

TECHNICAL REPORT



Performance of high-voltage direct current (HVDC) systems with line-commutated converters— Part 1: Steady-state conditions

IEC/TR 60919-1:2010

<https://standards.iteh.ai/catalog/standards/sib/94024683-95b5-481d-b79e-660380e0a54e/iec-tr-60919-1-2010>



THIS PUBLICATION IS COPYRIGHT PROTECTED
Copyright © 2013 IEC, Geneva, Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either IEC or IEC's member National Committee in the country of the requester.
If you have any questions about IEC copyright or have an enquiry about obtaining additional rights to this publication, please contact the address below or your local IEC member National Committee for further information.

IEC Central Office
3, rue de Varembe
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

About the IEC

The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigenda or an amendment might have been published.

Useful links:

IEC publications search - www.iec.ch/searchpub

The advanced search enables you to find IEC publications by a variety of criteria (reference number, text, technical committee,...).

It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished

Stay up to date on all new IEC publications. Just Published details all new publications released. Available on-line and also once a month by email.

Electropedia - www.electropedia.org

The world's leading online dictionary of electronic and electrical terms containing more than 30 000 terms and definitions in English and French, with equivalent terms in additional languages. Also known as the International Electrotechnical Vocabulary (IEV) on-line.

Customer Service Centre - webstore.iec.ch/csc

If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: csc@iec.ch.

[https://standards.iteh.ai/catalog/standards/sist/74987683-95b5-481d-b79e-660380e0a54e/iec-](https://standards.iteh.ai/catalog/standards/sist/74987683-95b5-481d-b79e-660380e0a54e/iec-60919-1-2010)

[60919-1-2010](https://standards.iteh.ai/catalog/standards/sist/74987683-95b5-481d-b79e-660380e0a54e/iec-60919-1-2010)

TECHNICAL REPORT



**Performance of high-voltage direct current (HVDC) systems with line-commutated converters—
Part 1: Steady-state conditions**

<https://standards.iteh.ai/catalog/standards/sist/974924683-95b5-481d-b79e-660380e0a54e/iec-tr-60919-1-2010>

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.200; 29.240.99

ISBN 978-2-8322-0794-9

Warning! Make sure that you obtained this publication from an authorized distributor.

CONTENTS

FOREWORD.....	7
1 Scope.....	9
2 Normative references	10
3 Types of HVDC systems.....	11
3.1 General.....	11
3.2 HVDC back-to-back system.....	11
3.3 Monopolar earth return HVDC system	13
3.4 Monopolar metallic return HVDC system	15
3.5 Bipolar earth return HVDC system.....	16
3.6 Bipolar metallic return HVDC system.....	19
3.7 Two 12-pulse groups per pole	20
3.8 Converter transformer arrangements.....	21
3.9 DC switching considerations.....	25
3.10 Series capacitor compensated HVDC systems	28
4 Environment information.....	32
5 Rated power, current and voltage.....	34
5.1 Rated power.....	34
5.1.1 General	34
5.1.2 Rated power of an HVDC system with transmission line	35
5.1.3 Rated power of an HVDC back-to-back system.....	35
5.1.4 Direction of power flow	35
5.2 Rated current.....	35
5.3 Rated voltage.....	35
6 Overload and equipment capability.....	36
6.1 Overload	36
6.2 Equipment capability.....	36
6.2.1 General.....	36
6.2.2 Converter valve capability	37
6.2.3 Capability of oil-cooled transformers and reactors	37
6.2.4 AC harmonic filter and reactive power compensation equipment capability.....	37
6.2.5 Switchgear and buswork capability	38
7 Minimum power transfer and no-load stand-by state.....	38
7.1 General.....	38
7.2 Minimum current.....	38
7.3 Reduced direct voltage operation	38
7.4 No-load stand-by state	39
7.4.1 General	39
7.4.2 Converter transformers – No-load stand-by	39
7.4.3 Converter valves – No-load stand-by.....	39
7.4.4 AC filters and reactive compensation – No-load stand-by	39
7.4.5 DC reactors and d.c. filters – No-load stand-by.....	39
7.4.6 Auxiliary power system – No-load stand-by.....	39
7.4.7 Control and protection – No-load stand-by.....	39

