signal-to-noise ratio with respect to possible converter interference. Lower carrier frequencies might be used at some distance from the HVDC substations because the lower frequencies have less attenuation. Due attention should also be given to possible interference at crossings between the dc line and ac lines, and possible interference with communications circuits from the ac lines to the dc converter station.

13.4 Microwave. While not necessarily essential for control of dc transmission, a microwave link may be the preferred alternative for fast transmission of the large amounts of information needed to implement a more sophisticated control and protection of HVDC systems as might be needed for enhancement of contiguous ac system(s) performance, reliability, and stability.

13.5 Radio Link. A radio link may be considered at long sea crossing with HVDC cable transmissions, when PLC does not provide sufficient speed or is otherwise limited.

13.6 Optical Telecommunication. If available, an optical telecommunication link may be used for control and protection of HVDC systems.

Optical telecommunication normally will provide fast transmission of large amounts of information with a high degree of immunity from interference.

13.7 Classification of Data To Be Transmitted. A list of classes of the different types of information to be transmitted between the HVDC substations is given in 13.7.1 through 13.7.7. For each of these classes, the different requirements such as speed, resolution, and reliability should be identified.

13.7.1 Order Signals For Continuous Control

(1) Power order
(2) Current order
(3) Frequency control
(4) Damping control

13.7.2 Operation Orders

(1) Change of control mode of operation
(2) Interlocking of protection
(3) Operation of switches
(4) Block/deblock

13.7.3 State Indications

(1) Position of switches
(2) Transformer tap position
(3) Number of converters in operation

13.7.4 Measured Values

13.7.5 Alarm Signals

13.7.6 Voice Communication

13.7.7 DC Line Fault Location

13.8 Fast Response Telecommunication. The following control applications may require a fast telecommunication channel, such as microwave, where a greater than 1200 Bd channel is needed for:

(1) Damping control of ac systems
(2) Frequency control of ac systems
(3) Fast power control of ac and dc systems
(4) DC line fault location

13.9 Reliability. Generally a telecommunication system can be provided with an automatic self-checking system.

When a redundant or stand-by telecommunication system is available, automatic switchover should be provided, thus maintaining the full degree of control of the HVDC system. When a redundant system is not available, then after loss of communication the operation of the HVDC system should continue uninterrupted under a defined control strategy that does not require continuous communication.

14. Auxiliary Power Supplies

14.1 General. Auxiliary power supplies, which usually have a total rating equivalent to 0.2% to 1% of the HVDC substation rating, are needed for cooling pumps and fans, control, protection and motorized drives of disconnects, etc, and for general substation service needs. To ensure adequate security of supply and freedom from interruption, these supplies are usually derived directly from the high-voltage ac network at the substation.

Where a separately and independently energized distribution network supply is available, this should be utilized as a back-up source to give added protection against auxiliary power failure, such as failure of medium- and low-voltage switchgear supply transformers.

14.2 Reliability and Load Classification. Short interruptions in the auxiliary supply should not disturb the HVDC power flow and safe controlled shutdown of the HVDC substation must take place in the event the ac auxiliary supply bus has been tripped by the protection. (Since HVDC converters are line-commutated, there can be no sustained power transmission if the ac system generation is lost, although protection may be needed to prevent pseudo-commutation by filters or reactive power compensators).

Control, protection, and data recording systems are not usually able to accommodate even a very brief interruption in their power supplies. Accordingly, they are supplied from station batteries or when ac supplies are needed, from an uninterruptible power system (UPS). Duplication of batteries is not always necessary, but full redundancy of the battery chargers and the UPS may be required to meet the desired reliability criteria. All breakers and disconnects essential to the safe shutdown following a fault should be operated by stored energy, for example, compressed air or battery supplies.

Different considerations apply to the operation of disconnect switches and the closing of breakers to reinstate the transmission capability following a fault-caused shutdown, perhaps at a lower capacity. When the requirement for a restart from a totally dead bus can be expected, a diesel generator may be necessary when adequate battery capacity is unrealistic.

Only brief power interruptions for valve cooling fans and pumps can be allowed, because of the short thermal time constant of thyristor valves. Automatic changeover between two independently derived supplies is preferable, but if one is dependent upon the distribution network, it must be recognized that the security of such a supply will be rather low and the changeover should be such that reconnection to the primary system source is automatically accomplished as quickly as possible.

Since HVDC power transmission is possible only when the ac system bus is energized, the loss of auxiliary supplies during an ac system disturbance or converter disconnection does not cause a further loss of availability, unless the subsequent restart of auxiliary loads is delayed.

A lower security of supply can be accepted for those general station services, the loss of which does not directly affect the power flow. Even so, changeover capability between alternative and independent supplies should be regarded as the norm, but need not necessarily be automatic.

An emergency supply that will be maintained even when the HVDC substation is isolated from the ac network may be needed. Typically, this emergency supply will be from diesel generators and apart from supplying general services may be arranged to power the battery chargers, particularly when the possibility of prolonged outages can be anticipated.

14.3 AC Auxiliary Supplies. The total auxiliary load of the HVDC substation and the number and rating of motors larger than 30 kW must be established at first to approximately define the overall auxiliary bus power requirements. Secondly, details of possible sources of supply and the capacity, fault level and relationship to the point of coupling of the converter to the ac network need to be defined. This should be augmented with the aid of a single line diagram. From these data, it will be possible to specify security of supplies, duration of interruptions due to fault interruption, distortion, voltage, and frequency limits. A voltage stability analysis should be carried out on any design proposal to ensure that changeover times and phase differences between alternative supplies, voltage reductions on motor starting and fault interruptions are within acceptable limits. Induction motors, particularly, may be sensitive to the amplitude of negative sequence voltage, low voltage, or extreme frequency excursions. Finally, an accurate figure of the auxiliary power load will be needed for loss guarantee purposes.

14.4 Batteries and Uninterruptible Power Supplies

14.4.1 It is usual to have separate dedicated batteries to limit mutual interference for at least

(1) HVDC system control for each pole
(2) Other substation control and protection
(3) Telecommunication equipment

These batteries will usually be of different rated voltages. The time for which each battery can supply its rated load, within the rated voltage range in the event of failure of the charger or its supply must be specified. A typical time is six hours. The recharging time, while the battery is also supplying rated load, and acceptable ripple voltage must also be specified. A room should be set aside for batteries and chargers, but with modern equipment, separation of these two items is not usually justified.

14.4.2 For batteries it is necessary to consider and specify

(1) Nominal voltage
(2) Capacity, amperehour
(3) Voltage range from charge (with boost if necessary) to discharge
(4) Type of cell
(5) Discharge rate

The charging system should meet the requirements of the battery and the load.

