BS EN 60071-5:2015

BSI Standards Publication

Insulation co-ordination

Part 5: Procedures for high-voltage direct current (HVDC) converter stations

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National foreword

This British Standard is the UK implementation of EN 60071-5:2015. It is identical to IEC 60071-5:2014.

The UK participation in its preparation was entrusted to Technical Committee GEL/28, Electrical Insulation Co-ordination.

A list of organizations represented on this committee can be obtained on request to its secretary.

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English Version

Insulation co-ordination - Part 5: Procedures for high-voltage direct current (HVDC) converter stations (IEC 60071-5:2014)

Coordination de l'isolement -
Partie 5: Procédures pour les stations de conversion à courant continu haute tension (CCHT)
(IEC 60071-5:2014)

Isolationskoordination -
Teil 5: Verfahren für Hochspannungs-Gleichstrom-Stromrichterstationen (HGÜ-Stromrichterstationen)
(IEC 60071-5:2014)

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Foreword

The text of document 28/218/FDIS, future edition 1 of IEC 60071-5, prepared by IEC/TC 28 "Insulation co-ordination" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 60071-5:2015.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2015-08-28
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2017-11-28

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Endorsement notice

The text of the International Standard IEC 60071-5:2014 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

IEC 60099-5:1996	NOTE	Harmonized as EN 60099-5:1996 [1] (modified).
IEC 60505:2011	NOTE	Harmonized as EN 60505:2011 (not modified).
IEC 60721-3-0:1984	NOTE	Harmonized as EN 60721-3-0:1993 (not modified).
IEC/TR 60919-2:2008	NOTE	Harmonized as CLC/TR 60919-2:2010 (not modified).
IEC 60700-1:1998	NOTE	Harmonized as EN 60700-1:1998 (not modified).
IEC 60700-1:1998/A1:2003	NOTE	Harmonized as EN 60700-1:1998/A1:2003 (not modified).
IEC 60700-1:1998/A2:2008	NOTE	Harmonized as EN 60700-1:1998/A2:2008 (not modified).

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[1] Superseded by EN 60099-5:2013 (IEC 60099-5:2013) - DOW = 2016-06-26.

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

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

NOTE 1 When an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cenelec.eu

Publication	Year	Title	EN/HD	Year
IEC 60060-1	-	High-voltage test techniques - Part 1: General definitions and test requirements	EN 60060-1	-
IEC 60071-1	2006	Insulation co-ordination - Part 1: Definitions, principles and rules	EN 60071-1	2006
IEC 60071-2	1996	Insulation co-ordination - Part 2: Application guide	EN 60071-2	1997
IEC 60099-4 (mod)	2004	Surge arresters - Part 4: Metal-oxide surge arresters without gaps for a.c. systems	EN 60099-4	2004
IEC 60633	-	Terminology for high-voltage direct current (HVDC) transmission	EN 60633	-
IEC/TS 60815-1	2008	Selection and dimensioning of high-voltage insulators intended for use in polluted conditions - Part 1: Definitions, information and general principles		
IEC/TS 60815-2	2008	Selection and dimensioning of high-voltage insulators intended for use in polluted conditions - Part 2: Ceramic and glass insulators for a.c. systems	-	-
IEC/TS 60815-3	2008	Selection and dimensioning of high-voltage insulators intended for use in polluted conditions - Part 3: Polymer insulators for a.c. systems	-	-

CONTENTS

INTRODUCTION

The IEC 60071 series consists of the following parts under the general title *Insulation co-ordination:*

Part 1: Definitions, principles and rules

Part 2: Application guide

Part 4: Computational guide to insulation co-ordination and modelling of electrical networks

Part 5: Procedures for high-voltage direct current (HVDC) converter stations

INSULATION CO-ORDINATION –

Part 5: Procedures for high-voltage direct current (HVDC) converter stations

1 General

1.1 Scope

This part of IEC 60071 provides guidance on the procedures for insulation co-ordination of high-voltage direct current (HVDC) converter stations, without prescribing standardized insulation levels.

This standard applies only for HVDC applications in high-voltage a.c. power systems and not for industrial conversion equipment. Principles and guidance given are for insulation co-ordination purposes only. The requirements for human safety are not covered by this standard.

1.2 Additional background

The use of power electronic thyristor valves in a series and/or parallel arrangement, along with the unique control and protection strategies employed in the conversion process, has ramifications requiring particular consideration of overvoltage protection of equipment in converter stations compared with substations in a.c. systems. This standard outlines the procedures for evaluating the overvoltage stresses on the converter station equipment subjected to combined d.c., a.c. power frequency, harmonic and impulse voltages. The criteria for determining the protective levels of series and/or parallel combinations of surge arresters used to ensure optimal protection are also presented.

The basic principles and design objectives of insulation co-ordination of converter stations, in so far as they differ from normal a.c. system practice, are described.

Concerning surge arrester protection, this standard deals only with metal-oxide surge arresters, without gaps, which are used in modern HVDC converter stations. The basic arrester characteristics, requirements for these arresters and the process of evaluating the maximum overvoltages to which they may be exposed in service, are presented. Typical arrester protection schemes and stresses of arresters are presented, along with methods to be applied for determining these stresses.

This standard includes insulation co-ordination of equipment connected between the converter a.c. bus (including the a.c. harmonic filters, the converter transformer, the circuit breakers) and the d.c. line side of the smoothing reactor. The line and cable terminations in so far as they influence the insulation co-ordination of converter station equipment are also covered.

Although the main focus of the standard is on conventional HVDC systems where the commutation voltage bus is at the a.c. filter bus, outlines of insulation co-ordination for the capacitor commutated converter (CCC) as well as the controlled series compensated converter (CSCC) and some other special converter configurations are covered in the annexes.

This standard discusses insulation co-ordination related to line commutated converter (LCC) stations. The insulation coordination of voltage sourced converters (VSC) is not part of this standard.

2 Normative references

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

IEC 60060-1, *High-voltage test techniques – Part 1: General definitions and test requirements*

IEC 60071-1:2006, *Insulation co-ordination – Part 1: Definitions, principles and rules*

IEC 60071-2:1996, *Insulation co-ordination – Part 2: Application guide*

IEC 60099-4:2004, *Surge arresters – Part 4: Metal-oxide surge arresters without gaps for a.c. systems*

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

IEC TS 60815-1:2008, *Selection and dimensioning of high-voltage insulators intended for use in polluted conditions – Part 1: Definitions, information and general principles*

IEC TS 60815-2:2008, *Selection and dimensioning of high-voltage insulators intended for use in polluted conditions – Part 2: Ceramic and glass insulators for a.c. systems*

IEC TS 60815-3:2008, *Selection and dimensioning of high-voltage insulators intended for use in polluted conditions – Part 3: Polymer insulators for a.c. systems*

3 Terms and definitions

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

NOTE Many of the following definitions refer to insulation co-ordination concepts (IEC 60071-1), or to arrester parameters (IEC 60099-4).

3.1
insulation co-ordination
selection of the dielectric strength of equipment in relation to the operating voltages and overvoltages which can appear on the system for which the equipment is intended and taking into account the service environment and the characteristics of the available preventing and protective devices

[SOURCE: IEC 60071-1: 2006, 3.1]

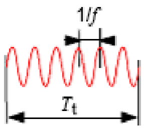
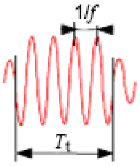
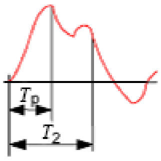
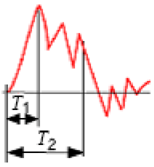
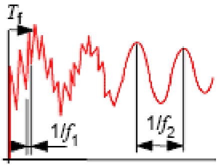
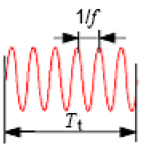
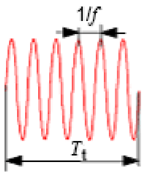
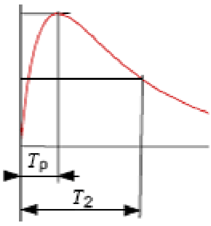
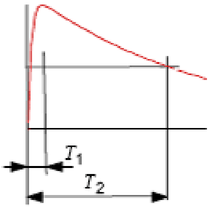
3.2
nominal d.c. voltage
mean value of the direct voltage required to transmit nominal power at nominal current

3.3
highest d.c. voltage
highest value of d.c. voltage for which the equipment is designed to operate continuously, in respect of its insulation as well as other characteristics

3.4
overvoltage
voltage having a value exceeding the corresponding highest steady state voltage of the system

Note 1 to entry: Table 1 presents (as per IEC 60071-1) the classification of these voltages which are defined in 3.4.1 to 3.4.2.3.

Table 1 – Classes and shapes of overvoltages, standard voltage shapes and standard withstand voltage tests

Class	Low frequency		Transient		
	Continuous	Temporary	Slow-front	Fast-front	Very-fast-front
Voltage or over-voltage shapes					
Range of voltage or over-voltage shapes	f = 50 Hz or 60 Hz $T_t \geq 3\,600$s	10 Hz < f < 500 Hz 0,02 s ≤ T_t ≤ 3 600 s	20 µs < T_p ≤ 5 000 µs $T_2 \leq$ 20 ms	0,1 µs < T_1 ≤ 20 µs $T_2 \leq$ 300 µs	T_f ≤ 100 ns 0,3 MHz < f_1 < 100 MHz 30 kHz < f_2 < 300 kHz
Standard voltage shapes	 f = 50 Hz or 60 Hz T_t [a]	 48 Hz ≤ f ≤ 62 Hz T_t = 60 s	 T_p = 250 µs T_2 = 2 500 µs	 T_1 = 1,2 µs T_2 = 50 µs	[a]
Standard withstand voltage test	[a]	Short-duration power frequency test	Switching impulse test	Lightning impulse test	[a]

[a] To be specified by the relevant apparatus committees.

3.4.1
temporary overvoltage

overvoltages of relatively long duration (ranging from 0,02 to 3 600 s as per IEC 60071-1)

Note 1 to entry: The overvoltage may be undamped or weakly damped.

3.4.2
transient overvoltage

short-duration overvoltage of a few millisecond or less, oscillatory or non-oscillatory, usually highly damped

[SOURCE: IEC 60071-1: 2006, 3.17.3]

3.4.2.1
slow-front overvoltage

transient overvoltage, usually unidirectional, with time to peak 20 µs < $T_p \leq$ 5 000 µs, and tail duration $T_2 \leq$ 20 ms

Note 1 to entry: For the purpose of insulation co-ordination, slow-front overvoltages are classified according to their shape, regardless of their origin. Although considerable deviations from the standard shapes occur on actual systems, in this standard it is considered sufficient in most cases to describe such overvoltages by their classification and peak value.

[SOURCE: IEC 60071-1:2006, 3.17.3.1]

3.4.2.2
fast-front overvoltage

overvoltage at a given location on a system, due to a lightning discharge or other cause, the shape of which can be regarded, for insulation co-ordination purposes, as similar to that of the standard impulse (IEC 60060-1) used for lightning impulse tests

Note 1 to entry: Fast-front overvoltage is defined as transient overvoltage, usually unidirectional, with time to peak 0,1 μs $< T_1 \leq 20$ μs, and tail duration $T_2 \leq 300$ μs in IEC 60071-1:2006, 3.17.3.2.

Note 2 to entry: For the purpose of insulation co-ordination, fast-front overvoltages are classified according to their shape, regardless of their origin. Although considerable deviations from the standard shapes occur on actual systems, in this standard it is considered sufficient in most cases to describe such overvoltages by their classification and peak value.

3.4.2.3
very-fast-front overvoltage

transient overvoltage, usually unidirectional, with time to peak $T_f < 0,1$ μs, and with or without superimposed oscillations at frequency 30 kHz $< f <$ 100 MHz

[SOURCE: IEC 60071-1:2006, 3.17.3.3]

3.4.2.4
steep-front overvoltage

transient overvoltage classified as a kind of fast-front overvoltage with time to peak 3 ns $< T_1 <$ 1,2 μs

Note 1 to entry: A steep-front impulse voltage for test purposes is defined in IEC 60700-1.

Note 2 to entry: The front time is decided by means of system studies.

3.4.2.5
combined overvoltage

overvoltage consisting of two voltage components simultaneously applied between each of the two-phase terminals of a phase-to-phase (or longitudinal) insulation and earth

Note 1 to entry: Combined overvoltage can include temporary, slow-front, fast-front or very-fast front overvoltages.

Note 2 to entry: It is classified by the component of higher peak value.

3.5
representative overvoltages
U_{rp}

overvoltages assumed to produce the same dielectric effect on the insulation as overvoltages of a given class occurring in service due to various origins

Note 1 to entry: In this standard it is generally assumed that the representative overvoltages are characterized by their assumed or obtained maximum values.

[SOURCE: IEC 60071-1:2006, 3.19]

3.5.1
representative slow-front overvoltage
RSFO

voltage value between terminals of an equipment having the shape of a standard switching impulse

Note 1 to entry: This note applies to the French language only.

3.5.2
representative fast-front overvoltage
RFFO
voltage value between terminals of an equipment having the shape of a standard lightning impulse

Note 1 to entry: This note applies to the French language only.

3.5.3
representative steep-front overvoltage
RSTO
voltage value with a standard shape having a time to crest less than that of a standard lightning impulse, but not less than that of a very-fast-front overvoltage as defined by IEC 60071-1

Note 1 to entry: A steep-front impulse voltage for test purposes is defined in Figure 1 of IEC 60700-1:2008. The front time is decided by means of system studies.

Note 2 to entry: This note applies to the French language only.