8	AC system.....	39
8.1	General.....	39
8.2	AC voltage.....	40
8.2.1	Rated a.c. voltage.....	40
8.2.2	Steady-state voltage range.....	40
8.2.3	Negative sequence voltage.....	41
8.3	Frequency.....	41
8.3.1	Rated frequency.....	41
8.3.2	Steady-state frequency range.....	41
8.3.3	Short-term frequency variation.....	41
8.3.4	Frequency variation during emergency.....	41
8.4	System impedance at fundamental frequency.....	41
8.5	System impedance at harmonic frequencies.....	41
8.6	Positive and zero-sequence surge impedance.....	42
8.7	Other sources of harmonics.....	42
8.8	Subsynchronous torsional interaction (SSTI).....	42
9	Reactive power.....	42
9.1	General.....	42
9.2	Conventional HVDC systems.....	42
9.3	Series capacitor compensated HVDC schemes.....	44
9.4	Converter reactive power consumption.....	44
9.5	Reactive power balance with the a.c. system.....	44
9.6	Reactive power supply.....	45
9.7	Maximum size of switchable VAR banks.....	45
10	HVDC transmission line, earth electrode line and earth electrode.....	45
10.1	General.....	45
10.2	Overhead line(s).....	45
10.2.1	General.....	45
10.2.2	Electrical parameters.....	46
10.3	Cable line(s).....	46
10.3.1	General.....	46
10.3.2	Electrical parameters.....	46
10.4	Earth electrode line.....	47
10.5	Earth electrode.....	47
11	Reliability.....	47
11.1	General.....	47
11.2	Outage.....	47
11.2.1	General.....	47
11.2.2	Scheduled outage.....	47
11.2.3	Forced outage.....	48
11.3	Capacity.....	48
11.3.1	General.....	48
11.3.2	Maximum continuous capacity P_m	48
11.3.3	Outage capacity P_o	48
11.3.4	Outage derating factor (ODF).....	48
11.4	Outage duration terms.....	48
11.4.1	Actual outage duration (AOD).....	48
11.4.2	Equivalent outage duration (EOD).....	48

11.4.3	Period hours (PH)	49
11.4.4	Actual outage hours (AOH)	49
11.4.5	Equivalent outage hours (EOH)	49
11.5	Energy unavailability (EU)	49
11.5.1	General	49
11.5.2	Forced energy unavailability (FEU)	50
11.5.3	Scheduled energy unavailability (SEU)	50
11.6	Energy availability (EA)	50
11.7	Maximum permitted number of forced outages	50
11.8	Statistical probability of outages	50
11.8.1	Component faults	50
11.8.2	External faults	50
12	HVDC control	50
12.1	Control objectives	50
12.2	Control structure	51
12.2.1	General	51
12.2.2	Converter unit firing control	51
12.2.3	Pole control	53
12.2.4	HVDC substation control	55
12.2.5	Master control	55
12.3	Control order settings	55
12.4	Current limits	56
12.5	Control circuit redundancy	56
12.6	Measurements	56
13	Telecommunication	57
13.1	Types of telecommunication links	57
13.2	Telephone	57
13.3	Power line carrier (PLC)	57
13.4	Microwave	58
13.5	Radio link	58
13.6	Optical fibre telecommunication	58
13.7	Classification of data to be transmitted	58
13.8	Fast response telecommunication	59
13.9	Reliability	59
14	Auxiliary power supplies	60
14.1	General	60
14.2	Reliability and load classification	60
14.3	AC auxiliary supplies	61
14.4	Batteries and uninterruptible power supplies (UPS)	61
14.5	Emergency supply	62
15	Audible noise	62
15.1	General	62
15.2	Public nuisance	62
15.2.1	General	62
15.2.2	Valves and valve coolers	63
15.2.3	Converter transformers	63
15.2.4	DC reactors	63
15.2.5	AC filter reactors	63