14.4.3 The uninterruptable power supplies (UPS) for ac loads can be based upon dedicated units or a common system for the HVDC substation. The latter is usually preferred because it makes the provision of adequate redundancy more realistic. Usually the UPS will include its own dedicated battery.

The following information must be specified for the UPS

(1) Rated voltage, number of phases, and permissible distortion
(2) Voltage tolerance
(3) Rated frequency and tolerance
(4) Rated and maximum load
(5) Type of load
(6) Maximum allowable interruption for which the UPS must function
(7) Overload capabilities

Special consideration should be given to (4), (5), (6), and (7). UPS are often very sensitive to overload and surge starting conditions of induction motors and power supplies having large storage capacitors or any other type of load having a substantial nonlinear type characteristic. With many UPS, the continuity of supply is only within its specified limits and is not generally uninterruptible in an absolute sense. Care should therefore be taken to ensure that the UPS is correctly specified to meet system requirements.

Reliability of the UPS should also be carefully assessed. Many commercial-quality systems suitable for enhancing the quality of distribution system supplies may actually degrade the security of the auxiliary supply in a converter substation where the supply is derived directly from the high-voltage system and is therefore inherently very secure, but not noninterruptible.

14.5 Emergency Supply. When an emergency generator is necessary consideration should be given to the following information when preparing its specification:

(1) How much of the total auxiliary load must be supplied
(2) Determine if start-up, changeover or shutdown, or both, will be automatic
(3) If automatic, care should be taken to ensure that conditions causing frequent restarting cannot occur, otherwise its starting battery might become fully discharged.
(4) Quantity of fuel which should be stored on site

To ensure reliable operation when required for emergency conditions, it is desirable that the generator is started and loaded for periodic testing so that it reaches correct operating conditions on a regular basis. The auxiliary system should be designed to achieve this without putting the dc power transmission at risk in any way by the failure of auxiliary supply equipment to make a correct changeover.

15. Audible Noise

15.1 General. Noise from the HVDC substation could be troublesome and might incur prescriptive mandatory sanctions, which may be difficult to resolve once the station is built. Therefore, limiting specifications should be prepared at the start of the project taking into account requirements of any applicable regulations or codes of practice. The effects of noise are generally treated as those concerning nuisance to the public outside the boundary of the HVDC substation and noise effects in the working environment. While the latter are important, public nuisance limits are often more difficult to specify.

15.2 Public Nuisance. The impact of HVDC substation noise on the public outside the confines of the station, and whether or not it is seen as a nuisance depends mainly upon the noise level, the preexisting level, the nature of the surrounding area, and the nearness of residential property.

As a first step, the acceptable noise level at the boundary should be specified having regard to the relevant factors. Reference [6] gives a method for determination of an acceptable level. Next the level and spectrum of noise expected from each major source should be defined. These can then be summed to decide whether or not the total noise will be acceptable. The location of equipment, that is, the distance from the property line, is of particular importance. Special noise abatement measures may need to be used to keep the total to an acceptable figure.

Other noise-producing equipment may be installed at the same location and if so must also be considered, for example, ac system transformers and reactive power compensators. Typical HVDC substation plant items most likely to produce significant noise are discussed in 15.2.1 through 15.2.4.

15.2.1 Valves and Valve Coolers. The noise associated with indoor valves can usually be disregarded so far as the public is concerned, since in most cases the attenuation introduced by the valve hall will adequately suppress it. A main source of noise will probably be from the fans of outdoor coolers. These will usually be closed-cycle evaporative coolers or forced air coolers drawn from a standard product range and, as such, the cooling equipment manufacturer should be able to supply noise spectrum and level data. Evaporative coolers are generally less noisy. In both types, the noise level can be reduced by using larger, lower-speed fans. Substantial noise reduction can also be achieved by using screen walls to deflect the noise upwards.

15.2.2 Converter Transformers. Converter transformer noise level is likely to be comparable to similarly sized ac system transformers. But because of the effects of the harmonic currents, principally of order 5, 7, 11, and 13 and the small residual direct current in the converter transformer valve windings, its noise spectrum will be different in actual operation and may be as much as 10 dB higher than the noise level measured in factory ac tests. The tank and cooler noise levels can be reduced by conventional means, if necessary, for example, enclosures, mufflers, and lower speed fans.

15.2.3 DC Reactors. Noise will come from the core, structure, and coolers of the dc reactors. Core and structure noise can be expected to have peaks at the 12th and 24th harmonic frequencies, corresponding to harmonic order of 6 and 12. It is probably not practicable to carry out valid factory tests of dc reactor noise. The noise level can be reduced, if necessary, by some of the same measures as are applicable to transformers, for example, enclosures.

15.2.4 AC Filter Reactors. Filter reactors are usually air cored. For these, noise is not likely to be a problem, except where extremely low noise levels are required.

15.3 Noise in Working Areas. The noise level to which persons within the boundary of the HVDC substation may be subjected must be considered with regard for safety, hearing impairment, and the effect noise can have on working efficiency.

Many countries have established codes or mandatory regulations that seek to safeguard the hearing of those exposed to high noise levels and these should be examined and incorporated within the specification as appropriate. Problems of this kind are unlikely in HVDC substations other than during maintenance procedures in the immediate vicinity of certain types of fans used for cooling of air-cooled valves. In most cases, it is possible to meet the requirements of the regulations, when maintenance personnel wear hearing protectors as necessary.

The general noise level within the building is determined primarily by the valves and the indoor part of their cooling systems, any rotating machinery, and the dc reactors (and transformers) where these are partially or fully enclosed within the building. Low noise levels should be specified where mental concentration is routinely expected, as in control rooms.

16. Harmonic Interference — AC

16.1 AC Side Harmonic Generation. Converter systems of all types are sources of voltage and current harmonics. To an ac network, the HVDC substation acts as a source of harmonic currents. These harmonic currents flowing into the ac system impedance give rise to harmonic voltage distortion. In addition, they can propagate throughout the ac system giving rise to local resonances or telephone interference.

If a converter is fed from a balanced three-phase source of voltage, if the impedances of the three phases are equal, and if the converter control angles are equal, characteristic ac side harmonics are generated of an order, determined by the pulse number p, of the converter, $k\text{p} \pm 1$, where k is an integer. For the ideal case, the amplitude and phase of the generated characteristic harmonics in relation to the fundamental component, depend solely on the control angle α or β and the angle of overlap μ.