3.6
co-ordination withstand voltage
U_{cw}
for each class of voltage, value of the withstand voltage of the insulation configuration, in actual service conditions, that meets the performance criterion (IEC 60071-1)

3.7
required withstand voltage
U_{rw}
test voltage that the insulation must withstand in a standard withstand voltage test to ensure that the insulation will meet the performance criterion when subjected to a given class of overvoltages in actual service conditions and for the whole service duration. The required withstand voltage has the shape of the co-ordination withstand voltage, and is specified with reference to all the conditions of the standard withstand voltage test selected to verify it

[SOURCE: IEC 60071-1:2006, 3.27]

3.8
withstand voltage
U_{w}
test voltage suitably selected equal to or above the required withstand voltage (U_{rw})

Note 1 to entry: For a.c. equipment, values of withstand voltages U_{w} are standardized as per IEC 60071-1. For HVDC equipment, there are no standardized values for the withstand voltages which are rounded up to convenient practical values.

Note 2 to entry: The standard impulse shapes used for withstand tests on equipment as well as the test procedures are defined in IEC 60060-1 and IEC 60071-1. For some d.c. equipment (e.g. the thyristor valves), the standard impulse shapes may be modified in order to more realistically reflect expected conditions.

3.8.1
switching impulse withstand voltage
SIWV
withstand voltage of insulation with the shape of the standard switching impulse

Note 1 to entry: This note applies to the French language only.

3.8.2
lightning impulse withstand voltage
LIWV
withstand voltage of insulation with the shape of the standard lightning impulse

Note 1 to entry: This note applies to the French language only.

3.8.3
steep-front impulse withstand voltage
STIWV
withstand voltage of insulation with the shape specified in IEC 60071-1

Note 1 to entry: This note applies to the French language only.

3.9
continuous operating voltage of an arrester
$U_{\mathbf{c}}$
permissible r.m.s. value of power frequency voltage that may be applied continuously between the terminals of the arrester

[SOURCE: IEC 60099-4:2004, 3.9]

3.10
continuous operating voltage of an arrester including harmonics
$U_{\mathbf{ch}}$
r.m.s. value of the combination of power frequency voltage and harmonics that may be applied continuously between the terminals of the arrester.

Note 1 to entry: It may be noted that this definition only pertains to coordination of arrester protective levels and not to assessing arrester energy duty.

3.11
crest value of continuous operating voltage
CCOV
highest continuously occurring crest value of the voltage at the equipment on the d.c. side of the converter station excluding commutation overshoots

See: Figure 5.

Note 1 to entry: This note applies to the French language only.

3.12
peak value of continuous operating voltage
PCOV
highest continuously occurring crest value of the voltage at the equipment on the d.c. side of the converter station including commutation overshoots and commutation notches

See: Figure 5.

Note 1 to entry: This note applies to the French language only.

3.13
equivalent continuous operating voltage of an arrester
ECOV
r.m.s. value of the sinusoidal power frequency voltage at a metal-oxide surge arrester stressed by operating voltage of any wave-shape that generates the same power losses in the metal-oxide materials as the actual operating voltage

Note 1 to entry: This note applies to the French language only.

3.14
residual voltage of an arrester
peak value of voltage that appears between the terminals of an arrester during the passage of a discharge current

[SOURCE: IEC 60099-4:2004, 3.36]

3.15
co-ordination currents of an arrester

for a given system under study and for each class of overvoltage, the current through the arrester for which the representative overvoltage is determined

Note 1 to entry: Standard shapes of co-ordination currents for steep-front, lightning and switching current impulses are given in IEC 60099-4.

Note 2 to entry: The co-ordination currents are determined by system studies.

3.16
protective levels of an arrester

for each voltage class, residual voltage that appears between the terminals of an arrester during the passage of a discharge current corresponding to the co-ordination current

Note 1 to entry: For HVDC converter equipment the following specific definitions 3.16.1 to 3.16.3 apply.

3.16.1
switching impulse protective level
SIPL

residual voltage of a surge arrester subjected to a discharge current corresponding to the co-ordination switching impulse current

Note 1 to entry: This note applies to the French language only.

3.16.2
lightning impulse protective level
LIPL

residual voltage of a surge arrester subjected to a discharge current corresponding to the co-ordination lightning impulse current

Note 1 to entry: This note applies to the French language only.

3.16.3
steep-front impulse protective level
STIPL

residual voltage of a surge arrester subjected to a discharge current corresponding to the co-ordination steep-front impulse current

Note 1 to entry: This note applies to the French language only.

3.17
directly protected equipment

equipment connected in parallel to a surge arrester for which the separation distance can be neglected and any representative overvoltage be considered equal to the corresponding protective level

3.18
thyristor valve protective firing

method of protecting the individual thyristors from excessive forward voltage stresses across individual thyristors, by firing them

3.19
creepage distance

shortest distance, or the sum of the shortest distances, along the insulating parts of the insulator between those parts which normally have the operating voltage between them

Note 1 to entry: The surface of cement or of any other non-insulating jointing material is not considered as forming part of the creepage distance.

Note 2 to entry: If a high resistance coating, e.g. semi-conductive glaze, is applied to parts of the insulating part of an insulator, such parts are considered to be effective insulating surfaces and the distance over them is included in the creepage distance.

[SOURCE: IEC 60815-1: 2008, 3.1.5]

3.20
unified specific creepage distance
USCD

creepage distance of an insulator divided by the r.m.s. value of the highest operating voltage across the insulator

Note 1 to entry: This definition differs from that of specific creepage distance where the line-to-line value of the highest voltage for the equipment is used.

Note 2 to entry: For 'U_m' see IEC 60050-604:1987, 604-03-01 [5][1].

Note 3 to entry: It is generally expressed in mm/kV and usually expressed as a minimum.

Note 4 to entry: This note applies to the French language only.

[SOURCE: IEC/TS 60815-1:2008, 3.1.6]

3.21
separation distance

distance between the high voltage terminal of the protected equipment and the connection point of the arrester high voltage conductor

4 Symbols and abbreviations

4.1 General

The list covers only the most frequently used symbols and abbreviations, some of which are illustrated graphically in the single-line diagram of Figure 1 and Table 2. For a more complete list of symbols which has been adopted for HVDC converter stations, and also for insulation co-ordination, refer to the standards listed in the normative references (Clause 2) and to the Bibliography.

4.2 Subscripts

0 (zero)	at no load (IEC 60633)
d	direct current or voltage (IEC 60633)
i	ideal (IEC 60633)
max	maximum (IEC 60633)
n	pertaining to harmonic component of order n (IEC 60633)

4.3 Letter symbols

K_a	altitude correction factor (IEC 60071-1)
K_c	co-ordination factor (IEC 60071-1)
K_s	safety factor (IEC 60071-1)
U_c	continuous operating voltage of an arrester
U_{ch}	continuous operating voltage of an arrester including harmonics
U_{di0}	ideal no-load direct voltage (IEC 60633)

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

U_{di0m}	maximum value of U_{di0} taking into account a.c. voltage measuring tolerances, and transformer tap-changer offset by one step
U_{s}	highest voltage of an a.c. system (IEC 60071-1 and 60071-2)
U_{m}	highest voltage for the equipment
U_{v0}	no-load phase-to-phase voltage on the valve side of converter transformer, r.m.s. value excluding harmonics
U_{rp}	representative overvoltage
U_{cw}	co-ordination withstand voltage
U_{rw}	required withstand voltage
U_{w}	standard withstand voltage
α	delay angle (IEC 60633); “firing angle” also used in this standard
β	advance angle (IEC 60633)
γ	extinction angle (IEC 60633)
μ	overlap angle (IEC 60633)

4.4 Abbreviations

CCC	capacitor commutated converter
CSCC	controlled series compensated converter
CCOV	crest value of continuous operating voltage
GIS	gas-insulated switchgear
PCOV	peak continuous operating voltage
ECOV	equivalent continuous operating voltage
RSFO	representative slow-front overvoltage (the maximum voltage stress value)
RFFO	representative fast-front overvoltage (the maximum voltage stress value)
RSTO	representative steep-front overvoltage (the maximum voltage stress value)
RSIWV	required switching impulse withstand voltage
RLIWV	required lightning impulse withstand voltage
RSTIWV	required steep-front impulse withstand voltage
SIPL	switching impulse protective level
LIPL	lightning impulse protective level
STIPL	steep-front impulse protective level
SIWV	switching impulse withstand voltage
LIWV	lightning impulse withstand voltage
STIWV	steep-front impulse withstand voltage
p.u.	per unit

5 Typical HVDC converter station schemes

Figure 1 shows the single line diagram of typical HVDC converter stations equipped with two 12-pulse converter bridges in series. It may be noted that Figure 1 shows possible arrester locations covered in this standard. Some of these arresters may be redundant and could be excluded depending on the specific design.

Figure 2 shows an example for a single line diagram and arrester arrangement of a back-to-back converter station. Other arrangements with different earthing connections are also common, e.g. earthing at the mid-point between the two six-pulse bridges. The location of the smoothing reactor, if applicable, may change accordingly.

The a.c. and d.c. filter configurations could be more complex than those shown in these figures.

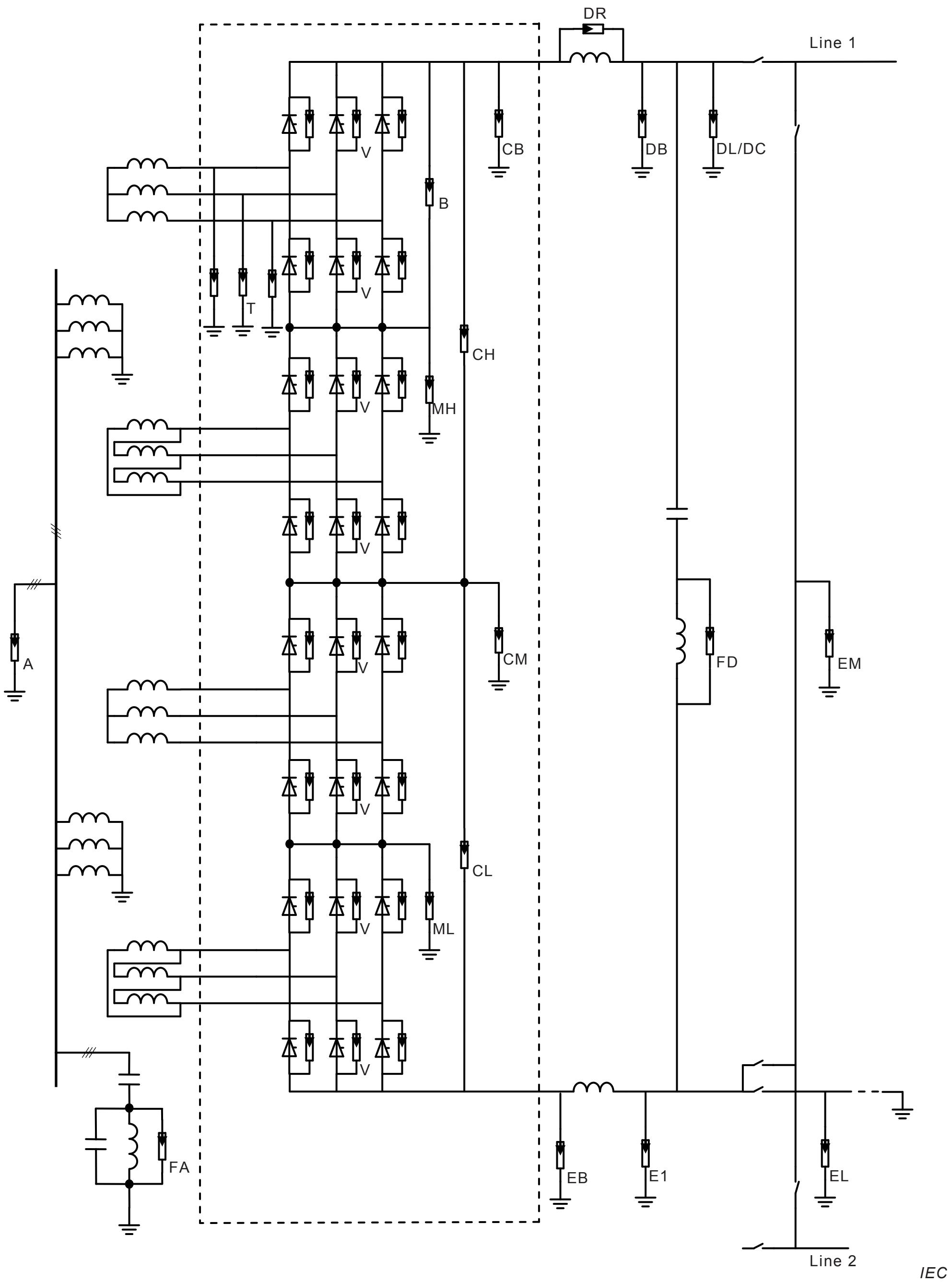
Table 2 presents the graphical symbols used in this standard.

The thyristor valves being voltage sensitive require strict overvoltage protection, which is provided by valve arresters that are connected directly across the valve terminals.

The valve arresters in combination with other arresters typically provide protection to transformer valve windings and in general separate phase-phase and phase-earth arresters are not provided. Transformer valve winding phase-to-earth arresters may be considered at 800 kV and above to lower the insulation levels especially to the top valve group.

Each voltage level and component is protected by either a single arrester or a combination of series or parallel connected arresters.