15.3	Noise in working areas	63
16	Harmonic interference – AC.....	64
16.1	AC side harmonic generation.....	64
16.2	Filters.....	64
16.3	Interference disturbance criteria	67
16.4	Levels for interference.....	68
16.5	Filter performance	69
17	Harmonic interference – DC	69
17.1	DC side interference.....	69
17.1.1	Harmonic currents in HVDC transmission line.....	69
17.1.2	Characteristic and non-characteristic harmonics	69
17.1.3	Groups of harmonics	70
17.1.4	Calculation of harmonic currents	70
17.1.5	Calculation of induced voltages	70
17.1.6	Personnel safety.....	70
17.1.7	DC filters	70
17.2	DC filter performance	71
17.2.1	Requirements for voice communication circuits	71
17.2.2	Levels of interference	72
17.2.3	Safety.....	72
17.3	Specification requirements	72
17.3.1	Economic level of filtering.....	72
17.3.2	General criteria.....	73
17.3.3	Factors to be taken into account for calculations	73
17.3.4	Calculation of currents.....	74
18	Power line carrier interference (PLC).....	75
18.1	General.....	75
18.2	Performance specification	75
19	Radio interference	76
19.1	Radio interference (RI) from HVDC systems.....	76
19.1.1	RI sources.....	76
19.1.2	RI characteristics.....	76
19.2	RI performance specification	76
19	Radio frequency interference.....	76
19.1	General.....	78
19.2	RFI from HVDC systems.....	78
19.2.1	RFI sources	78
19.2.2	RFI propagation.....	79
19.2.3	RFI characteristics.....	79
19.3	RFI performance specification	80
19.3.1	RFI risk assessment	80
19.3.2	Specification RFI limit and its verification.....	80
19.3.3	Design aspects	81
20	Power losses.....	81
20.1	General.....	81
20.2	Main contributing sources.....	82
20.2.1	General	82
20.2.2	AC filters and reactive power compensation	82

20.2.3 Converter bridges	82
20.2.4 Converter transformer	82
20.2.5 DC reactor	82
20.2.6 DC filter	82
20.2.7 Auxiliary equipment	83
20.2.8 Other components	83
21 Provision for extensions to the HVDC systems	83
21.1 General	83
21.2 Specification for extensions	83
Annex A (informative) Factors affecting reliability and availability of converter stations	86
Bibliography	93
Figure 1 – Twelve-pulse converter unit	9
Figure 2 – Examples of back-to-back HVDC systems	12
Figure 3 – Monopolar earth return system	13
Figure 4 – Two 12-pulse units in series	14
Figure 5 – Two 12-pulse units in parallel	15
Figure 6 – Monopolar metallic return system	16
Figure 7 – Bipolar system	18
Figure 8 – Metallic return operation of the unfaulted pole in a bipolar system	19
Figure 9 – Bipolar metallic return HVDC system	20
Figure 10 – Bipolar system with two 12-pulse units in series per pole	23
Figure 11 – Bipolar system with two 12-pulse units in parallel per pole	25
Figure 12 – DC switching of line conductors	26
Figure 13 – DC switching of converter poles	27
Figure 14 – DC switching – Overhead line to cable	28
Figure 15 – DC switching – Two-bipolar converters and lines	29
Figure 16 – DC switching – Intermediate	30
Figure 17 – Capacitor commutated converter configurations	31
Figure 18 – Variations of reactive power Q with active power P of an HVDC converter	43
Figure 19 – Control hierarchy	52
Figure 20 – Converter voltage-current characteristic	54
Figure 21 – Examples of a.c. filter connections for a bipole HVDC system	65
Figure 22 – Circuit diagrams for different filter types	66
Figure 23 – RY COM noise meter results averaged – Typical plot of converter noise levels on the d.c. line corrected and normalized to 3 kHz bandwidth $-0,775 \text{ V}$ 1 mW corresponding to 0,775 V at a pole-to-pole surge impedance of 600 Ω	76
Figure 24 – Extension methods for HVDC systems	85
Figure 25 – Recommended measurement procedure with definition of measuring point	81
Table 1 – Information supplied for HVDC substation	32
Table 2 – Performance parameters for voice communication circuits: Subscribers and trunk circuits	71