However, in practice, ac systems that are coupled with HVDC substations are not perfectly balanced in voltage or phase. This leads to negative sequence voltage or current components typically in the range 0.25% to 1% of the system

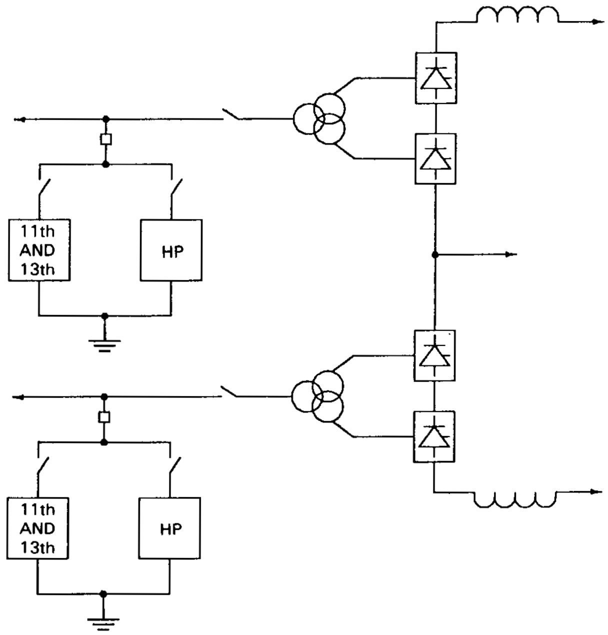


Fig 18
Example of AC Filter Connections for a Bipole HVDC System

fundamental. Other sources of imbalance include converter transformer commutation inductance differences (typically ±2% to ±5%), and firing angle imbalances (typically 0.1° to 0.25° in steady-state for modern HVDC control systems). These imbalances result in generation of noncharacteristic harmonics, thus adding to the harmonic interference from the converter.

16.2 Filtering. AC harmonic filters are generally provided at HVDC substations for absorbing the harmonics generated by the converters, and in addition, for reactive power compensation (see Section 9). An example of ac harmonic filters connected to the infeed ac feeders for a bipolar HVDC system is shown in Fig 18.

In order that the loss of any single filter will not prevent system operation at full power, two filter arms of each type may be specified. The filter arms may be made switchable on the basis of individual arms on each pole. Sizing individual filters to be switchable must take into consideration:

(1) Reactive power and voltage regulation requirements

(2) Reduced and light load conditions

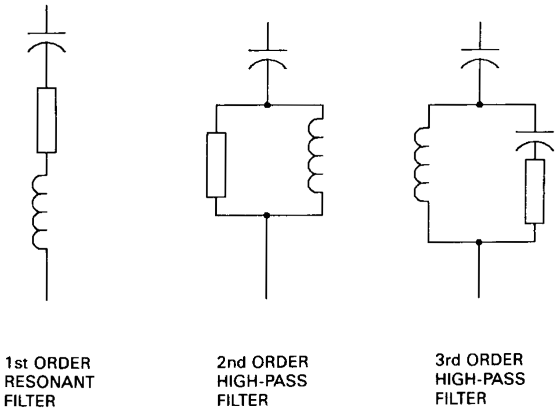
(3) Possible resonance between the filters and the ac network impedance with each switched configuration

(4) Reliability criteria

(5) Economic constraints

Filters of either the series-resonant RLC, or the damped high-pass type are generally used on HVDC systems (see [14] and [15]). Examples of the most frequently used filter types are shown in Fig 19.

Fig 19
Circuit Diagrams for Different Filter Types



For optimum harmonic filter design, the system impedance at harmonic frequencies should be known over the frequency range of interest. The ac system impedance seen by the HVDC substation may be specified by ample impedance (R/X) circle diagram over the frequency range from fundamental to the 50th harmonic. Alternatively, the system may be specified in detail by harmonic impedances of lines and generators, etc, normally extending to five to eight buses from the HVDC substation (see Section 8). The design of ac harmonic filters should also take into account any harmonics that may flow into the filters from other harmonic sources (see [15]).

16.3 Interference Disturbance Criteria. Interference performance is normally defined in terms of individual harmonic distortion D_n; total effective harmonic distortion D_{eff}; telephone influence factor TIF (current TIF usually preferred); telephone harmonic form factor THFF; and IT, weighted current product. The sensitivity of the human ear, response of the telephone receiver, and the coupling between power and telephone circuits all vary with frequency. These variations can be taken into account by appropriate weighting factors. Two systems of weighting are used. These take into account the response of telephone equipment and the sensitivity of the human ear, namely: Psophometric weighting as recommended by [7] and [8]. Each of the above terms is defined as follows:

Individual harmonic distortion according to CCITT or BTS-EEI.

$$D_n = \frac{V_n \cdot 100}{V_1}, \ \%$$

where

V_1 = rated fundamental rms voltage
V_n = nth harmonic rms voltage considered

Total effective harmonic distortion:

$$D_{eff} = \sqrt{\sum_{n=2}^{50} \left(\frac{V_n \cdot 100}{V_1}\right)^2}, \ \%$$

The telephone harmonic form factor (THFF in the CCITT system) and the telephone influence factor (TIF in the BTS-EEI system) are both used to describe the interference influence of a power transmission line on a telephone line, and serve as guidelines for specifying interference performance. TIF and THFF are defined similarly.

In the BTS-EEI system:

$$\text{Voltage TIF} = \frac{\left[\sum_{f=0}^{\infty} (k_f p_f V_f)^2\right]^{1/2}}{V}$$

$$\text{Current TIF} = \frac{\left[\sum_{f=0}^{\infty} (k_f p_f V_f)^2\right]^{1/2}}{I}$$

where

k_f = $5000 \left(\frac{f}{1000}\right) = 5f$
p_f = C-message weighting
V_f = rms voltage of frequency f on power line
I_f = rms current of frequency f on power line
V = $\sqrt{\sum V_f^2}$ = rms voltage, unweighted
I = $\sqrt{\sum I_f^2}$ = rms current, unweighted

And in the CCITT system:

$$\text{THFF} = \frac{\left[\sum_{f=0}^{\infty} (k_f p_f V_f)^2\right]^{1/2}}{V}$$

where

k_f = $\frac{f}{800}$
p_f = $\frac{\text{psophometric weighting}}{1000}$
V_f = rms voltage of frequency f on power line
V = $\sqrt{\sum V_f^2}$ = rms voltage, unweighted

NOTE: The upper frequency limit of the 80th harmonic of the power frequency (50 Hz or 60 Hz) is recommended.

The approximate relationship between TIF and THFF is

TIF/THFF = 4000, that is, a TIF equal to 40 is roughly equivalent to a THFF equal to one percent.

The harmonic currents of power transmission lines are represented by a single current obtained by weighting each harmonic current with the corresponding factor of the system used.