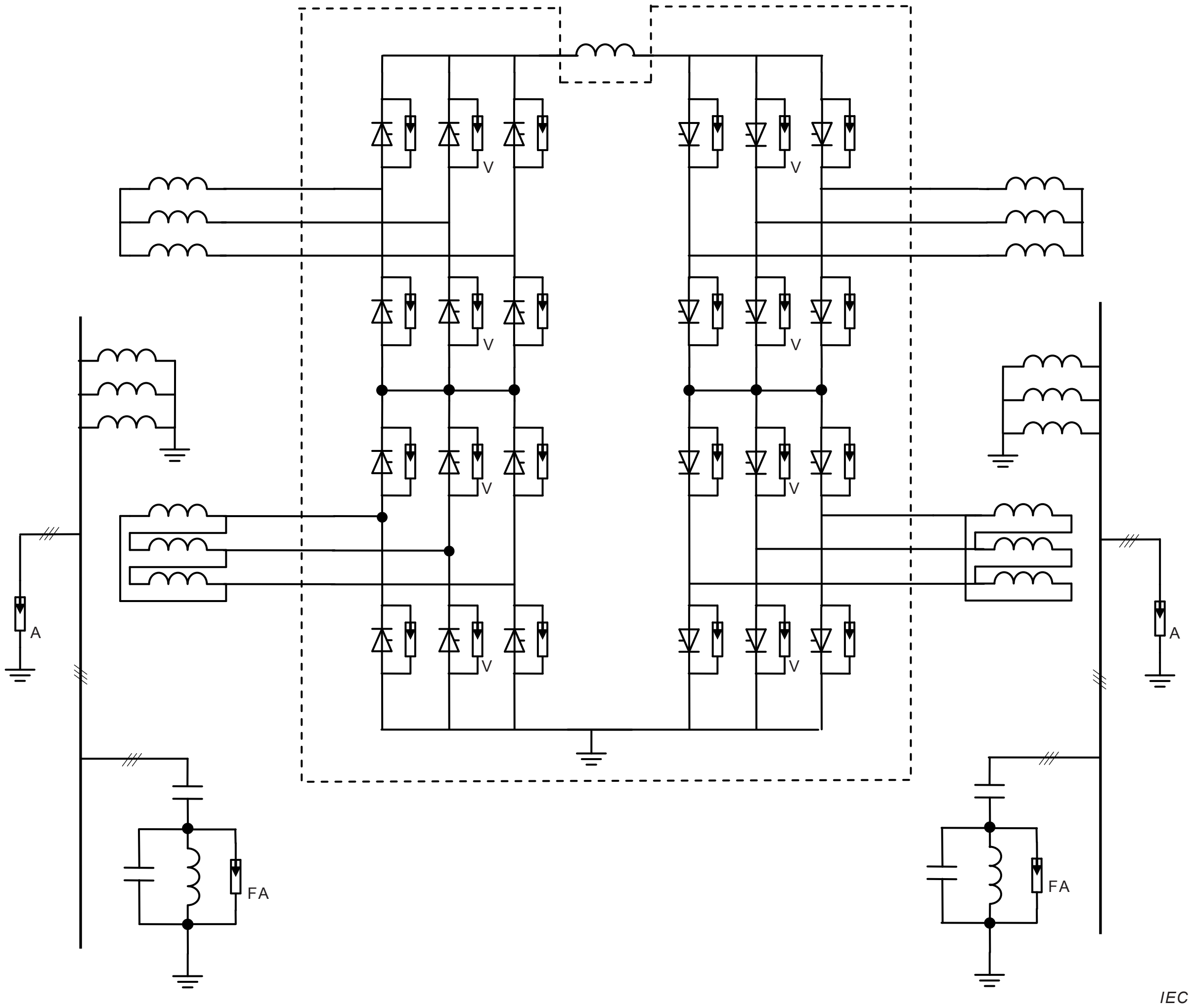
Arrester designations and details on their design and specific roles are presented in Clause 8.



Key

A:	AC bus arrester
FD:	DC filter arrester
E1:	DC neutral bus arrester
EB:	Converter neutral arrester
V:	Valve arrester
T:	Transformer valve winding arrester
DR:	Smoothing reactor arrester
DL:	DC line arrester
CL:	LV converter unit arrester
CH:	HV converter unit arrester
FA:	AC filter arrester
EL:	Electrode line arrester
EM:	Metallic return arrester
B:	Bridge arrester (6-pulse)
CB:	Converter unit d.c. bus arrester
DB:	DC bus arrester
DC:	DC cable arrester
CM:	Arrester between converters
MH:	Mid-point bridge arrester (HV bridge)
ML:	Mid-point bridge arrester (LV bridge)

Figure 1 – Possible arrester locations in a pole with two 12-pulse converters in series



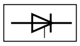
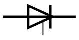
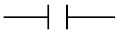
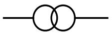
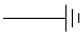
IEC

Key

A:	AC bus arrester	FA:	AC filter arrester
V:	Valve arrester		

Figure 2 – Possible arrester locations for a back-to-back converter station

Table 2 – Symbol description

Symbol	Description
	Valve (commutation group)
	Valve (one arm)
	Arrester
	Reactor
	Capacitor
	Transformer with two windings
	Earth

6 Principles of insulation co-ordination

6.1 General

The primary objectives of insulation co-ordination are:

- to establish the maximum steady state, temporary and transient overvoltage levels to which the various components of a system may be subjected in practice,
- to select the insulation strength and characteristics of equipment, including the protective devices, used in order to ensure a safe, economic and reliable installation in the event of overvoltages.

6.2 Essential differences between a.c. and d.c. systems

The insulation co-ordination applied to an HVDC converter station is basically the same in principle as that of an a.c. substation. However, essential differences exist which warrant particular consideration when dealing with HVDC converter stations. For example, there is a need to consider the following:

a) the requirements of series-connected valve groups involving surge arresters connected across individual valves and between terminals away from earth potential which involves the use of different insulation levels for different parts of the HVDC converter station;

b) the topology of the converter circuits with no direct exposure to the external overvoltage since these circuits are bounded by inductances of converter transformers and smoothing reactors (see also 8.3.5.4);

c) the presence of reactive power sources and harmonic filters on both the a.c. and d.c. sides giving rise to potential overvoltages and higher probability of resonance conditions;

d) applications involving long overhead transmission lines and/or cables without intervening switching stations, with potential for resonance conditions on the d.c. side;

e) the presence of converter transformers with the valve side not directly connected to earth potential, and a d.c. voltage offset;

f) the characteristics of the converter valves resulting in composite voltage wave shapes (which include in some cases a combination of direct voltage, fundamental frequency voltage, harmonic voltages and high frequency components), commutation failures, etc.;

g) control malfunction resulting in possible valve misfires, trigger failure, current extinction;

h) fast control and protection action reducing overvoltages;

i) voltage polarity effects of d.c. stress which, by attracting greater contaminants to the d.c. insulation because of constant polarity, lead to greater creepage and clearance requirements and to worse pollution and flashover performance compared with a.c. insulation under the same environment;

j) interaction between the a.c. and d.c. systems, particularly where the a.c. system is relatively weak;

k) the various operating modes of the converter such as monopolar, bipolar, parallel or multi-terminal;

l) no standard insulation levels exist in the case of d.c. systems.

6.3 Insulation co-ordination procedure

The general method of investigation for an HVDC converter station contains the following:

a) selection of the d.c. circuit configuration, for example location of the d.c. smoothing reactors, location of the d.c. side earthing, converter transformer valve winding connection (star or delta) to the higher d.c. voltage terminal;

b) selection of arrester arrangement according to the selected d.c. circuit configuration;

c) evaluation of the characteristics of the a.c. system at the commutation bus and the d.c. system and their interaction to determine different representative overvoltages and current/energy stresses imposed on surge arresters;

d) optimization of the design by iterative assessment of equipment insulation and arrester requirements.

6.4 Comparison of withstand voltage selection in a.c. and d.c. systems

As described in IEC 60071-1 there are four main steps in the insulation coordination procedure which can be identified as below:

step 1: determination of the representative overvoltages (U_{rp})

step 2: determination of the co-ordination withstand voltages (U_{cw})

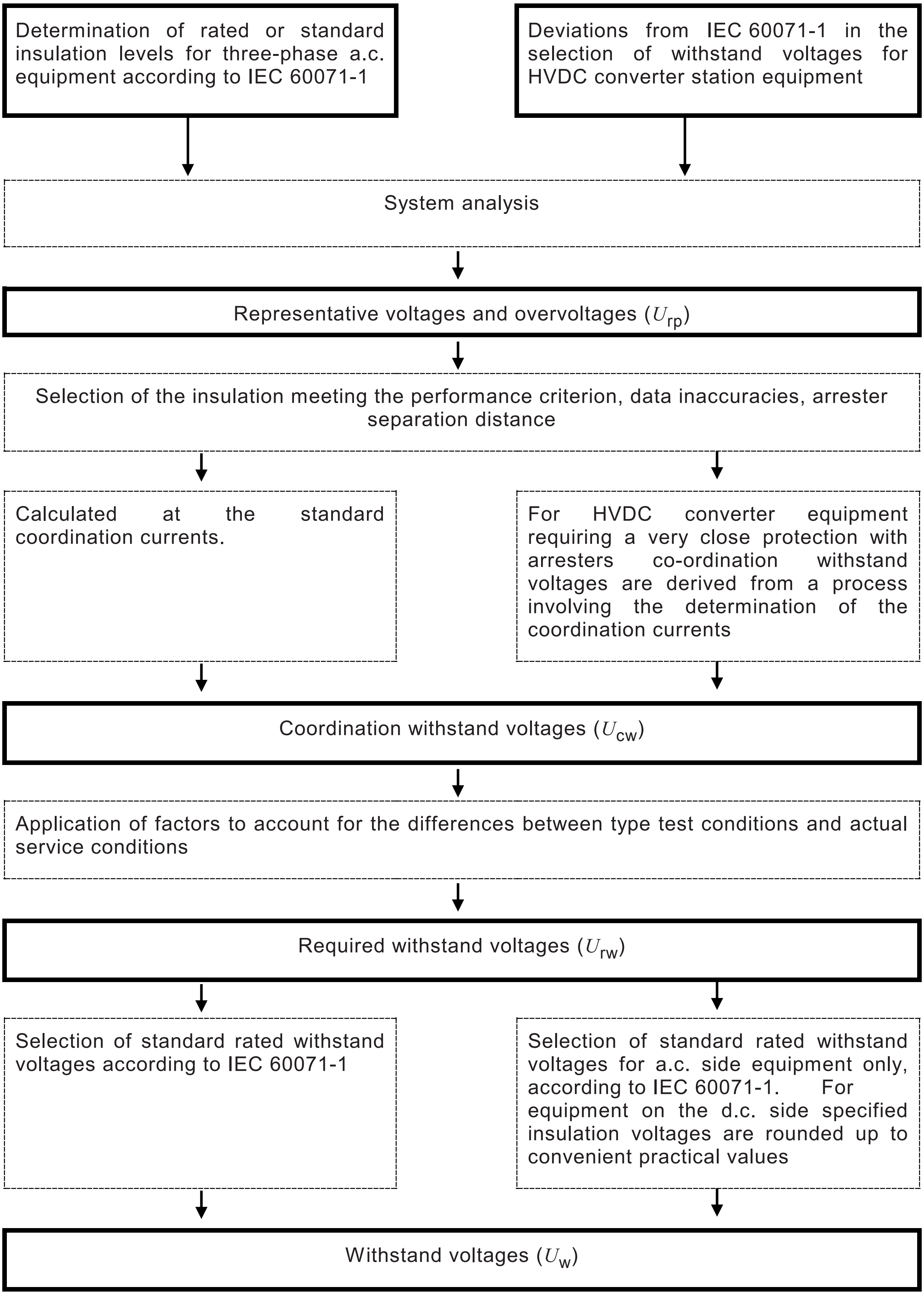
step 3: determination of the required withstand voltages (U_{rw})

step 4: determination of the standard withstand voltages (U_{w})

Table 3 is a flow chart showing the procedure in selecting the withstand voltages (U_{w}) in both a.c. (Figure 1 of IEC 60071-1:2006) and d.c. systems with the differences in the d.c. case being identified.

The individual steps involved in the selection process are detailed in IEC 60071-1 for the a.c. system application and in Clause 9 of this standard for the d.c. system.