INTERNATIONAL ELECTROTECHNICAL COMMISSION

**PERFORMANCE OF HIGH-VOLTAGE DIRECT CURRENT
(HVDC) SYSTEMS WITH LINE-COMMUTATED CONVERTERS –****Part 1: Steady-state conditions**

FOREWORD

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
- 2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
- 3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
- 5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this publication.
- 7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
- 8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
- 9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

This consolidated version of IEC/TR 60919-1 consists of the third edition (2010) [documents 22F/213/DTR and 22F/218/RVC] and its amendment 1 (2013) [documents 22F/277/DTR and 22F/286A/RVC]. It bears the edition number 3.1.

The technical content is therefore identical to the base edition and its amendment and has been prepared for user convenience. A vertical line in the margin shows where the base publication has been modified by amendment 1. Additions and deletions are displayed in red, with deletions being struck through.

The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC 60919-1, which is a technical report, has been prepared by subcommittee 22F: Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment.

This edition includes the following significant technical changes with respect to the previous edition:

- a) the changes have been made to the description of multi 12-pulse groups per pole, especially for a large scale ultra high-voltage direct current (UHVDC) converter arrangement;
- b) the different arrangements of d.c. smoothing reactors have been included;
- c) the figures depicting two 12-pulse groups per pole arrangement have been added.

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

A list of all parts of the IEC 60919 series, published under the general title *Performance of high-voltage direct current (HVDC) systems with line-commutated converters*, can be found on the IEC website

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

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

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

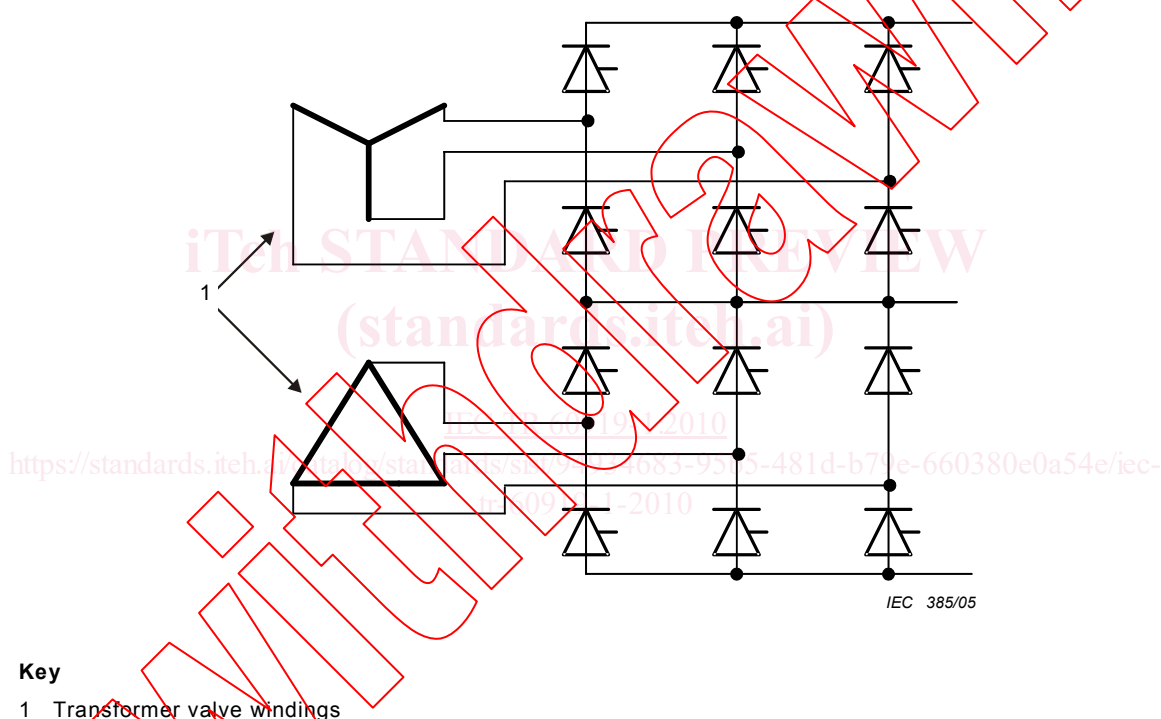
IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