The weighted current product IT is computed as follows:

$$IT = \sqrt{\sum_{f=0}^{\infty} (T_f I_f)^2}$$

where

I_f = n^{th} harmonic rms current

T_f = corresponding single frequency current TIF, which is not necessarily equal to the voltage TIF

Calculation of the weighted current product *IT* in individual lines requires a knowledge of the harmonic impedances of individual lines connected to the converter ac bus to be meaningful in specifying interference performance of HVDC installations. The *IT* product should be specified for individual lines, but only when the harmonic impedances of all lines from the HVDC substation ac bus are specified.

Specifying performance limits simultaneously for all harmonic interference factors D_n, *TIF*, and *IT* may not be practical if the values must reflect the real impact of the injected harmonics on inductive coupling. This is particularly true when IT is specified for meshed systems. These values vary from station bus to station bus and along the line, thus acceptable performance can only be assured in the design when line parameters, soil resistivity along the transmission line, geometric coupling factors, etc, are accurately known.

16.4 Levels for Interference. Examples of typical maximum levels of harmonic interference factors that have been specified for HVDC substations are as follows: (These are not recommended specification values and should not be taken as limits without specific studies for a given system):

(1) Individual distortion D_n, one percent at any harmonic

(2) Effective harmonic distortion, D_{eff}, 2%-5%

(3) Telephone influence factor, current-TIF 25-50; THFF in the range of 0.6%-1.25%

(4) IT product 25 000 per line

When generators are connected near the HVDC substation, the sum of the negative sequence 5^{th} and positive sequence 7^{th} noncharacteristic harmonic currents flowing into any generator should be considered in the design specification for the HVDC substations. Consideration should be given to specification of acceptable methods of calculation and expected acceptable level of confidence for the above factors.

16.5 Filter Performance

16.5.1 HVDC system operating conditions that should be considered when specifying performance requirements of ac harmonic filters include:

(1) Range of dc values from minimum to the specified overload

(2) Reduced dc voltage operation over the range of required dc values for the reduced voltage operation

(3) Operation at larger-than-normal angles for reactive power absorption as specified

(4) Operation with any filter bank or reactive power bank out of service. A filter bank is understood as one filter element that can be removed from service by the operation of switching equipment. This condition should apply only for the normal operating modes of the HVDC system

(5) Steady-state range of ac power system frequency and voltage

(6) Loss of sufficient capacitor units to the extent that a first level alarm results

(7) Extremes of ambient temperature conditions coupled with maximum filter loading

(8) Initial filter tuning errors

(9) Any change in system configuration

16.5.2 Filters should not be required to meet performance limits under the following conditions, but should be capable of operation without damage during:

(1) Emergency frequency variations as specified

(2) Dynamic overvoltage conditions including ferroresonance following load rejection or fault recovery

(3) Short-term overload

When specifying harmonic interference limits for a HVDC substation, certain data (see Section 8) must be included in the specification to enable appropriate optimization of ac filter designs.

When filter bank switching is needed for different load levels, the designer may wish to take advantage of reduced interference level, which might be expected in specifying the filter performance levels.

17. Harmonic Interference — DC

17.1 DC — Side Interference

17.1.1 The operation of the converter equipment in a HVDC substation generates harmonic voltages on the dc side of the substation that causes harmonic currents to flow in the dc line. Where the transmission line consists of overhead line and cable, the cable generally acts as a filter to the harmonic current, so that only harmonic currents of small magnitudes flow into the line beyond the cable. Such systems still require evaluation for interference along the overhead line sections. Underground or submarine dc cables are so well shielded that generally no noise problem exists on the dc side.

17.1.2 In modern converter unit design, 12-pulse converter units are generally used, so only the 12 k characteristic harmonics (k being an integer) should be considered. In addition to these *characteristic* harmonics, which appear under idealized conditions, there are also harmonics of other orders, the *noncharacteristic* harmonics. The characteristic harmonic voltages generated by the converter operation depend on the following factors: direct voltage, direct current, the commutating reactances, and the firing angle. Noncharacteristic harmonic voltages are caused by such factors as differences between the delay angles, imbalances in the commutating reactance, and asymmetry in the network ac voltage (negative sequence voltage component) feeding the converter.

17.1.3 Two groups of harmonics should be considered: the higher order harmonic group (7th to 48th) responsible for the voice telephone interference and the low order harmonic group (1st to 6th) that may introduce other interference problems, such as:

(1) Personnel and equipment safety from induced voltage

(2) Effects on data transmission and railway signalling circuits

(3) Effects other than voice interference in voice communication circuits

(4) Secondary induction effects

(5) Possible excitation of resonance conditions between the dc line and the electrode line

(6) Unacceptable dc in the converter transformers

(7) Impact on minimum current

17.1.4 The harmonic currents circulating in the dc line poles and in the overhead shield wire can be calculated by the usual formulas for long line calculations and modal analysis, in case there are imbalances in the circuit. If the distance between the dc line and a telephone circuit is short (less than 200 m), the calculation should consider the currents in the poles and in the shield wire(s) separately, with their respective coupling factors.

In computing the longitudinal noise voltage imposed on a voice communication circuit, the harmonic currents are weighted by a factor (psophometric or C-message) to take into account the response of the human ear to each frequency.

17.1.5 The longitudinal C-message or psophometric voltage $V_{g(x)}$ induced per kilometer of exposure of a telephone circuit can be calculated considering the currents coming from both ends of the dc line, at any location x km from one end of a dc line, the weighting factor, the shielding factor of communication circuits, and the mutual impedance between the dc line and the communication circuit. The transverse voltage is given by $k_b V_g$ where k_b is the balance factor of the communication facility being considered.

17.1.6 When considering personnel safety, the voltage value is calculated as the square root of the sum of the squares (rss) of the induced harmonic voltages to ground, flat weighted. For the other interference problems in nonvoice communication circuits, there is no standardized procedure and, therefore, the procedure to be used should be agreed upon between the entities involved.

17.1.7 DC filters are used to reduce the magnitude of the harmonic currents circulating in the dc line to avoid unacceptable interferences. The need for the dc filters depends on:

(1) The characteristics of the transmission system, overhead line, or overhead line and cables

(2) The earth resistivity

(3) The density, proximity, and type of telephone and railway signal circuits near the dc line route

When establishing the need for a filter scheme, other cost effective means available to satisfy the noise criteria should be taken into account. The evaluation should consider any changes in the communication circuits and modifications to the converter station such as use of a dc reactor, already required for other reasons, either with or without a reduced level of filtering; capacitors connected between the ground electrode line connection and earth (a resonant circuit with the electrode line inductance should be avoided); and switches to permit paralleling of two (pole) filters when in monopolar operation. The influence of these on the operation and in the overall performance of the converter station should be examined before deciding as to the extent of needed limitation of the harmonics on the dc side.