Table 3 – Comparison of the selection of withstand voltages for a.c. equipment with that for HVDC converter station equipment



7 Voltages and overvoltages in service

7.1 Continuous operating voltages at various locations in the converter station

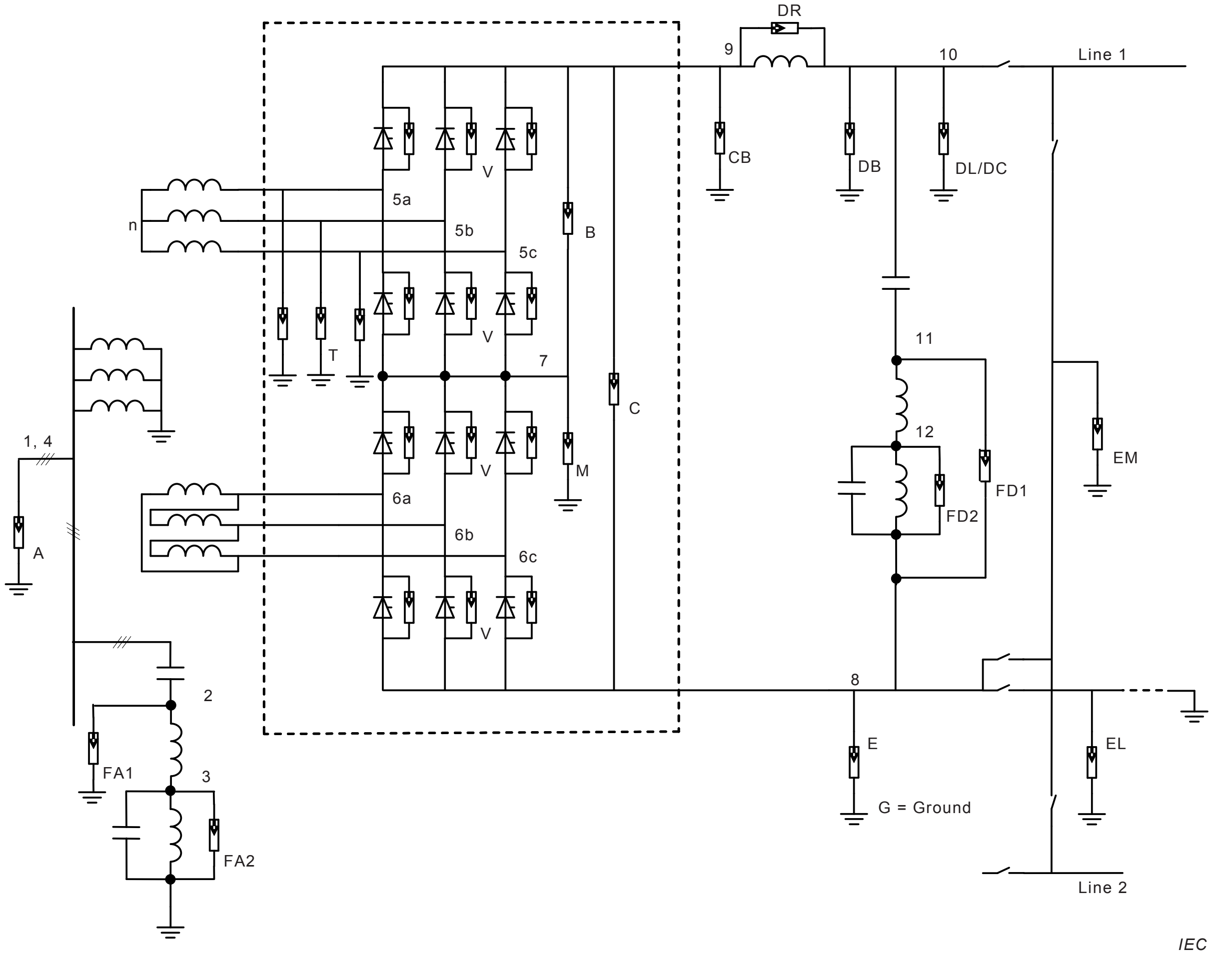
The continuous operating voltages at various locations in an HVDC converter station differ from the a.c. system in that they consist of not simply the fundamental frequency voltages. They could be a combination of direct voltage, fundamental frequency voltage, harmonic voltages, and high frequency transients, depending upon the location.

Figure 3 shows an HVDC converter station with one single 12-pulse converter per pole configuration. In general phase-earth arresters on the valve side of the converter transformer (T) are not provided for HVDC schemes up to 600 kV.

Figure 1 shows an HVDC scheme with two 12-pulse converters per pole configuration, which has been used for the early 600 kV scheme and some of the recent 800 kV schemes.

Figure 4 shows typical waveforms of continuous operating voltages excluding commutation overshoots at various locations in the HVDC converter station either to earth (G) or to another point for the typical configuration of Figure 3. The numbers and alphabetical designations, in Figure 3, identify node numbers and arrester designations respectively. These waveforms have been produced with a simulation tool considering typical d.c. parameters.

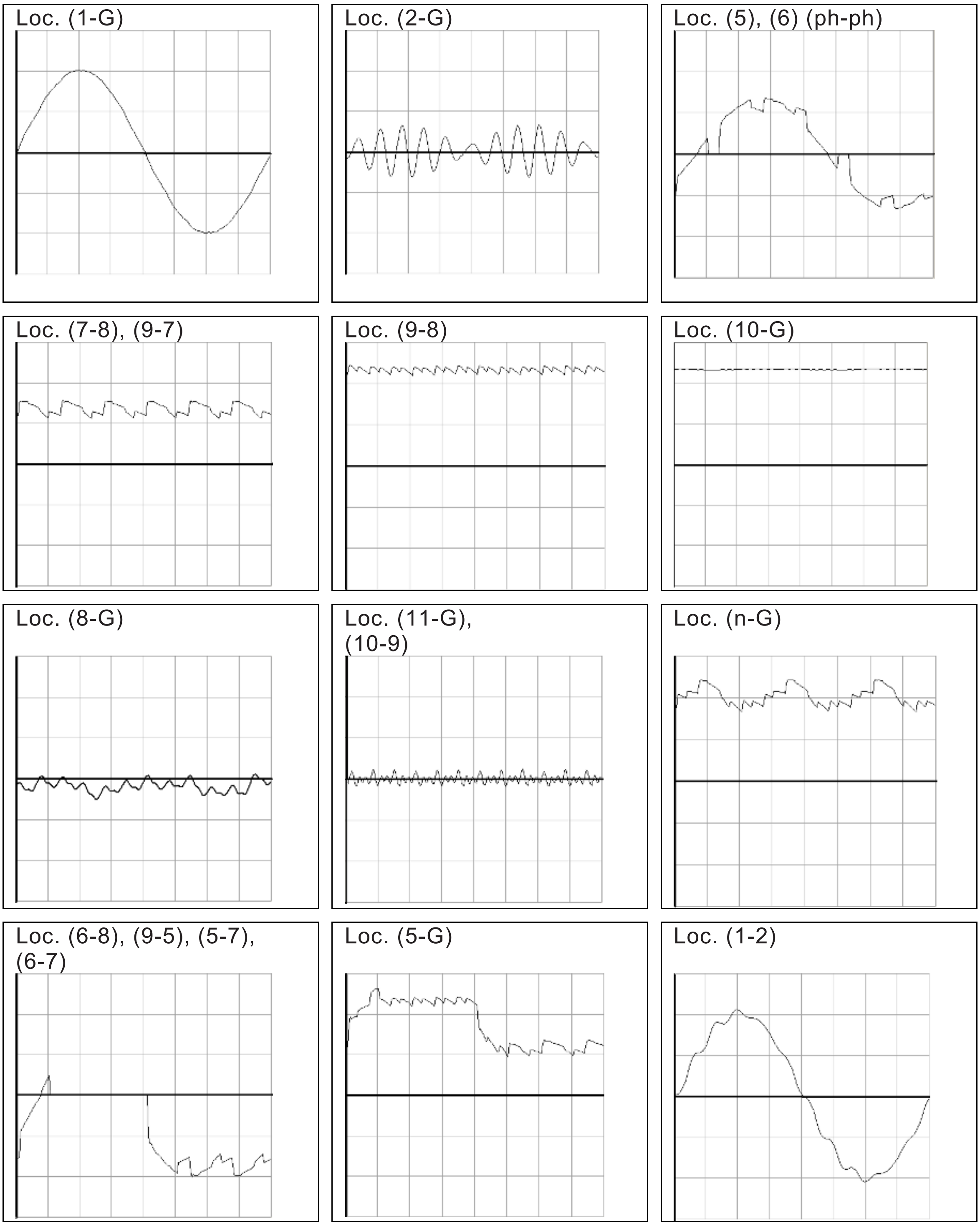
Note that Figures 1, 2 and 3 show possible arrester locations, and some of them may be eliminated because of specific designs.



Key

A: AC bus arrester
M: Mid-point bridge arrester
E: DC neutral bus arrester
V: Valve arrester
T: Transformer valve winding arrester
DR: Smoothing reactor arrester
DL: DC line arrester
FA1, FA2: AC filter arresters
EM: Metallic return arrester
EL: Electrode line arrester
B: Bridge arrester (6-pulse)
C: Converter unit arrester
DB: DC bus arrester
DC: DC cable arrester
FD1, FD2: DC filter arresters

Figure 3 – HVDC converter station with one 12-pulse converter bridge per pole


Loc. (1-G)
Loc. (2-G)
Loc. (5), (6) (ph-ph)
Loc. (7-8), (9-7)
Loc. (9-8)
Loc. (10-G)
Loc. (8-G)
Loc. (11-G), (10-9)
Loc. (n-G)
Loc. (6-8), (9-5), (5-7), (6-7)
Loc. (5-G)
Loc. (1-2)

IEC

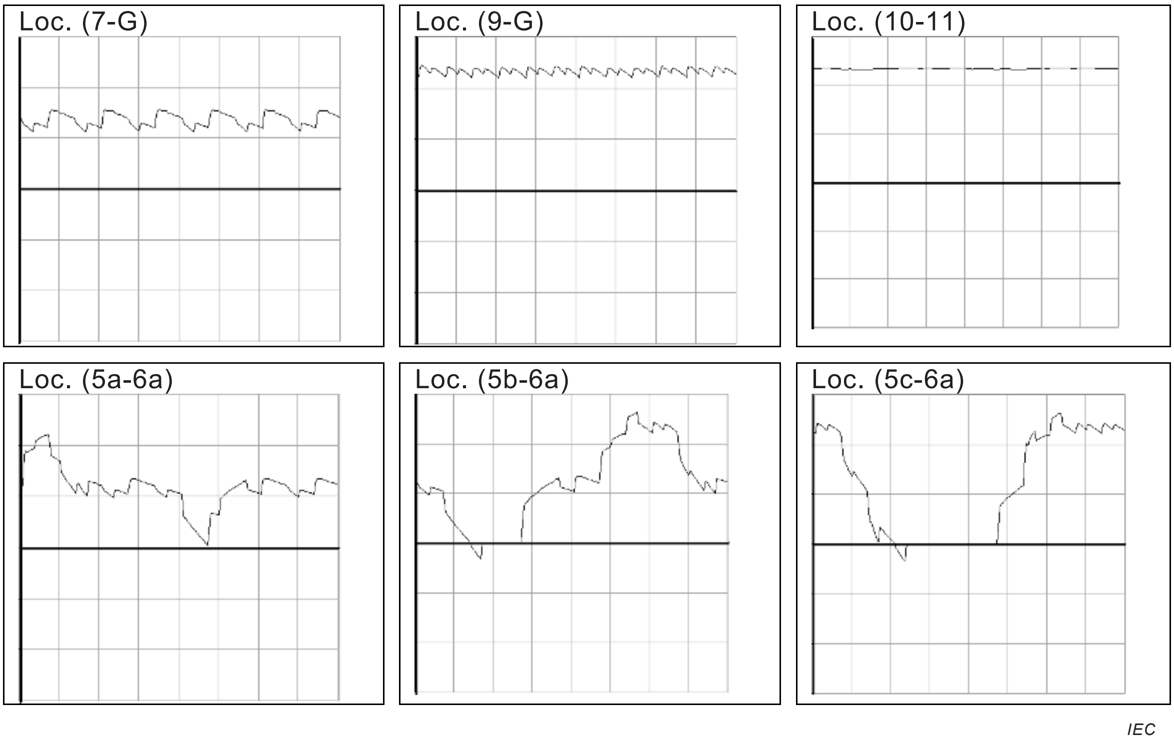


Figure 4 – Continuous operating voltages at various locations (location identification according to Figure 3)

The harmonics generated on the a.c. side are assumed to be filtered by the connected filters and thus the voltage at (1-G) is considered sine wave of fundamental frequency without any harmonics.

Voltage shape at (1-2) is also predominantly a fundamental frequency sine wave but superimposed by harmonics. The content of harmonics strongly depends on the filter configuration, tuning frequencies as well as operating condition of the converters. Typically the content is less than 30 % of the fundamental frequency.

The voltages across the 6-pulse bridges (Loc. 7-8 and 9-7) are the d.c. voltages across the bridges consisting of about 60° arcs of line-line a.c. voltages ($60°-\mu$, duration) and the average of line-line voltages (duration, μ).

The voltage at the 6-pulse bridge to earth (Loc. 7-G) can be identical to Loc. (7-8) if the station is earthed via the station earth as well as during symmetrical operation of a bipole. However, in case of unsymmetrical bipolar operation or monopolar operation an additional d.c. offset will be superimposed.

The voltage across the 12-pulse bridge (Loc. 9-8) comprises of 30° arcs of line-line a.c. voltages with superimposed influence of firing delay and overlap angles.

The voltage across the 12-pulse bridge to earth (Loc. 9-G) can be identical to Loc. (9-8) or include an additional dc offset due to the same reasons as described for Loc. (7-G) (see above).

Voltage shapes of Loc. (5b-6a) and (5c-6a) show the voltage between two different phases of the two six-pulse groups. This wave shape is relevant only in case of three-phase 3-winding transformers.

The voltage at Loc. (10-G) is the smoothed out voltage due to the influence of the smoothing reactor and d.c. filter, if applicable.

The voltages at Loc. (6-8) and (9-5) are the voltages across a valve in rectifier mode indicating the valve conduction period and commutation in its own row and the other row of thyristors in a 6-pulse bridge.

The voltage across the transformer valve winding phase-phase is shown in Loc. (5), (6) (ph-ph). The zero voltage shows the commutation process involving the valves connected to the corresponding two phases, while the notches indicate the commutation involving valves that are connected to one of the phases.

Neutral bus voltage (Loc. 8-G) and voltages across the filters are indicative of typical voltages and they depend on electrode circuit and filter parameters. Loc. (8-G) can also include a d.c. offset especially during monopolar metallic return operation.

The voltage at location (n-G) has a d.c. component equal to 3/4 of pole voltage (Loc. 10-G) plus the ripple of the lower 6-pulse bridge and half of the ripple of the upper 6-pulse bridge.