PERFORMANCE OF HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS WITH LINE-COMMUTATED CONVERTERS –

Part 1: Steady-state conditions

1 Scope

This part of the IEC 60919 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 comprised of three-phase bridge (double-way) connections (see Figure 1), but it does not cover multi-terminal HVDC transmission systems. Both terminals are assumed to use thyristor valves as the main semiconductor valves and to have power flow capability in both directions. Diode valves are not considered in this report.



Key

- 1 Transformer valve windings

Figure 1 – Twelve-pulse converter unit

Only line-commutated converters are covered in this report, which includes capacitor commutated converter circuit configurations. General requirements for semiconductor line-commutated converters are given in IEC 60146-1-1, IEC/TR 60146-1-2 and IEC 60146-1-3. Voltage-sourced converters are not considered.

This technical report, which covers steady-state performance, is followed by additional documents on dynamic performance and transient performance. All three aspects should be considered when preparing two-terminal HVDC system specifications.

The difference between system performance specifications and equipment design specifications for individual components of a system should be realized. Equipment specifications and testing requirements are not defined in this report. Also excluded from this report are detailed seismic performance requirements. In addition, because there are many variations between different possible HVDC systems, this report does not consider these in detail; consequently, it should not be used directly as a specification for a particular project, but rather to provide the basis for an appropriate specification tailored to fit actual system requirements.

Frequently, performance specifications are prepared as a single package for the two 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 co-ordination of each part with the overall HVDC system performance objectives and the interface of each with the system should be clearly defined. Typical of such parts, listed in the appropriate order of relative ease for separate treatment and interface definition, are:

- a) d.c. line, electrode line and earth electrode;
- b) telecommunication system;
- c) converter building, foundations and other civil engineering work;
- d) reactive power supply including a.c. shunt capacitor banks, shunt reactors, synchronous and static reactive power (VAR) compensators;
- e) a.c. switchgear;
- f) d.c. switchgear;
- g) auxiliary systems;
- h) a.c. filters;
- i) d.c. filters;
- j) d.c. reactors;
- k) converter transformers;
- l) surge arresters;
- m) series commutation capacitors;
- n) valves and their ancillaries;
- o) control and protection systems.

NOTE The last four items are the most difficult to separate, and, in fact, separation of these four may be inadvisable.

A complete steady-state performance specification for a HVDC system should consider Clauses 3 to 21 of this report.

Terms and definitions for high-voltage direct current (HVDC) transmission used in this report are given in IEC 60633.

Since the equipment items are usually separately specified and purchased, the HVDC transmission line, earth electrode line and earth electrode (see Clause 10) are included only because of their influence on the HVDC system performance.

For the purpose of this report, an HVDC substation 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 a.c. switching substations in this report, a.c. filters and reactive power sources are included, although they may be connected to an a.c. bus separate from the HVDC substation, as discussed in Clause 16.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60146-1-1, *Semiconductor converters – General requirements and line commutated converters – Part 1-1: Specifications of basic requirements*

IEC/TR 60146-1-2, *Semiconductor convertors – General requirements and line commutated convertors – Part 1-2: Application guide*

IEC 60146-1-3, *Semiconductor convertors – General requirements and line commutated convertors – Part 1-3: Transformers and reactors*

IEC 60633, *Terminology for high-voltage direct current (HVDC) transmission*

3 Types of HVDC systems

3.1 General

This part of the specification should include the following basic data:

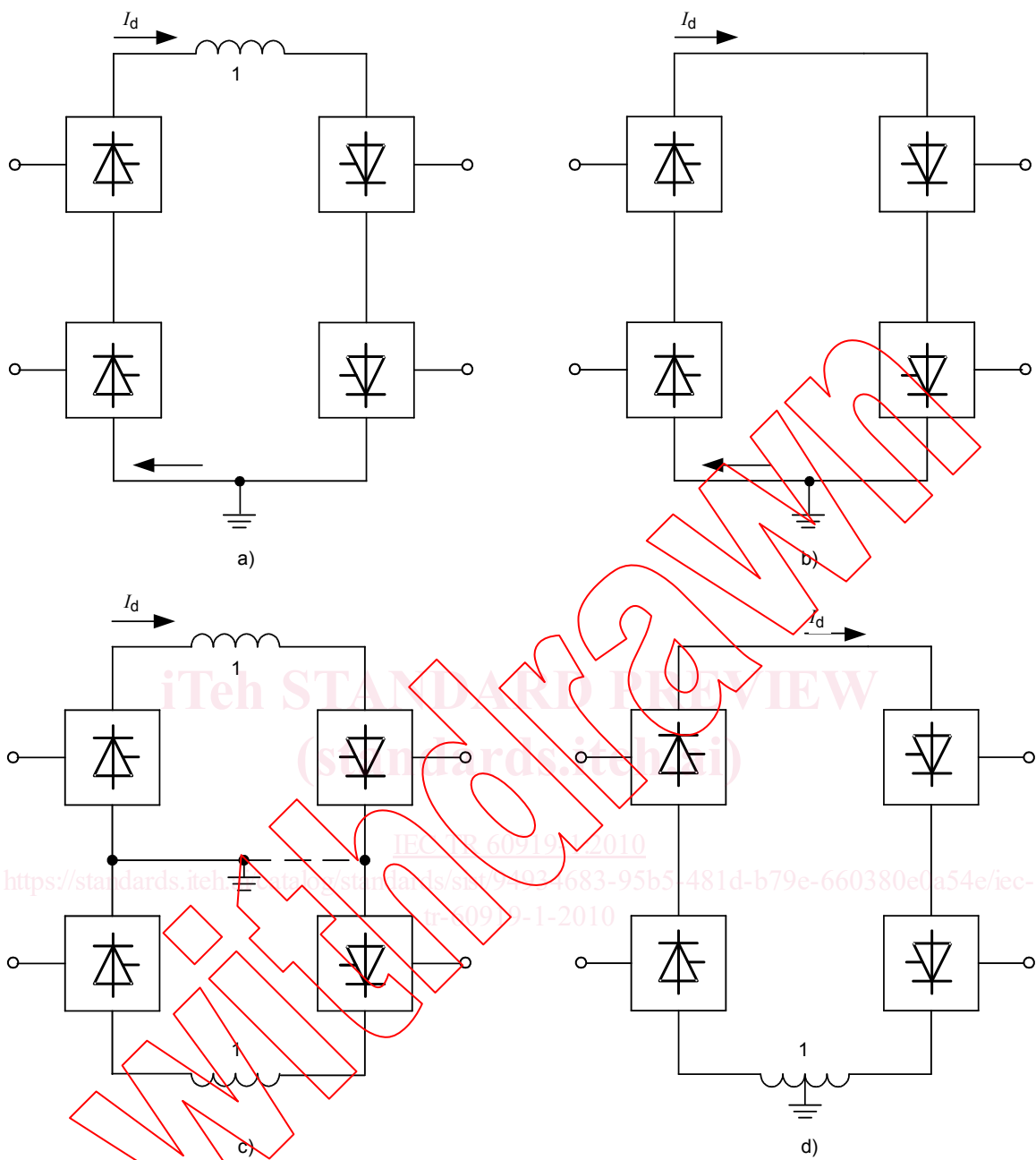
- a) general information on the location of the HVDC substations and the purpose of the project;
- b) type of system needed, including a simple one-line diagram;
- c) number of 12-pulse converter units;
- d) pertinent information derived from the discussion in this section.

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

In terms of the type of system, the relatively new development of “capacitor-commutated converter (CCC)” and “controlled series capacitor converter (CSCC)” technology may be suitable alternatives to a conventional HVDC scheme. These are described in 3.10.