17.2 DC Filter Performance

17.2.1 Understanding of communication and railway companies' requirements is necessary to arrive at the best overall solution for interference problems.

Table 2 indicates the requirements for voice communication circuits, prescribed by [9].

17.2.2 When defining the filter performance, the levels of interference should be specified for

Table 2
Performance Parameters for Voice Communication Circuits

	Subscribers and Trunk Circuits*		
	CCITT	AT&T	REA
1. Balances			
Cable circuits (dB)	50-60	60	50-60
Open line (dB)	46-56	50	
2. Transversal — metallic			
Noise limit (dBrnC)	26	20†	31‡ 26/[20]§

*It is American practice (AT&T) to use a characteristic impedance of 600 Ω for a trunk circuit and 900 Ω for a subscriber circuit. CCITT and REA use 600 Ω. Zero dBrnC corresponds to 10^{-12} W (1 pW) at 1000 Hz.

†This value is the total noise. From a single source (HVDC line, for example) the maximum value should be 17 dBrnC.

‡This value refers to a trunk circuit.

§The value in brackets refers to the design objective and the other to the maximum acceptable value.

the operating modes of the HVDC system. From the interference point of view, bipolar operation with equal positive and negative voltages is the mode requiring less filtering. Monopolar operation, either with ground or metallic return, gives higher values of noise voltage than bipolar operation for the same dc filter configuration, however, operation in this configuration usually occurs for a low percentage of time. Monopolar operation with metallic return gives less interference than monopolar operation with ground return. In practice for bipolar systems the performance requirements of a dc filtering scheme are primarily based on the bipolar operating mode. A higher interference level on voice communications is usually considered acceptable during monopolar operation, for example, at two or three times the level permitted during bipolar balanced operation.

In addition to the basic HVDC operating modes discussed above, the specification should indicate any other modes or conditions under which the transmission system could eventually operate. The filter should be rated for all these conditions; however, the interference level under the several modes or conditions should lie between the normal bipolar balanced operating mode and the worst monopolar mode. Provision may be made in the specification for the system capability for emergency operation.

17.2.3 As to personnel safety there is not yet a specific limit for hazardous induction caused by harmonics. For the fundamental frequency (50 Hz and 60 Hz), the CCITT and the AT&T prescribe 60 V ac rms and 50 V ac rms, respectively. These limits should be considered as the maximum rss value of the induced longitudinal harmonic voltages for the low order harmonics (1st to 6th), for personnel and equipment safety. In addition, any higher order harmonics with unusually high current values should also be included in the rss calculation.

17.3 Specification Requirements

17.3.1 The preferred way to determine the economic level of filtering that satisfies interference performance requirements is to perform an inductive coordination study and optimize the cost of filters with the cost of changes in the communication circuits, considering the points discussed earlier. From such a study, the ideal specification for the filters could indicate the profile of the maximum disturbing current along the line, as defined in 17.3.4, required to maintain the interference level below the specified values.

Usually the above studies are not feasible during the specification stage, therefore, one of the following three alternative approaches is usually followed:

17.3.1.1 Specify use of the *Equivalent Disturbing Current Method* as an option for optimizing the dc filtering. In this, the total composite interfering effect of all harmonic frequencies on a power line can be represented with reasonable accuracy by a current at a single frequency that produces the same interfering effect (The concepts are described in [10] and [11]).

This procedure permits initial determination of: required dc filter performance; the expected induced noise in adjacent wire-line communications circuits; and from mutual coupling, earth resistivity, etc, analysis of those circuits that might be affected. This would allow the establishment of preliminary evaluations of the options for control and mitigation of possible telephone inductive interference problems.

17.3.1.2 Establish the filter cost based on the nonsimultaneous maximum values for each harmonic current (on a pole basis), at the dc line terminals, and subsequently select the optimum design after a complete inductive coordination study. This procedure has some of the drawbacks of the previous one and the method to establish the set of harmonic voltages is complicated due to other considerations given in 17.3.3.

17.3.1.3 For the third alternative the following steps should be taken:

(1) Obtain information on the characteristics (shielding and balance factors, length, routes, etc) of the communication lines and railways, installed or planned, within the area of influence of the dc line (10 km from the center line of the right-of-way, for example).

(2) Perform tests on representative soil samples taken within the limits of the area of influence of the dc line, to determine the different values of earth resistivity to be considered in the inductive coordination studies.

With the information obtained and considering the normal mode of system operation (bipolar), it should be possible to establish two profiles of disturbing currents and two limits of the maximum allowable low order harmonic current magnitudes:

(a) One not requiring any change in the communication circuits

(b) The second requiring, for example, changes in perhaps 25% of the communication circuits located in the area of influence.

Finally, with the information on filter cost and the cost for changes in the communication circuits, it should be possible to determine the optimum trade-offs between the filtering system and communication circuit changes.

17.3.2 In addition, to specify the level of filtering in accordance with one of the alternatives indicated in 17.3.1, the following general criteria should be followed:

(1) The level of harmonic current filtering should be determined under bipolar balanced operation and under the nominal condition defined for the HVDC system. For any other operating mode or condition specified, the level of noise should not be higher than the one resulting from the worst monopolar operation, except for the unusual contingency of operation without filters.

(2) The specification should also define the maximum value of the disturbing current profiles to be accepted under monopolar operation.

(3) In addition to requirements (1) and (2), the maximum low order harmonic current values (1st to 6th) should be specified.

(4) The specification should also address the limits of system operating conditions under which the filter performance requirements are to be met for each mode of operation and for each stage of development of the HVDC system. For example:

(a) Range of direct voltage and direct current
(b) Range of normal operating ac bus voltage
(c) Negative sequence component of fundamental frequency ac voltages
(d) Maximum ac frequency deviation within a normal cycle range or which may be maintained for more than one minute
(e) Maximum temperature variations expected
(f) Maximum number of capacitor unit or element failures permissible before mandatory filter removal
(g) Initial mistuning to the limit possible in the design

17.3.3 The performance calculations should take into account

(1) Calculation of the harmonic current profiles to determine the compliance with the performance specified, should consider: the phase-angle relationship between the ac systems; the most onerous combination of firing angles; direct-current magnitudes; commutation reactance differences among the phases of a 6-pulse bridge, between the transformers of the 6-pulse in a 12-pulse unit between 12-pulse units of a pole and between poles of a bipole, that will result in the worst consistent set of harmonic driving voltages. The consistent set of harmonic voltages includes voltages occurring simultaneously and giving the highest value of C-message or psophometric profile of disturbing current along the line and also complying with the levels of low order harmonic currents specified.