7.2 Peak continuous operating voltage (PCOV) and crest continuous operating voltage (CCOV)

The switching action of the valves produces high frequency turn-on and turn-off commutation transient voltages which are superimposed on the commutation voltage. The overshoot at turn-off increases the transformer valve-side winding voltage and in particular the off-state (reverse-blocking) voltage across the valves and associated valve arresters. The amplitude of the overshoot is determined by:

a) the inherent characteristics of the thyristors (particularly the recovery charge);
b) the distribution of the recovered charge in a series-connected string of thyristors in a valve;
c) the damping resistors and capacitors at individual thyristor levels;
d) the various capacitances and inductances within the valve and commutation circuit;
e) the firing and overlap angles;
f) the valve commutation voltage at the instant of turn-off.

Special attention shall be paid to the commutation overshoots, including wave shape with respect to power dissipation in the valve arresters and other arresters on the d.c. side.

The continuous operating voltage waveform across the valve (Loc. 6-8 and 9-5) and valve arrester (V), during rectifier operation, is shown in Figure 5.

The CCOV (defined in Clause 3) is proportional to the $U_{\mathrm{di0m},}$ and is given by:

$$\mathrm{CCOV} = \frac{\pi}{3} \times U_{\mathrm{di0m}} = \sqrt{2} \times U_{\mathrm{v0}}$$

Refer to 4.3 for the definition of U_{di0m} and U_{v0}.

Operation with large delay angles α increases the commutation overshoots, and special care shall be taken that these do not overstress the arresters.

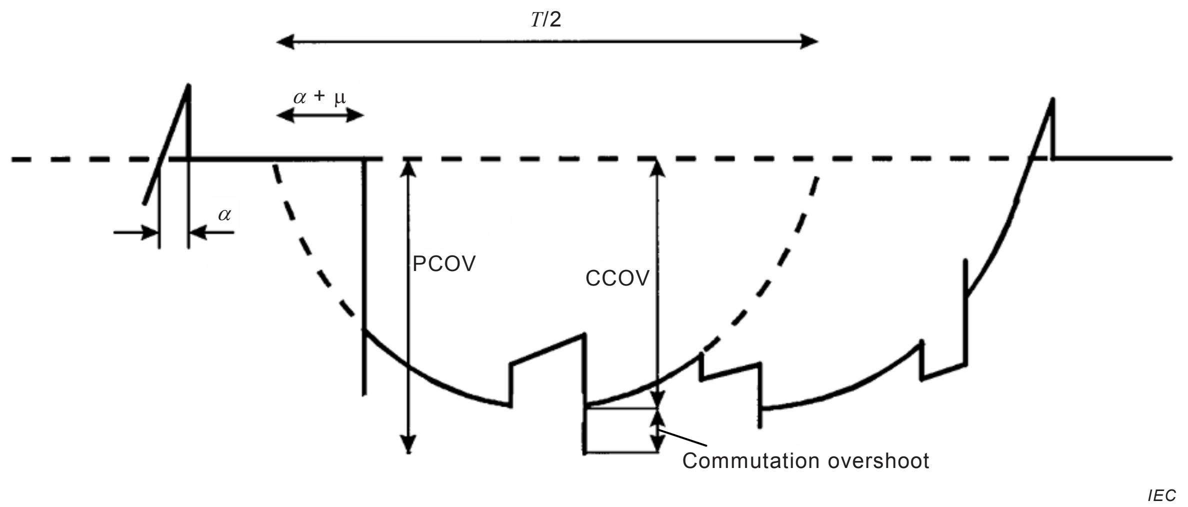


Figure 5 – Operating voltage of a valve arrester (V), rectifier operation

The continuous operating voltage waveforms across the mid-point arrester (M) (Loc. 7-G) and across the converter bus arrester (CB) (Loc. 9-G) are shown in Figures 6 and 7, respectively.

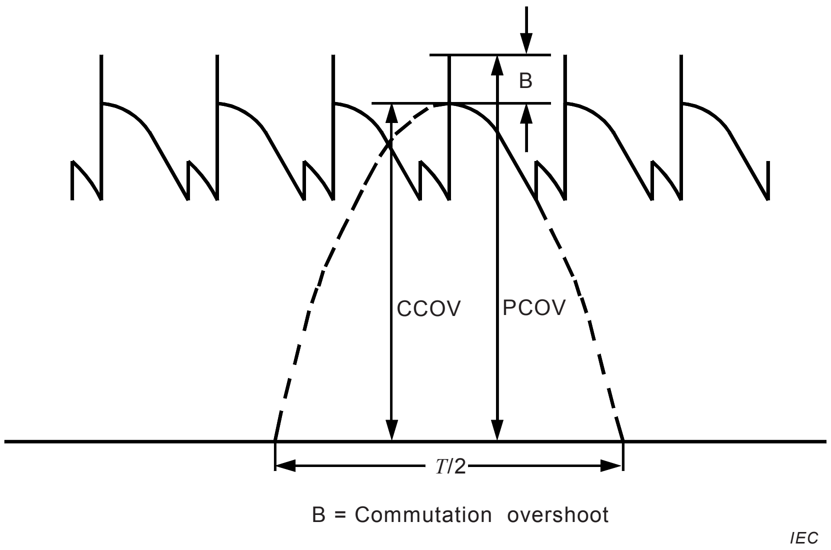


Figure 6 – Operating voltage of a mid-point arrester (M), rectifier operation

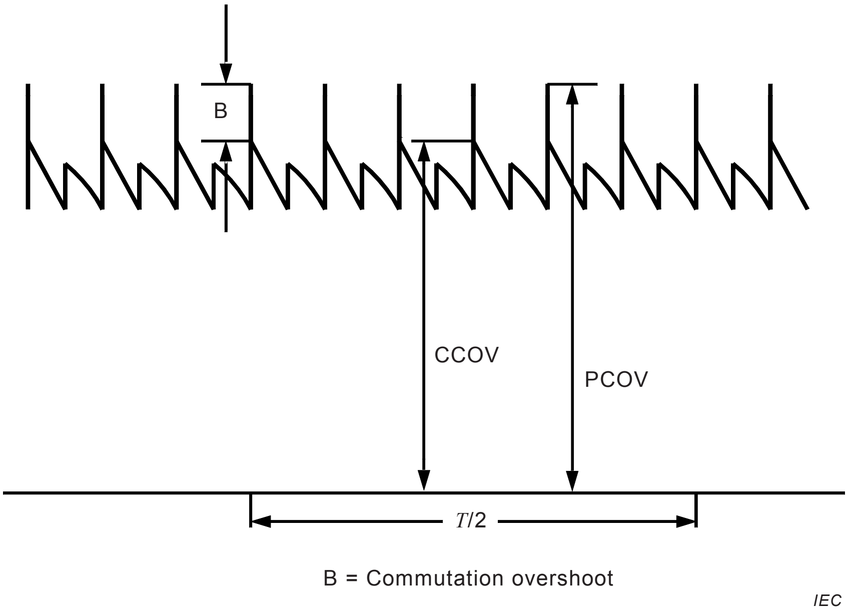


Figure 7 – Operating voltage of a converter bus arrester (CB), rectifier operation

7.3 Sources and types of overvoltages

Overvoltages on the a.c. side may originate from switching, faults, load rejection or lightning. The dynamic characteristics of the a.c. network, its impedance and also its effective damping at dominant transient oscillation frequencies, and the proper modelling of the converter transformers, static and synchronous compensators and the filter components, are important in evaluating the overvoltages. If the lengths of busbars in the a.c. switchyard are significant, they shall be taken into account in the evaluation of lightning and fast-front overvoltages (e.g. distance effects) and in the location of arresters.

Overvoltages on the d.c. side may originate from either the a.c. system or the d.c. line and/or cable, or from in-station flashovers or other fault events.

In assessing the overvoltages, the configuration of the a.c. and d.c. systems shall be taken into account as well as the dynamic performance of the valves and controls, and credible worst case combinations, as discussed in Clauses 8 and 10.

Impacts on arrester requirements are discussed in Clause 8.

While the origin of overvoltages can result from different phenomena (switching, fault and lightning) as described above, the overvoltages are categorized according to their shape and duration as:

- temporary overvoltages (power frequency overvoltage of relatively long duration),
- transient overvoltages (short-duration overvoltage of few milliseconds or less, oscillatory or non-oscillatory, usually highly damped).

Transient overvoltages can be further classified as:

- slow front overvoltages,
- fast-front overvoltages,
- very-fast-front overvoltages,
- steep-front overvoltages.

7.4 Temporary overvoltages

7.4.1 General

A temporary overvoltage is defined as an oscillatory overvoltage of relatively long duration which is undamped or only weakly damped. The temporary overvoltages can originate either from the a.c. side or the d.c. side.

7.4.2 Temporary overvoltages on the a.c. side

These overvoltages are usually generated due to switching operations or faults. The highest temporary overvoltages usually occur in conjunction with sudden loss of load caused by faults either on the a.c. system or the d.c. system with a.c. reactive sources still connected. If the connected reactive elements and the a.c. system result in resonance conditions the temporary overvoltages can be more severe both from the overvoltage magnitude and arrester energy duty point of view.

Together with the highest a.c. operating voltages (U_s), the temporary overvoltages will be decisive for setting the rated voltage of a.c. bus arresters (A).

Temporary overvoltages together with high firing or extinction angles should also be considered for valve arresters (V).

Temporary overvoltages due to a.c. side faults resulting in asymmetrical and distorted a.c. voltages result in second harmonic voltages on the d.c. side which in turn cause third harmonic voltages on the a.c. side stressing the a.c. filter arresters (FA). When the converters are blocked with firing pulses given to by-pass pairs, the arresters across the non-conducting valves can be exposed to phase-phase voltages.

7.4.3 Temporary overvoltages on the d.c. side

An uncontrolled energization of the rectifier with the far end being blocked could result in high overvoltages, especially for a cable transmission system.

Another case that can result in overvoltages is the blocking of an inverter at high current without firing of a by-pass pair. This will result in an application of fundamental frequency voltage at the inverter, and if the d.c. circuit is resonant close to the fundamental frequency, could result in high overvoltages stressing the d.c. bus arrester (CB).

7.5 Slow-front overvoltages

7.5.1 General

Slow-front and temporary overvoltages occurring on the a.c. side are important to the study of arrester applications. Together with the highest a.c. operating voltages (U_s) they determine the overvoltage protection and insulation levels of the a.c. side of the HVDC converter station. They also influence valve insulation co-ordination.

7.5.2 Slow-front overvoltages on the a.c. side

7.5.2.1 General

Slow-front overvoltages on the a.c. bus of an HVDC converter station, can be caused by switching on transformers, reactors, static var compensators, a.c. filters and capacitor banks connected to the converter a.c. bus, and by fault initiation and fault clearing as well as by closing and reclosing of lines. Slow-front overvoltages occur with high amplitude only for the first half cycle of the transient with significantly reducing amplitudes for subsequent cycles. Slow-front overvoltages which originate at locations in the a.c. network remote from the HVDC converter station usually have magnitudes which are relatively low in comparison with those caused by events occurring close to the converter a.c. bus.

During the operating life of the equipment, switching of equipment connected to the converter a.c. bus may occur many times. The overvoltages caused by these routine switching operations are generally less severe than the slow-front overvoltages caused by faults. However, the switching-off of a circuit breaker can, in rare cases, produce a restrike phenomenon and this gives rise to overvoltage.

The selection of a.c. arresters for HVDC converter stations should consider the presence of existing arresters connected in parallel in the a.c. network in order to prevent the existing arresters from being overloaded during slow-front and temporary overvoltages.

7.5.2.2 Overvoltages due to switching operations

Because of the frequency of these operations, it is generally desirable that the surge arresters used to protect equipment do not absorb appreciable energy during these events. Hence, in some cases, the slow-front overvoltages arising from such routine operations are minimized by the use of circuit breakers incorporating closing and/or opening resistors, or by synchronizing the closing and/or opening of the circuit breaker poles, or equipping the breaker with arresters across the poles. The HVDC control system can also be used to effectively damp certain overvoltages such as temporary overvoltages.

Energization of transformers causes inrush current, due to saturation effects, containing harmonics dominated by second order harmonics and other low order harmonics. If one or more of these harmonic currents meet resonant conditions, in a network with low damping, high harmonic voltages are produced in the network leading to overvoltages. In an HVDC converter station, resonant conditions are often more severe because of the presence of a.c. filters and capacitor banks. These capacitances lower the resonance frequency and second or third harmonic resonances may be present.

The temporary overvoltages can last for several seconds, or in rare cases up to a minute.

7.5.2.3 Overvoltages due to faults

When an asymmetric fault occurs in the a.c. network, transient and temporary overvoltages occur on the healthy phases, influenced by the zero sequence network. In solidly earthed systems that are typical for networks connected to HVDC converter stations, the transient overvoltages (phase-to-earth) normally range from 1,4 p.u. to 1,7 p.u. and the temporary overvoltage from 1,2 p.u. to 1,4 p.u.

Symmetric as well as asymmetric faults could result in transformer saturation. The influence of transformer saturation on overvoltages depends on the instant of fault inception as well as fault clearance. It is therefore necessary to vary the fault conditions when this phenomenon is studied. This fault case is discussed further in Clause 8.

The highest temporary overvoltages most likely occur in conjunction with sudden three-phase faults and complete load rejection if the converters block at the same time as a consequence of the fault without simultaneous disconnection of the filters. The filters and capacitor banks together with the a.c. system can result in low resonance frequencies. The temporary overvoltages due to faults can be more severe both from the overvoltage point of view and with regard to possible arrester energy stresses. The presence of filters tuned or damped at frequencies between the second and the fifth harmonic can often be effective in reducing the distortion of the voltage and thereby the stresses on the arresters. AC active filters may also be used for this purpose.