3.2 HVDC back-to-back system

In this arrangement there is no d.c. 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 or separately as outdoor valves. Similarly, many other items for the two converters, such as the control system, cooling equipment, auxiliary system, etc., 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 Figure 2. The performance and economics of these configurations differ and must be evaluated. D.C. filters are not needed.



IEC 386/05

Key

1 DC reactor

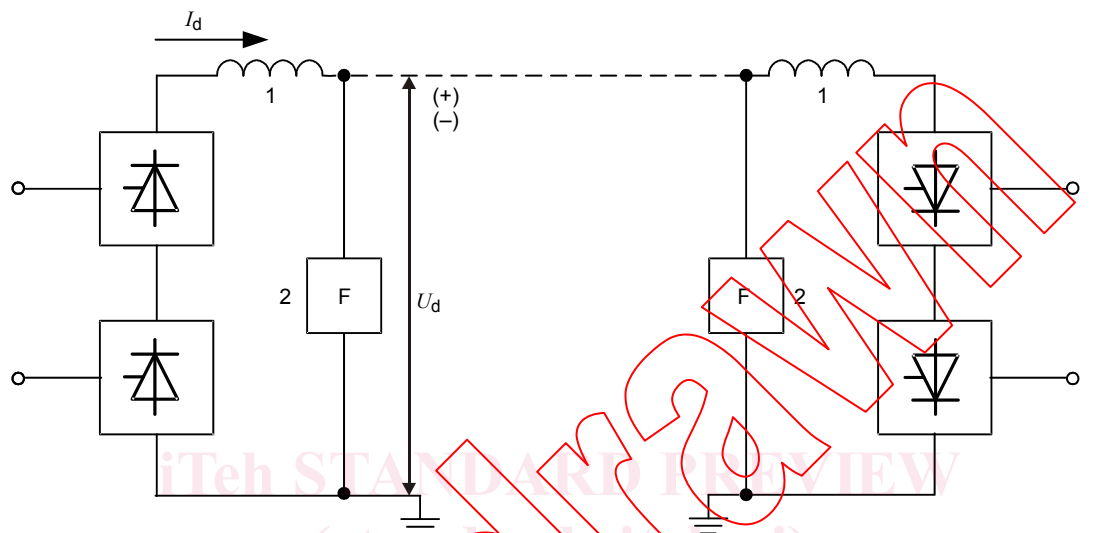
Figure 2 – Examples of back-to-back HVDC systems

The voltage and current ratings for a given power rating should be optimized to achieve the lowest system cost, including the evaluated cost of losses. 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, to provide for a future extension of for some other reason. Economics dictate that each converter will usually be a 12-pulse converter unit, however it is not mandatory. Where operating criteria require that the 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 systems. For this, some of the equipment of the back-to-back systems can, for economic reasons, be located in the same area or even physically integrated, but events which could cause a failure of equipment required by all

back-to-back systems need to be carefully considered and preventive measures taken where appropriate.

3.3 Monopolar earth return HVDC system

Cost considerations often lead to the adoption of a monopolar earth return system (Figure 3), particularly for cable transmission which may be expensive.



Key

- 1 DC reactor
- 2 DC filters

Figure 3 – Monopolar earth return system

The monopolar earth return configuration might also be the first stage in the development of a bipolar scheme. Monopolar arrangements may include one or more 12-pulse units in series or in parallel at the ends of the HVDC transmission (Figures 4 and 5). More than one 12-pulse unit might be used for the following purposes:

- a) to ensure partial transmission capacity during converter unit outages;
- b) to complete the project in stages;
- c) because of the physical limitations of transformer transport.

This arrangement requires one or more d.c. reactors at each end of the HVDC overhead line or cable; these are usually located on the high-voltage side. However, the d.c. reactors may be divided into two parts and located on the high-voltage side and the earth side respectively if the resulting performance is acceptable, especially for a large scale ultra high voltage direct current (UHVDC) converter arrangement.

If the line is overhead, d.c. filters are likely to be needed at each end (see Clause 17). It also requires an earth electrode line and a continuously operable earth electrode at the two ends of the transmission which involves consideration of issues such as corrosion, magnetic field effects, etc.