(2) The frequency dependent parameters of the dc and electrode lines, and their termination and the characteristics of the ground electrode as given in the specification, should be taken into account.

(3) The variation of the inductance and resistance of the dc reactor with load and frequency should be considered in determining the harmonic currents flowing to the dc line.

For the alternative indicated in 17.3.1.2 the set of harmonic driving voltages to be considered should be the highest nonsimultaneously occurring harmonic voltages.

17.3.4 For the purpose of meeting the performance criteria specified, the magnitude of the current at each frequency and at any point along the dc line should be considered as the root sum square (rss) value of the contribution at that point from the sending end and from the receiving end of the dc line, for the frequency being considered, using the following formula:

$$I_{e,x} = \frac{1}{C_{\text{base}}} \sqrt{\Sigma_f (C_f \cdot I_{x,f})^2}$$

where

$I_{e,x}$ = equivalent disturbing current at base frequency (800 Hz, CCITT or 1000 Hz, North America), at point x along the dc line
f = frequency of the harmonic current to be considered from the fundamental to the 48th harmonic
C_{base} = value of C_f at base frequency where C_f is psophometric C-message weighting factor at frequency f
$I_{x,f}$ = harmonic current of frequency f

In cases where the separation between the dc line and telephone line is less than 300 m or less than approximately 100 m for earth resistivity equal or higher than 10 000 Ω · m, the equivalent disturbing current I_P at 800 Hz should be calculated using the following formula:

$$I_{P,x} = \frac{1}{P_{\text{base}}} \sqrt{\Sigma_f \left(h_f \cdot A_f \cdot I_{x,f}\right)^2}$$

where

P_{base} = psophometric weight at base frequency divided by 1000
h_f = factor depending on the type of coupling at frequency f
A_f = C-message weighting value at frequency f
$I_{x,f}$ = harmonic current of frequency f

The characteristic harmonic currents should be calculated giving both magnitude and angle.

An internal source reactance not higher than $2n$ times the total commutation reactance of the pole ($4x_t$ per 12-pulse converter unit) should be used, where n is the number of 6-pulse bridges in operation for the mode of operation being analyzed.

18. Power-Line Carrier Interference

18.1 General. Power-line carrier interference from a HVDC substation is produced by the turn-off and turn-on sequences in the valves. The predominant component is produced during the voltage collapse in the turn-on sequence. These transients excite localized resonant circuits formed by the stray capacitance and inductive elements in the HVDC substation, transformers, reactors, bushings, etc. Interference energy is dependent on the magnitude of the voltage jumps produced by turn-on and turn-off of the valves and circuit parameters. Converter noise is somewhat independent of the current rating and actual loading of the valve groups.

Noise that may affect carrier includes: conducted converter-generated noise, and ac or dc line corona noise. Conducted noise is strongly frequency-dependent with the highest noise levels present at the low end of the carrier frequency spectrum.

Field experience shows that thyristor valves generate approximately 10 dB-15 dB less conducted noise interference than mercury-arc valves.

Measurements have shown that corona on dc lines is 10 dB-20 dB less than that on ac lines for the same conductor surface maximum voltage gradient. Typical corona noise level ranges from -40 dBm (1 mW) to -30 dBm (1 mW), and is essentially constant in the carrier spectrum (20 kHz-500 kHz) over the entire length of the dc line.

RF filters can be specified to reduce conducted carrier noise interference on both the ac and dc side of the HVDC substations.

The filter series-inductor elements and shunt capacitor elements should be rated for full current and rated voltage respectively. Therefore, economic consideration should be given to filter design noise alternatives based on existing carrier channel requirements, interference with other carrier, ultimate channel requirements, and the feasibility of channel movement from the lower end of the carrier frequency spectrum.

18.2 Performance Specification. When specifying performance of HVDC systems the following carrier interference considerations are important:

18.2.1 If the utility expects to use the entire allocated communication spectrum, then the HVDC interference specification should cover frequencies down to 20 kHz.

An example of carrier noise frequencies generated on the dc line from solid-state converters is presented in Fig 20.

18.2.2 For design of the carrier filters, the specification should consider that harmful interference to power-line carrier systems on HV transmission lines connected to the HVDC substations may be prevented by limiting the interference level from the HVDC substation over the power-line carrier spectrum to -20 dBm (1 mW) or less, measured in a nominal 3 kHz band, flat weighting.

Where dBm (1 mW) is defined as a means of interference measurement in which 0 dB is specified at 0.775 V, this would be the voltage that

19.1.2.4 The noise is essentially independent of the operating current level.

19.1.2.5 The noise that comes out from the valve hall is predominantly the noise conducted through the wall or transformer bushings provided the valve hall is designed with good rf shielding.

19.1.2.6 The RI level does not increase appreciably as the number of converter units is increased from 1 to 3.

19.2 RI Performance Specification Considerations

19.2.1 RI Consequences. The RI performance specification for a HVDC substation should consider the different consequences of RI such as: interference with AM radio reception and interference with the operation of nondirectional beacons (NDB). The specification should also require verification that the HVDC substation RI with other communication facilities such as VHF, microwave and UHF is within the specified limits. The limits to be established should include the RI due to dipole-radiation generated by converter operation and the RI generated by corona.

19.2.2 Steady-State Operating Modes. The specification should define all steady-state operating modes and conditions, and weather conditions during which the basic criteria should be met.

Specification of a single basic criterion to be applied to all operating modes, at any load up to and including the full load rated value, and within the design range of firing angle, is recommended. This performance criterion should apply over the normal ac and dc operating voltage ranges and under fair weather conditions.

19.2.3 RI Criteria Application. The RI performance criteria should apply at all frequencies within the range of 0.15 MHz to 30 MHz.

Measurements should be quasi-peak and should include at least three complete frequency scans at each measurement location. The RI level at a particular frequency should be considered the mean value of all measurements at that frequency and location. Instrumentation for RI measurement is described in [12].

19.2.4 NDB Characteristics. The specification should indicate the rated range and band characteristics of the NDB to be protected against harmful interference from the HVDC substation. The protected bandwidth should be given in ±kHz from the NDB frequency. As an example, this bandwidth has been specified as ±10 kHz. In addition, the specification should give main data and location of the NDB installations to be protected. Generally only the installations within a radius of 30 km from the HVDC substation need to be studied.

19.2.5 Radio-Interference Criteria. The most important item to be defined in the RI performance specification is the maximum RI level outside a defined perimeter around the HVDC substation.

19.2.5.1 Corona and Valve RI Contribution. In setting an acceptable level of RI, μV/m, the noise contribution from corona and valve operation should be considered. The value to be specified depends on local conditions such as: AM radio station signal strength, the characteristics of the NDB, and any existing regulations as to the acceptable signal-to-noise ratio.