7.5.3 Slow-front overvoltages on the d.c. side

Except for the a.c. side overvoltages transmitted through the converter transformers, the d.c. side insulation co-ordination for slow-front overvoltages and temporary overvoltages is mainly determined by fault generated slow-front overvoltages on the d.c. side.

Events to be considered include d.c. line-to-earth faults, d.c. side switching operations, events resulting in an open earth electrode line, generation of superimposed a.c. voltages due to faults in the converter control (e.g. complete loss of control pulses) misfiring, commutation failures, earth faults and short-circuits within the converter unit. These contingencies are discussed in more detail in Clause 8.

Energization of the d.c. line with the remote inverter terminal open (rectifier at peak d.c. output voltage) should also be considered if measures have not been taken to avoid such an event.

In HVDC converter stations with series connected converter bridge units, events such as a by-pass operation on one converter while the second converter bridge unit is in operation shall be considered, particularly during inverter operation. Special attention shall be paid to insulation co-ordination of parallel connected converter bridge units. Some information on these and other special converter configurations is given in Annex C.

7.6 Fast-front, very-fast-front and steep-front overvoltages

The different sections of HVDC converter stations should be examined in different ways for fast-front and steep-front overvoltages. The sections include:

- a.c. switchyard section from the a.c. line entrance up to the line side terminals of the converter transformers;
- d.c. switchyard section from the line entrance up to the line side terminal of the smoothing reactor;
- converter bridge section between the valve side terminal of the converter transformers and the valve side terminal of the smoothing reactor.

The converter bridge section is separated from the other two sections by series reactances, i.e. at the one end, the inductance of the smoothing reactor and at the other end, the leakage reactance of the converter transformers. Travelling waves such as those caused by lightning strokes on the a.c. side of the transformer or on the d.c. line beyond the smoothing reactor, are attenuated (but may be capacitively transferred as discussed in 8.3.5.4) due to the combination of series reactance and shunt capacitance to earth to a shape similar to slow-front overvoltages. Consequently they should be considered as part of the slow-front overvoltage co-ordination.

The a.c. and d.c. switchyard sections have low impedance compared with overhead lines due to the presence of filters and possibly shunt capacitor banks. The differences from most conventional a.c. switchyards are the presence of a.c. filters, d.c. filters and possibly large shunt capacitor banks, all of which may have an attenuating effect on the incoming overvoltages.

Steep-front overvoltages caused by earth faults in the HVDC converter station, including locations inside the valve hall, are important for insulation co-ordination, especially for the valves. These overvoltages typically have a front time of the order 0,5 μs to 1,0 μs and durations up to 10 μs. The values and waveshapes to be specified should be determined by digital simulation studies; both peak magnitude and maximum rate of change of voltage can be important.

In the a.c. switchyard section, very-fast-front overvoltages with front times of 5 ns to 150 ns may also be initiated by operation of disconnectors or circuit breakers in gas-insulated switchgear (GIS). Some further information on the effect of GIS is given in Clause C.6.

8 Arrester characteristics and stresses

8.1 Arrester characteristics

Since the late 1970s, overvoltage protection of HVDC converter stations has been based exclusively on metal-oxide surge arresters. This is largely due to their superior protection characteristics compared with the gapped silicon carbide arresters (earlier technology) and their reliable performance when connected in series or parallel with other arresters. The actual arrangement of the arresters depends on the configuration of the HVDC converter station and the type of transmission circuit. The basic criteria used however is that each voltage level and the equipment connected to it is adequately protected at a cost commensurate with the desired reliability and equipment withstand capability.

Metal-oxide surge arresters without gaps are used for the protection of equipment in most modern day HVDC converter stations and are increasingly being used to replace other types of arresters on systems already in service. These arresters provide superior overvoltage protection for equipment compared with gapped silicon carbide arresters due to their low dynamic impedance and high energy absorption capability. The ability of the metal-oxide arrester blocks to share arrester discharge energy when connected in parallel if they are selected to have closely matched characteristics allows any desired discharge energy capability to be realized. Metal-oxide blocks may be connected in several parallel paths within one arrester unit and several arrester units may be connected in parallel to achieve the desired energy capability. Also, parallel connection of metal-oxide blocks may be used to reduce the residual voltage of the arrester, if required.

For metal-oxide arresters, the variation of voltage U with current I can be represented by the equation:

$$I = k \times U^{\alpha}$$

where k is a constant and α is a non-linearity coefficient of the element material that depends upon the disk formulation and current range being studied. Within the operating range of the arrester the value of this coefficient is high for zinc oxide, typically in the range 10 to 50, as compared to silicon carbide elements used in gapped arresters which exhibit a coefficient of typically 3.

The protective characteristics of an arrester are defined by the residual arrester voltages for maximum steep-front, lightning and switching current impulses that can occur in service. Typical current waveshapes used to define the arrester protective levels are 8/20 μs for the LIPL and 30/60 μs for the SIPL (IEC 60099-4). The STIPL is usually defined for a current impulse of 1 μs front time. The resulting voltage waveforms across the arrester differ because of the high non-linearity coefficient of the arrester block material. The amplitude of the current for which the protective level is specified, which is referred to as the co-ordination current, is usually selected differently for different types of current waveshapes and locations of the arresters. These co-ordination currents are determined from detailed studies carried out during the final stages of the design (see Clause 10).

The arresters used on the a.c. side are usually specified as for arresters in a normal a.c. system by their rated voltage and maximum continuous operating voltage. The rated voltage is the maximum permissible r.m.s. value of power frequency voltage between the terminals at which the arrester is designed to operate correctly, as established in the operating duty tests. The maximum continuous operating voltage is used as a dimensioning parameter for the specification of operating characteristics.

For the arresters on the d.c. side of an HVDC converter station, the continuous operating voltage is defined differently because the voltage waveshape which continuously appears across the arresters consists, in many cases, of superimposed direct, fundamental and harmonic components and, in some cases, also of commutation overshoots. The arrester voltages are specified in terms of peak continuous operating voltage (PCOV), crest value of continuous operating voltage (CCOV), and equivalent continuous operating voltage (ECOV), as defined in Clause 3. This means that the tests specified for these arresters shall be adjusted for the particular applications, different from standard tests usually applicable for a.c. arresters. The required energy capability of the arresters shall consider the applicable waveshapes as well as the amplitudes, duration and the number of respective discharges.

For filter arresters, the higher losses due to harmonics shall be taken into account.

8.2 Arrester specification

The residual voltage of an arrester is the peak voltage that appears between the terminals of an arrester during passage of a discharge current. The arrester currents for which the maximum residual voltages are specified are called the co-ordination currents as illustrated in Table 7.

The values of co-ordination currents are determined by system studies, usually carried out by the supplier. The process involves taking into account the energy duty in arresters, the number of arrester columns in parallel and the peak current in each arrester which depends on the number of arresters in parallel. The final choice for peak current in the arresters is the co-ordination current for which the corresponding residual voltage leads to the representative overvoltage for directly protected equipment. What is looked for is the “best balance” between overall arrester specifications and design and HVDC converter equipment voltage withstand requirements and design, this process resting on the choice of co-ordination currents.

For arrester testing purposes and protection levels assessment, standard shapes defined in IEC 60099-4 for switching, lightning and steep current impulse are applied to the co-ordination currents.

For the sections of the HVDC converter station exposed to atmospheric overvoltages, the determination of the arrester co-ordination current for lightning stresses shall consider the design of the station shielding (particularly for outdoor valves). The maximum current at shielding failure may be determined, for example, according to [11] or [14].

Arrester discharge currents during contingencies may be of various durations. In specifying the arrester energy capability, consideration shall be given to both the amplitude and duration of the discharges, including repetitive stresses due to the relevant operating sequence. Repetitive current impulses occurring over several cycles of fundamental frequency are considered as one single discharge, having an equivalent energy content and duration as the accumulated values of the actual energy impulses, and taking into account current amplitudes and durations of the combined impulses. From a thermal stability point of view, repetitive current impulses shall be considered over a longer period of time. When determining the equivalent energy, it shall also be taken into account that the energy withstand capability of metal-oxide arresters is reduced with shorter pulse duration, less than 200 μs [4].

In specifying the arrester capability, the calculated arrester energy value from the studies may consider a reasonable safety factor. This safety factor is in the range of 0 % to 20 %, depending on allowances for tolerances in the input data, the model used, and the probability of the decisive fault sequence giving higher stresses than the cases which have been studied.

8.3 Arrester stresses

8.3.1 General

A typical arrester arrangement between the a.c. side of the converter bridges and the d.c. transmission circuit is shown in Figure 3 for a two-terminal bipolar HVDC scheme with one 12-pulse converter per pole. It should be noted however, that some of the arresters may not be used, depending upon the overvoltage withstand capability of the equipment connected at that point, and upon the overvoltage protection afforded by a combination of other arresters at the same point. For example, the d.c. bus can be protected by a series combination of the bridge (B) and mid-point d.c. bus (M) arresters, instead of the converter unit d.c. bus arrester (CB).

Similar protective arrangements may be used for stations with two 12-pulse converters per pole or for back-to-back stations. In the latter case, only the valve arresters (V) are normally needed on the valve side since the operating voltage is much lower than for a line or cable transmission scheme. However, mid-point bus (M) or bridge (B) arresters are sometimes included.

For HVDC converter stations connected directly to d.c. cables, the d.c. bus/line arresters (DB and DL) may be deleted since the pole may not be exposed to fast-front overvoltages.

On the a.c. side of the HVDC converter station, phase-to-earth arresters (A) are normally provided to protect the converter a.c. bus and the a.c. filter bus.

Arresters are also normally connected across both a.c. and d.c. harmonic filter reactors or from the high-voltage terminals of the filter reactors to earth, as shown in Figure 3.

In systems involving a combination of d.c. cables and/or overhead lines, arresters may be needed at the cable terminations to protect them from overvoltages originating from the overhead line.

The basic principles when selecting the arrester arrangement are that:

- overvoltages generated on the a.c. side should, as far as practicable, be limited by arresters on the a.c. side. The main protection is given by the a.c. bus arresters (A);
- overvoltages generated on the d.c. line or earth electrode line should, in a similar way, be limited by d.c. bus, d.c. line/cable arresters (DB and DL/DC), converter bus arresters (CB), and neutral bus arresters (E).

For overvoltages within the HVDC converter station, critical components should be directly protected by arresters connected close to the components, such as valve arresters (V) protecting the thyristor valves and a.c. bus arresters (A) protecting the line side windings of the transformers. Protection of the valve side of the transformers will usually be achieved by arresters connected in series, e.g. a combination of bridge arrester (B), mid-point arrester (M) and a valve arrester (V). However, where the HVDC converter station transformers may be disconnected from the bridges, provision should be made to protect the transformer valve windings.

8.3.2 AC bus arrester (A)

The a.c. side of an HVDC converter station is protected by arresters at the converter transformers and at other locations depending on the station configuration (see for example Figure 3). These arresters are designed according to the criteria for a.c. applications and they limit the overvoltages on both the line side and the valve side of the converter transformers, taking into account the overvoltages transferred from the line side to the valve side of the transformers through inductive and stray capacitance coupling.

The large size of reactive sources in the form of shunt capacitors and filter banks tend to limit the duty seen by the arresters due to switching and lightning overvoltages entering from the a.c. system. However, high energy duty could be imposed due to discharges of the charged shunt reactive banks.

These arresters are designed for the worst case of fault clearing followed by recovery, including transformer saturation overvoltages and overvoltages due to load rejection, as well as possible restrike of circuit breakers during their opening.

Because of possible saturation overvoltages of high amplitude and long duration, this arrester may need to be designed for high energy duty.

Care should be taken to coordinate the A arresters with any already exiting a.c. arresters at or near the commutating bus. Depending on the station layout long separation distances may dictate the use of a.c. bus arresters at several locations.

If these arresters are used to limit temporary overvoltages, especially during load rejection at weak a.c. system conditions under possible low order resonance conditions, they would be subjected to high energy duty requiring multiple columns.

8.3.3 AC filter arrester (FA)

The a.c. filter reactors and resistors may be protected by a.c. filter arresters.

The continuous operating voltage of the a.c. filter arrester consists of a power frequency voltage with superimposed harmonic voltages corresponding to the resonance frequencies of the filter branch. The ratings of these arresters are normally determined by the transient events. Since the harmonic voltages result in relatively high power losses in the arrester, these shall also be considered in the rating of arresters.

The events to be considered with respect to filter arrester duties are slow-front plus temporary overvoltages on the a.c. bus and discharge of the filter capacitors during earth faults on the filter bus. The former determines the required SIPL and the latter the LIPL and the energy discharge requirement. In certain cases, high energy discharge duties may also result from conditions of low order harmonic resonance, or may be due to low order non-characteristic harmonics generated by unbalanced operation during a.c. systems faults.

The arrester energy duties shall be the highest of the following duties:

a) Filter capacitors are charged to the maximum fundamental frequency phase-to-earth voltage.
b) The a.c. bus is charged to the switching surge protective level, prior to fault application.
c) Temporary overvoltages, especially during load rejection at weak a.c. system conditions under possible low order resonance conditions, especially for low-order harmonic filters.

8.3.4 Transformer valve winding arresters (T)

The valve arresters in combination with other arresters typically provide protection to transformer valve windings. In general phase-earth arresters on the valve side of the converter transformer (T) are not provided for HVDC schemes up to 600 kV.

However, at higher voltages (800 kV and above), phase-earth arresters connected to the valve winding of the top 6-pulse transformer may be considered with a view to reduce the phase-earth insulation level of the valve winding of the top 6-pulse transformer.