19.2.5.2 Radio-Interference Limits. An RI value of 100 μV/m is a typical specification limit. For conventional HVDC substation designs, the specified RI value should not be exceeded at points along a perimeter line 500 m from any energized HVDC substation component. The contour line for measurement should also include the ac and dc overhead lines leaving the HVDC substation at a distance of 150 m from the nearest conductor crossing the 500 m perimeter. As a rule of thumb, the contour line distance from the overhead ac and dc lines will decrease linearly with distance along the transmission lines to half of the width of the line right-of-way at approximately 5 km from the HVDC substation.

19.2.5.3 Valve Hall RI Shielding. The valve hall building design should incorporate necessary shielding to meet the RI requirements without any external switchyard screening. Special attention should be given to minimize the length of the connection extending from the valve hall building to the converter transformer or RI filter.

19.2.6 Radio Interference — Others. The specification should require a statement on any proposed method of limiting RI within the specified design limit and should also include the data and curves relating to the expected radio interference within the entire frequency range (0.15 MHz to 30 MHz).

The radio-interference levels should be calculated assuming earth resistivity as included in the specification for the substation site and for 5 km from the substation, along the dc line right-of-way.

20. Losses

20.1 General. It is a normal practice to establish loss figures for HVDC substations under rated power (Section 5) and no-load operating conditions (see 7.4), so as to permit an economic evaluation of the losses. In addition, losses at minimum load (see 7.4) or other intermediate levels may also be evaluated.

HVDC system losses can be determined by the summation of losses of the main contributing sources. Loss figures are usually based on a combination of factory and field tests, and calculations, since determination of total losses by field tests alone is not practical because of inadequate measuring accuracy.

The relevant environmental conditions and methods of the calculations should be specified. The tolerances for all loss measurements should be established.

If the HVDC system is erected in stages, then the loss figures per state should be determined. Total efficiency figures for monopolar and bipolar operation under the specified conditions should be verified.

20.2 Main Contributing Sources. For much HVDC equipment, harmonic currents contribute appreciably to total equipment losses. The basis for calculation of these harmonic losses should be specified. Temperatures at which losses are to be determined should be given.

20.2.1 AC Filters and Reactive Power Compensation. Loss figures are calculated for the ac filters and reactive power compensation. The harmonic losses in these are strongly load dependent. The loss figures should include all harmonic effects produced by the converters. Unless otherwise specified, harmonics entering from the ac system should not be taken into account in these calculations. For no-load loss calculations, none of the filters and var banks are assumed to be connected. For rated load, all filters and reactive power sources that are needed to provide the specified power factor ordinarily are assumed to be connected and all harmonics enter the filter only. For intermediate loads, the operating conditions should be specified. For static and synchronous reactive power compensators the operating conditions should also be specified.

20.2.2 Converter Bridges. Converter bridge losses can be calculated based on measurements made in the factory on the individual bridge elements. Loss figures include losses in all the components used in the bridges, for example, valves, snubber circuits, and reactors, assuming firing and overlap angles as required for the specified load condition. Under no-load, valves are assumed to be energized, but blocked. All valve cooling equipment losses required for the specified load conditions should be included.

20.2.3 Converter Transformer. The fundamental frequency losses in converter transformers can be established by no-load and short-circuit measurements in the factory with harmonic losses taken into account in accordance with [13]. All cooling equipment losses should be included to the extent that their operation is required for the specific load condition.

20.2.4 DC Reactor. Direct-current losses can be measured in the dc reactor at the factory and adjusted for the specified ambient temperature. Its harmonic losses should be calculated. All cooling equipment losses should be included to the extent that their operation is required for the specified load condition.

20.2.5 DC Filter. DC filter losses are calculated taking into account the harmonics actually entering the filter at the specified load conditions with the control and overlap angles as needed at those conditions.

20.2.6 Auxiliary Equipment. The equipment includes cooling (except converter transformer, dc reactor, and valve cooling), control, heating, lighting of the HVDC substation and auxiliary transformers. Losses can be determined as the summation of the measured or calculated losses of all individual items. Only that equipment needed for the specific operating point should be included in the loss calculation in meeting all requirements of the specifications.

20.2.7 Other Components. Losses of other components such as voltage and current transformers, and radio-interference filters should be determined under specified conditions (load level, ambient temperature, etc).

21. Provision for Extensions to the HVDC Systems

21.1 General. If extensions to HVDC systems are scheduled or planned in the future through separate specifications, the various applicable conditions after the extensions must be considered in advance. Otherwise, economically and technically disadvantageous situations might arise. Therefore, it is necessary to specify as far as possible the conditions for each step of the extensions applying Sections 3 through 19. For the scope of the equipment installations in each stage of the extensions and the performance specifications, careful consideration should be given to the complexity of the field work, to minimization of the influence of the field work and field tests on the operation of the existing system, to economy of advance investment and to the system performance requirements at each stage. The following matters should be specified in as much detail as possible to the extent they can be anticipated and included in the statement of scope of extensions.

21.2 Specification for Extensions

21.2.1 General Rating Specifications. Rated capacity, voltage, and current in each stage of the planned extensions should be given.

21.2.2 Form of Converter Bridge Extensions (Fig 21)

(1) Series
(2) Parallel
(3) Monopolar to bipolar
(4) Multiterminal, series, or parallel

Any special operating modes planned for the future, such as switching of poles from series operation to parallel operation during the outage of a dc line pole as discussed in Section 3 should be described.

21.2.3 AC System Parameters After Each Stage of the Extensions

(1) Additional ac lines
(2) Changes in nominal and range of steady-state ac voltage
(3) Additional generators
(4) Increased short-circuit capacity