8.3.5 Valve arrester (V)

8.3.5.1 General

Valve arresters (V) are installed, close to the valves, in parallel with each valve.

The main purpose of the valve arrester is to protect the thyristor valves from excessive overvoltages. This arrester and/or the protective firing of thyristors in the forward direction constitute the overvoltage protection of the valve. Since the cost of the valves and also their power losses are roughly directly proportional to the insulation level across the valves, it is essential to keep this insulation level and therefore the arrester protective level as low as possible.

8.3.5.2 Continuous operating voltage

The valve arrester continuous operating voltage consists of sine wave sections with commutation overshoots and notches as shown in Figure 5. Disregarding the commutation overshoots, the crest value of the continuous operating voltage (CCOV) is proportional to U_{di0m} and, as per 7.2, it is given by:

$$\mathrm{CCOV} = \frac{\pi}{3} \times U_{\mathrm{di0m}} = \sqrt{2} \times U_{\mathrm{v0}}$$

The peak continuous operating voltage (PCOV), which includes the commutation overshoot, shall be considered when the reference voltage of the arrester is determined. The commutation overshoot is dependent on the firing angle α and accordingly special attention shall be given to operation with large firing angles.

For normal firing angles (alpha and gamma) typical values of commutation overshoot range between 15 % to 25 % of the CCOV for a duration of 100 μs to 300 μs.

8.3.5.3 Temporary and slow-front overvoltages

8.3.5.3.1 General

The maximum temporary overvoltages are transferred from the a.c. side, normally, during fault clearances combined with load rejections close to the HVDC converter station. However, it shall be noted that only contingencies without blocking or with partial blocking of the converters need to be considered, since the valve arresters are relieved from stress when the valve is blocked and the by-pass pair is extinguished.

The events producing significant valve arrester currents of switching character are as follows:

a) earth fault between the converter transformer and the valve in the commutating group at highest potential;
b) clearing of an a.c. fault close to the HVDC converter station;
c) current extinction in only one commutating group (if applicable).

8.3.5.3.2 Earth fault between the converter transformer and the valve

A phase-to-earth fault on the valve side of the converter transformer of the bridge at the highest d.c. potential will give significant stresses on the valve arresters in the upper commutation group. The discharges through the arresters are composed in principle of two current peaks. Firstly, the stray and the damping capacitances of the converter are discharged giving steep-front surge stresses on the valve connected to the faulty phase (see 8.3.5.4). Secondly, the d.c. pole and line/cable capacitances are discharged through the d.c. reactor and the transformer leakage reactance giving a slow-front overvoltage type, approximately 1 ms to crest. This latter discharge might expose one of the arresters connected to the other phases with the highest current and energy. The parameters such as the d.c. voltage at the fault instant, d.c. reactor inductance, transformer leakage inductance and line/cable parameters determine which of the three upper arresters will be the most stressed and the magnitude of these stresses. For d.c. schemes having parallel connected converters, this phase-to-earth fault case implies additional stresses since the unfaulted converter will continue to feed current into the earth fault for some time before the protection trips the converters. Depending on current rating, control system dynamics, inductance of the d.c. reactor, and the protection scheme, this phase-to-earth fault case may be dimensioning for the energy and current rating of the arresters across the upper three valves.

In the above phase-to-earth fault case, the calculated stresses are highly dependent on the value of the d.c. bus voltage. It is recommended using the maximum d.c. voltage that can last for a number of seconds. It should be noted that this case may lead to an arrester with very high energy discharge capability. The final decision should consider the probability for the occurrence of voltages higher than the maximum operating voltage in combination with an earth fault.

8.3.5.3.3 Fault clearance

At fault clearing in the a.c. network, excessive overvoltages on the a.c. side arise only if the converters are blocked. If the converters continue to operate after the fault, this will damp out the overvoltages and the total discharge energy will be much smaller. Often the case that gives the maximum arrester energy is when the converter is permanently blocked with by-pass pairs. The blocking might imply that the converter transformer breakers are opened a few cycles later. If this is the case, the arresters are not exposed to any operating voltage after the fault is cleared. A realistic tap changer position for a relevant load flow shall be used when the transferred overvoltages from the line side are calculated. Unfavourable system conditions can result in ferroresonance between the a.c. filter/shunt capacitor and the converter transformer together with the a.c. network impedance. The fault inception and the instant of fault clearance instants should be varied in order to cover the variations in transformer saturation.

8.3.5.3.4 Current extinction

A current extinction in all three valves of one commutating group, while the valves in the commutating groups in series still conduct current, might be decisive for the arrester energy rating. The current is then forced to commutate to one of the arresters connected in parallel with the non-conducting valves. The energy dissipated in this arrester can be substantial if the current is not quickly reduced to zero.

Possible contingencies which may result in current extinction in the valves in only one commutating group include:

a) firing failure in a valve, e.g. due to a failure in the valve control unit;
b) blocking of all the valves in a converter without firing of the by-pass pairs. This contingency may give a converter current close to zero, during some transient conditions such that the current is only extinguished in one of the commutating groups connected in series. This case is often most stringent during inverter operation.

If current extinction is considered inconceivable then this event is excluded. Whether the current extinction is conceivable or not depends very much on the degree of redundancy and type of control/protection system.

8.3.5.4 Fast-front and steep-front overvoltages

The valves and the valve arresters within the converter area are separated from the a.c. switchyard and the d.c. switchyard by large series reactances, i.e. the converter transformers and the smoothing reactors. Travelling waves, caused by lightning strokes on the a.c. side of the transformers or on the d.c. line outside of the smoothing reactor, are attenuated by the combination of series reactances and earth capacitances to a smaller magnitude or a shape similar to slow-front overvoltages. However, in the case of large transformer ratios (e.g. back-to-back stations) the capacitive coupling is more predominant and may need consideration. The valve and valve arresters can in general only be subject to fast-front and steep-fronted overvoltages at back-flashovers and earth faults within the converter area. Direct lightning strokes shall be considered only if the lightning passes the shielding system. Direct strokes and back-flashovers can often be excluded in high-voltage HVDC converter stations with adequate shielding and earthing systems.

The most critical case for steep-front overvoltages is normally an earth fault on the valve side of the converter transformer of the bridge with the highest d.c. potential. The circuit is modelled in detail with its stray capacitances and bus inductances represented for the estimation of this case.

A contingency to be recognized in the design of the thyristor valve is when the valve is stressed by a forward overvoltage and the valve is fired during the overvoltage resulting in the immediate commutation of the arrester current from the arrester to the valve. It should be stressed that the arrester current to be considered for this commutation is not necessarily the specified co-ordination current for the valve arrester, which normally refers to an overvoltage in the reversed direction. For an overvoltage in the forward direction, it is adequate to assume a co-ordination current of switching character corresponding to the protective firing level across the valve. However, the tolerances in the arrester characteristics and redundant thyristors may be considered when the arrester current is estimated.

8.3.5.5 Valve protective firing (PF)

Protective firing may limit overvoltage across the valve by triggering the thyristors. There are two different strategies used to co-ordinate the protective firing level with the protective level of the valve arrester.

In the first strategy, the overvoltage protection between valve terminals in both the reverse and the forward direction is afforded by the valve arrester, and the thyristor firing threshold is set higher than the protective level of the valve arrester. In this strategy, protective firing action is used to protect the individual thyristor levels in the event of loss of firing signals, severe non-linear voltage distribution under fast transient or steep-front voltages within the valve.

In the second strategy, while the valve arrester limits overvoltages in the reverse direction, protective firing threshold in the forward direction for the valve is set lower, typically at 95 % to 98 % of the valve arrester protective level, thus providing the main overvoltage protection in the forward direction. However, the second strategy can be used only when the reverse withstand voltage of the thyristor is higher than the forward withstand voltage of the thyristor. This approach would normally lead to fewer thyristor levels in a valve than with the first strategy, resulting in reduced costs and improved converter efficiency. The protective firing threshold should be set sufficiently high to ensure that activation of protective firing is avoided during the highest temporary overvoltages (taking into account commutation transients and voltage imbalance) or during events which occur frequently (e.g. switching operations). This is to minimize undue interruption of power transmission and facilitate speedy recovery following faults which occur with the converter remaining in operation.

The level of the protective firing shall be co-ordinated with the overvoltages during different operating conditions. The level of protective firing and arrester protective levels should be stated as part of the valve design. Possible adverse effects of the protective firing on the transmission performance need only be considered during external faults when the pole remains in operation and then, in particular, during inverter operation.

Protective firing in rectifier operation during transients in the a.c. network does not give rise to any significant disturbance of the link. On the other hand, if a valve is fired earlier due to a protective firing during inverter operation, the result could be a commutation failure and the recovery time for the transmission after a fault clearing may be increased. In order not to affect the recovery of the link, the protective firing should not be activated during the highest overvoltage that may occur without permanent blocking of the converter acting as inverter.

8.3.6 Bridge arrester (B)

A bridge arrester may be connected between the d.c. terminals of a six-pulse bridge. The bridge arresters may be provided across the lower six-pulse bridge and/or the upper six-pulse bridge. The upper bridge arrester along with the mid-point arrester provides protection from the d.c. bus to earth.

Disregarding the commutation overshoots, the crest value of the continuous operating voltage (CCOV) is the same as for the valve arrester, described in 8.3.5.2. The peak continuous operating voltage (PCOV), which includes the commutation overshoot, shall be considered when the reference voltage of the arrester is determined. The commutation overshoot is dependent on the firing angle α and accordingly special attention shall be given to operation with large firing angles.

The following events may produce arrester currents of switching impulse type:

a) clearing of an a.c. fault close to the HVDC converter station;
b) current extinction in the corresponding six-pulse bridge (if applicable, see 8.3.5.3.4).

The switching overvoltages transferred from the a.c. side normally result in low arrester currents since the bridge arrester is then connected in parallel with a valve arrester.

8.3.7 Converter unit arrester (C)

A converter unit arrester may be connected between the d.c. terminals of a 12-pulse bridge, arrester C in Figure 3.

The maximum operating voltage is composed of the maximum direct voltage from one converter unit plus the 12-pulse ripple.

The theoretical maximum operating voltage for zero values of the firing delay and overlap angles is given by the following expression:

$$\mathrm{CCOV} = 2 \times U_{\mathrm{di0m}} \times \frac{\pi}{3} \times \cos(15°)$$

In practice the CCOV is smaller and can be estimated during the preliminary design stage using the following equation:

$$\mathrm{CCOV} = 2 \times U_{\mathrm{di0m}} \times \frac{\pi}{3} \times \cos^2(15°)$$

Digital simulations can be used to determine the CCOV under possible steady state operating conditions.

The commutation overshoots should be considered in the same way as for the valve arrester when the arrester is specified.

The converter unit arresters are normally not exposed to high discharge currents of switching character. For series connected converters, the formation of a by-pass pair during blocking of a valve group or accidental closing of the by-pass switch will stress this arrester. The arrester may limit overvoltages due to lightning stresses propagating into the valve area, although these stresses are not decisive for the arrester.

8.3.8 Mid-point d.c. bus arrester (M)

A mid-point d.c. bus arrester is sometimes provided to reduce the insulation level of the upper converter transformers of a 12-pulse converter. The mid-point arrester may be connected from the mid-point of a 12-pulse converter to earth (arrester M in Figure 3, MH and ML in Figure 1).

The mid-point arrester CCOV is equal to the valve arrester CCOV plus an offset due to the voltage drop in the return path, for the case of inverter operation. The commutation overshoots should be considered in the same way as for the valve arrester when this arrester is specified.

An event producing significant arrester stresses of switching character, when applicable (see 8.3.5.3 above), is current extinction in the lower six-pulse bridge. Also, operation of by-pass switches will give rise to stresses, in the case of series connected converter units. Lightning stresses may result from shielding failures.

8.3.9 Converter unit d.c. bus arrester (CB)

A converter unit d.c. bus arrester may be connected between the bus and earth (arrester CB in Figure 3), to protect the equipment, connected to the high voltage d.c. pole, on the converter side of the smoothing reactor.

The operating voltage is similar to that for the converter unit arrester with the addition of the voltage drop in the earth electrode line, for the case of inverter operation.

Due to the high protective level, the arrester will normally not be exposed to high discharge currents from slow-front overvoltages. Lightning stresses of moderate amplitude may result from shielding failures.

8.3.10 DC bus and d.c. line/cable arrester (DB and DL/DC)

The d.c. bus arrester DB is used to protect the d.c. switchyard equipment connected to the d.c. pole. Usually, separation distance considerations may dictate installation of arresters at more than one location to provide adequate protection to different parts of the station. If more than one arrester is provided, the arrester on the line (cable) entrance is designated as d.c. line (d.c. cable) arrester DL (DC). When the HVDC transmission comprises overhead line sections as well as cable sections, consideration should be given to the application of surge arrester DC at the cable-overhead line junction to prevent excessive overvoltages on the cable.

For HVDC converter stations where the d.c. cable is connected directly to the converter indoor bus, the d.c. bus/cable arrester (DB and DC) may not be used since the pole may not be exposed to fast-front overvoltages.

The maximum operating voltage is almost a pure d.c. voltage with a magnitude dependent on the converter and tap-changer control and possible measurement errors.

These arresters are mainly subjected to lightning stresses. Critical slow-front overvoltages can often be avoided by suitable selection of the parameters in the main circuit, thus avoiding critical resonances. A pole to earth fault in one pole of a bipolar overhead d.c. line will produce an induced overvoltage on the healthy pole. The magnitude of these overvoltages is dependent on the location of the fault, the line length and the termination impedance of the line. Normally, these types of overvoltages are not critical for the insulation of the terminals.

For faults at the cable junction, high switching surge type overvoltages could occur at the converter terminal on the opposite side of the faulted side, if the length of the cable is short.