21.2.4 Reactive Power Balance After Each Stage of the Extension

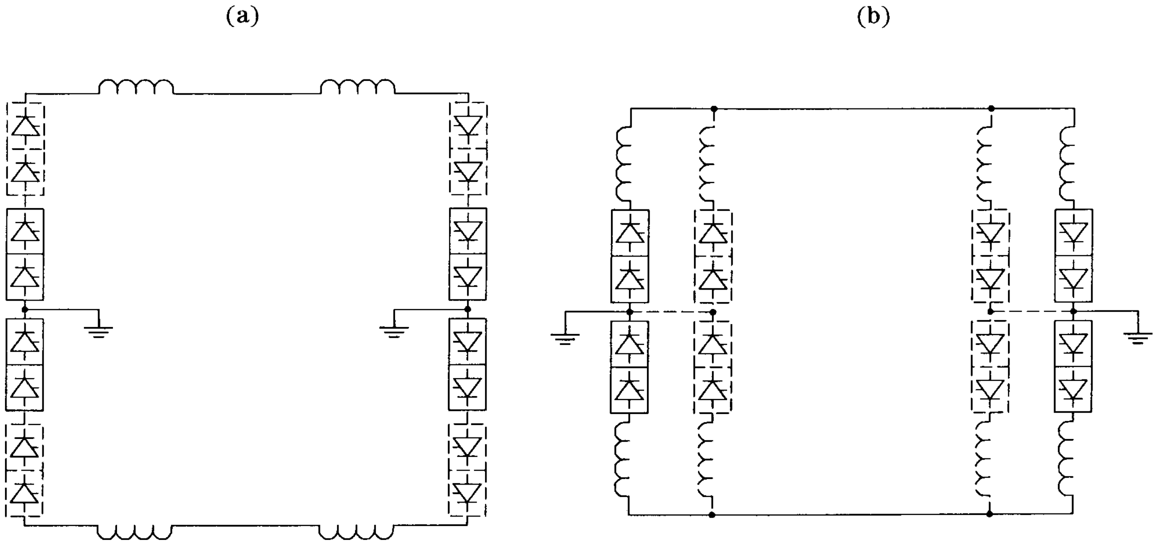
(1) Reactive power source to be installed at the HVDC substation
(2) Reactive power supplied from the ac system

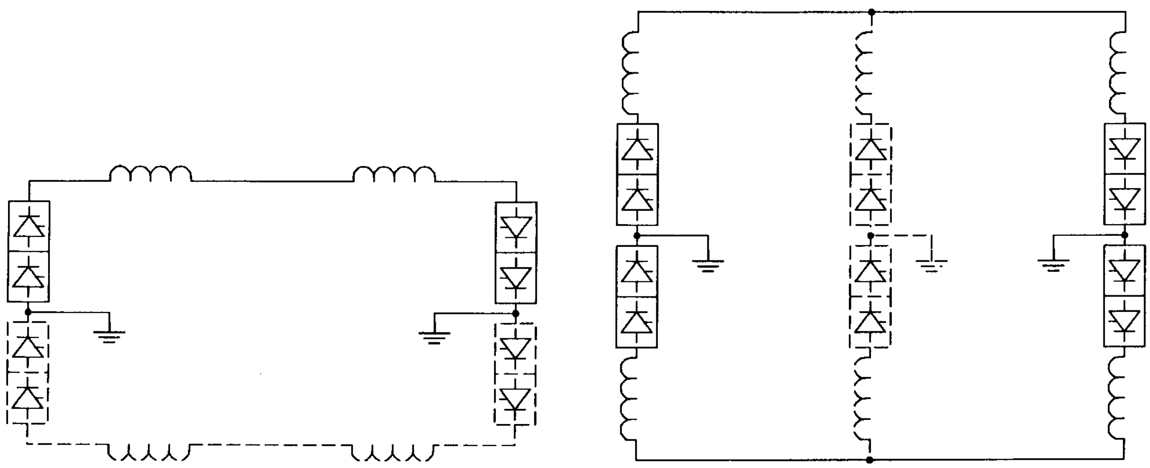
21.2.5 Circuit Configuration and Line Characteristics of the DC Line(s) After Extensions

21.2.6 Change of the Control Mode After Extensions, If Planned. The extension work on control and protection may restrict the operation of existing equipment for a long period. In this connection, therefore, the scope of control and protection equipment to be installed in each stage of extension should be examined.

21.2.7 Audible, Carrier, and Harmonic Interference. The allowable levels of audible noise, carrier interference, and harmonic interference in each stage of extension should also be specified including the levels in the final state after completion of extensions.

Fig 21
Forms of Converter Bridge Extensions
(a) Series Extension (b) Parallel Extension





(c) (d)

Fig 21 *(Continued)*
Forms of Converter Bridge Extensions
(c) Monopolar to Bipolar Extension (d) Multiterminal Bridge Extension

21.2.8 Order of Extension of AC Filters and DC Filters. When the dc line voltage changes as a result of a system extension, the design of filters will be different depending on whether filters for the final dc line voltage are used from the beginning or series extensions of capacitor units are made. Accordingly, it is necessary to clearly describe such changes.

22. Bibliography

[B1] IEC Publication 27-2A, Letter Symbols to Be Used in Electrical Technology. Part 2: Telecommunications and Electronics. First Supplement.

[B2] IEC Publication 50(551), International Electrotechnical Vocabulary.

[B3] IEC Publication 50(11), Static Converters.

[B4] IEC Publication 50(25), Generation, Transmission and Distribution of Electrical Energy.

[B5] IEC Publication 50(37), Automatic Controlling and Regulating Systems.

[B6] IEC Publication 50(131), Electric and Magnetic Circuits.

[B7] IEC Publication 50(351), Automatic Control.

[B8] IEC Publication 50(441), Switchgear and Control Gear.

[B9] IEC Publication 50(902), Radio Interference.

[B10] IEC Publication 76-4, Power Transformers. Part 4. Tappings and Connections.

[B11] IEC Publication 99-1, Lightning Arresters. Part 1. Nonlinear Resistor Type Arresters for AC Systems.

[B12] IEC Publication 117-6, Recommended Graphical Symbols. Part 6. Variability, Examples of Resistors, Elements and Examples of Electronic Tubes, Valves, and Rectifiers.

[B13] IEC Publication 117-7, Part 7. Semiconductor Devices, Capacitors.

[B14] IEC Publication 147, Essential Ratings and Characteristics of Semiconductor Devices and General Principles of Measuring Methods.

[B15] IEC Publication 148, Letter Symbols for Semiconductor Devices and Integrated Microcircuits.

[B16] IEC Publication 214, On-Load Tap Changers.

[B17] IEC Publication 271, List of Basic Terms, Definitions and Related Mathematics for Reliability.

[B18] IEC Publication 272, Preliminary Reliability Considerations.

[B19] IEC Publication 354, Loading Guide for Oil-Immersed Transformers.

[B20] IEC Publication 542, Application Guide for On-Load Tap Changers.

[B21] IEC Publication 551, Measurement of Transformer and Reactor Sound Levels.

[B22] IEC Publication 605-1, Equipment Reliability Testing. Part 1. General Requirements.

[B23] IEC Publication 606, Application Guide for Power Transformers.

[B24] IEC Publication 633, Terminology for High-Voltage Direct Current Transmission.

[B25] IEC Publication 651, Sound Level Meters.

[B26] IEC Publication 700, Testing of Semiconductor Valves for High-Voltage DC-Power Transmission.

[B27] IEC Publication 22B(CO)44, Method of Specifying the Performance and Test Requirements of Uninterruptible Power Systems.