In the case of HVDC transmission system with long cables, the energy rating of the cable arresters is decided by the discharge of the cable from the highest voltage it may attain during a contingency. This normally results in comparably low discharge currents, but possibly high energy discharge through the arresters. Contingencies to be considered are valve misfire and complete loss of firing pulses in one of the stations, starting the rectifier against open or blocked inverter.

For a line/cable junction the lightning stresses on the cable arresters DC are not significant due to low surge-impedance of the cable, if the overhead line is effectively shielded and towers are provided with low footing resistance values for at least a few spans from the junction.

8.3.11 Neutral bus arrester (E, EL, EM in Figure 3, EB, E1, EL, EM in Figure 1)

The neutral bus arrester protects the neutral bus and the equipment connected to it. In combination with valve arrester(s) it may also protect the bottom converter transformer(s). The separation distance between the arresters and the point of protection may dictate the installation of arresters at more than one location, to give adequate protection to different parts of the station.

The normal operating voltage of the arrester EB (with a smoothing reactor on the neutral line), would consist of ripple voltages and could be substantial.

For the rest of the neutral bus arresters E1, EL, EM the operating voltages are normally low. At balanced bipolar operation they will be practically zero.

However, during monopolar or metallic return operation the operating voltages on all these arresters EB, E1, EL and EM increase by the d.c. offset.

These arresters are provided to protect equipment from fast-front overvoltages entering the neutral bus and from the overvoltages described below.

These arresters should be designed to discharge large energies during an earth fault on the d.c. bus or d.c. line and an earth fault between the valves and the converter transformer. In the event of loss of return path during monopolar operation it could result in an excessive energy rating, and a sacrificial arrester may be a preferred choice under this event. An earth fault on the d.c. bus may cause the d.c. filter to discharge through the neutral bus arrester, giving a very high but short current peak, depending upon the d.c. filter and d.c. filter arrester configuration. The most essential assumption is the pre-fault voltage of the filter which normally is chosen as the maximum operating d.c. voltage. The fast discharge of the d.c. filter is followed by a slower fault current from the converter. The rate of rise is mainly limited by the d.c. reactor. The fault current will be shared between the earth electrode line and the neutral bus arrester. In the case of metallic return operation, the impedance in parallel with the arrester is the entire d.c. line impedance.

At an earth fault on a phase between the valve and the converter transformer, the a.c. driving voltage will be shared between the converter transformer impedance and the earth electrode line impedance. The decisive case can be found for the terminal which has the longest earth electrode line and, in the case of metallic return operation, in the unearthed terminal. The worst case occurs when the station is operating as rectifier, because of the polarity of the driving voltage.

A metallic return operation usually gives such high requirements on the neutral bus arrester, that it becomes advantageous to select a higher arrester rating in the unearthed station than in the station that is earthed during metallic return operation. This is also applicable for long electrode lines (normally for distances above 50 km).

Neutral bus capacitors have been included in recent schemes, mainly due to harmonic filtering requirements and due to suppression of overvoltages on the neutral bus, although they will influence the neutral bus arrester stresses and shall be included in the study model. The stresses on the neutral bus arrester will also depend on the converter control and protective actions taken during the fault.

When the energy rating results in an excessive design, under unlikely events, a sacrificial arrester may be considered. In particular, this is the preferred design when the replacement of the arrester does not significantly influence the outage time. In bipolar systems sacrificial arresters shall be located so that bipolar outages are avoided.

If a smoothing reactor is provided in the neutral bus special care should be taken in the coordination (reference voltages and energy requirements) of the neutral arresters (EB, E1, EM, EL). If a neutral blocking filter is provided it should be also considered for the arrester coordination.

8.3.12 DC reactor arrester (DR)

The DR arrester provides terminal-to-terminal protection for the smoothing reactor.

The smoothing reactor acts as a buffer between the d.c. line and the converter station for lightning surges entering from the d.c. pole. It is desirable to keep the arrester protective level/smoothing reactor insulation level as high as possible in order not to sacrifice this buffer effect.

The operating voltage of the d.c. reactor arrester consists only of a small 12-pulse ripple voltage from the converter.

The arrester will be subjected to lightning overvoltages of opposite polarity to the converter d.c. bus operating voltage (which may be termed subtractive lightning impulses). The possibility of lightning stresses being coupled through the arrester to the thyristor bridge shall be considered.

In many schemes the d.c. reactor arrester can be dispensed with when the reactor insulation level meets the voltage requirement from the d.c. line arrester combined with the maximum operating voltage of opposite polarity.

8.3.13 DC filter arrester (FD)

The d.c. filter reactors and resistors are protected by the d.c. filter arresters FD.

The normal operating voltage of the d.c. filter reactor arrester is low and usually consists of one or more harmonic voltages corresponding to the resonance frequency of the filter branch in question. Since the harmonic voltages result in relatively high power losses these shall be considered in the rating of arresters.

Arrester duties are mainly determined by filter capacitor discharge transients resulting from earth faults on the d.c. pole, and occasionally due to lightning surges.

8.3.14 Earth electrode station arrester

The equipment at the earth electrode station, for example distribution switches, cables and measuring equipment, requires protection from overvoltages entering via the earth electrode line. An arrester may be installed at the line entrance. The continuous operating voltage is insignificant. The arrester is dimensioned for lightning stresses entering via the overhead line.

8.4 Protection strategy

8.4.1 General

Because of the nature of the HVDC configurations some of the equipment/points are directly protected by a single arrester connected across their terminals while some others are protected by a series combination of more than one arrester.

8.4.2 Insulation directly protected by a single arrester

The maximum overvoltage between points directly protected by their own single arresters (for example valve arrester V across points 5 to 9 in Figure 3) is determined from the arrester characteristics together with the co-ordination current through the arrester. Some of the points that may be protected by a single arrester are listed below:

a) thyristor valve;
b) converter terminals;
c) d.c. mid-point bus;
d) converter transformer valve winding phase-to-earth (especially the upper six-pulse bridge);
e) neutral bus;
f) smoothing reactor;
g) d.c. filter components;
h) line side of d.c. bus;

i) valve side of d.c. bus;

j) a.c. bus;

k) a.c. filter components.

8.4.3 Insulation protected by more than one arrester in series

For insulation not directly protected by a single arrester, the protection can be achieved by a number of arresters connected in series as shown in Tables 4 and 5.

In this case the protective level of the insulation is defined by the sum of the voltages of the individual arresters, during the decisive event. It is to be noted that this may not necessarily be the sum of the protective levels of the individual arresters.

8.4.4 Valve side neutral point of transformers

For slow-front overvoltages and temporary overvoltages, the maximum voltage in the neutral is the same as the phase-to-earth voltage on the corresponding a.c. phase as shown in Tables 4 and 5.

8.4.5 Insulation between phase conductors of the converter transformer

Slow-front overvoltages can occur between the phases on the line side and the valve side of the converter transformers, stressing the air clearance between conductors in the switchyard. Usually, this is not a problem for the lower system voltages, but in the case of high a.c. system voltages and a number of series connected valve bridges, the maximum voltage shall be evaluated and air clearances between conductors in the switchyard designed accordingly.

The inter-winding voltages may stress different points inside the converter transformer depending on its construction (two- or three-winding, single- or three-phase transformer).

When the valves in a valve bridge are conducting, the phase-to-phase insulation is protected by one valve arrester V. When the valves are not conducting the phase-to-phase insulation is protected by the a.c. bus arresters A transferred to the valve side.

8.4.6 Summary of protection strategy

Tables 4 and 5 are a summary of the arrester protections for different points on the d.c. side, based on the examples of Figures 3 and 1 respectively. Such tables should be established in light of the specific design.

The tables assume that the converters are deblocked and that at each 3-pulse level there is at least one conducting valve. In that way, the protective level across each 6-pulse bridge is the voltage across one conducting valve and the voltage across one valve arrester, i.e. the protective level across the 6-pulse bridge will be V.

When the valves are not conducting, there are 2 cases to consider:

- Lightning surges coming from d.c. or a.c. sides are attenuated both in amplitude and slope as they only can penetrate through the d.c. pole reactor stray capacitances or through the converter transformer inter-winding capacitance. They will be distributed by the capacitances in the circuit, and the stresses will be lower than for the case with deblocked converters.
- Switching surges coming from the a.c. side are phase-to-phase voltages. As the valves are blocked there is no connection to earth and therefore the only overvoltage possible is the transferred phase-to-phase voltage, limited by the a.c. bus arresters in the primary side. Switching surges coming from the d.c. side will be distributed by the impedance of the blocked valves, and the stresses will be lower than for the case with deblocked converters.

Table 4 – Arrester protection on the d.c. side: Single 12-pulse converter (Figure 3)

Protected item	Protecting arrester(s)	Comments
Between terminals of a valve	V	
Between terminals of a 6-pulse bridge	(1) V (2) B	
Between terminals of the 12-pulse group	(1) C (2) 2·V	
Between terminals of a d.c. reactor	DR	May be omitted
DC bus line side of a d.c. reactor	DB, DL/DC	
DC bus, valve side of a d.c. reactor	(1) CB (2) C + E (3) B + M (4) 2·V + E	
Mid-point d.c. bus	(1) M (2) V + E	
Neutral bus	E, EL, EM	
HV transformer, phase-to-earth	(1) T (2) V + M (3) 2·V + E	
LV transformer, phase-to-earth	V + E	
HV and LV transformers, phase-to-phase	A arrester protective level transferred to the valve side	
NOTE The numbers ( ) above refer to possible alternatives. The minimum alternative can be selected.		

Table 5 – Arrester protection on the d.c. side: Two 12-pulse converters (Figure 1)

Protected item	Protecting arrester(s)	Comments
Between terminals of a valve	V	
Between terminals of a 6-pulse bridge	(1) V (2) B	
Between terminals of a 12-pulse group	(1) CH, CL (2) 2·V	
Between terminals of the 2 x 12-pulse group	(1) CB + EB (2) CH + CL (3) 4·V	
Between terminals of an HV d.c. reactor	DR	May be omitted
Between terminals of an LV d.c. reactor	EB + E1	Very conservative assumption. May be reduced
DC bus, line side of an HV d.c. reactor	DB, DL/DC	
DC bus, valve side of a d.c. reactor	(1) CB (2) CH + CM (3) 2·V + CM (4) 4·V + E	
Mid-point between 6-pulse bridges of the HV 12-pulse group	(1) MH (2) V + CM	
Mid-point d.c. bus	(1) M (2) 2·V + E	
Mid-point between 6-pulse bridges of the LV 12-pulse group	(1) ML (2) V + EB	
Neutral bus, valve side of LV d.c. reactor		

Protected item	Protecting arrester(s)	Comments
Neutral bus, line side of LV d.c. reactor	E1, EL, EM	
HV transformer, HV 12-pulse group, phase-to-earth	(1) T (2) V + MH	
LV transformer, HV, 12-pulse group, phase-to-earth	V + CM	
HV transformer, LV 12-pulse group, phase-to-earth	(1) V + ML (2) 2·V + EB	
LV transformer, LV 12-pulse group, phase-to-earth	V + EB	
HV and LV transformers, HV and LV 12-pulse groups, phase-to-phase	A arrester protective level transferred to the valve side	
NOTE The numbers ( ) above refer to possible alternatives. The minimum alternative can be selected.		

8.5 Summary of events and stresses

In Clauses 7 and 8 a description is provided about the expected continuous, temporary, slow-front, fast-front and steep-front stresses that the equipment and arresters would be exposed to in an HVDC converter station.

These events and stresses are summarized in Tables 6 and 7.

Table 6 relates to various contingencies and the affected arresters. Table 7 gives information concerning the type of stresses the different arresters experience, and whether the current or energy stresses can be of significance for particular contingencies and arresters. This information can be used to decide on the relevant system model for detailed studies.

Table 6 – Events stressing arresters: Single 12-pulse converter (Figure 3)

Event	Arresters (refer to Figure 3 for arrester designation)											
	FA	A	T	V B	M	CB C	E	EL	EM	DR	DB DL DC	FD
Earth fault, d.c. pole or d.c. line (nodes 9, 10, line 1)			x				x	x	x	x	x	x
Lightning from d.c. line							x		x	x	x	x
Slow-front overvoltages from d.c. line							x	x	x		x	x
Lightning from earth electrode line							x	x				
Earth fault a.c.-phase on valve side (nodes 5, 6)				x	x		x	x	x	x		
Current extinction three-pulse commutation group				x								
Current extinction six-pulse bridge				x	x							
Loss of return path, monopolar operation or commutation failure							x	x	x			
Earth faults and switching operation, a.c. side	x	x	x	x	x	x	x	x	x	x		x
Lightning from a.c. system	x	x										
Station shielding failure, pole bus (at nodes 9, 10, if applicable)				x	x	x						
Station shielding failure, neutral bus (at node 8, if applicable)							x	x	x			
Some events may not need to be considered due to a too low probability occurrence.												

Table 7 – Types of arrester stresses for different events: Single 12-pulse converter (Figure 3)

Event	Fast-front and steep-front stresses		Slow-front and temporary overvoltage stresses	
	Current	Energy	Current	Energy
Earth fault, d.c. pole or d.c. line (nodes 9, 10, line 1)	E, EL, EM, FD	E, EL, EM, FD	DB, DL/DC, DR, E, EL, EM, T	E, EL, EM
Lightning from d.c. line	DB, DL/DC, FD DR, E, EM			
Slow-front overvoltages from d.c. line			DB, DL/DC, E, EL, EM, FD	
Lightning from earth electrode line	E, EL			
Earth fault on bridge a.c. phase (nodes 5, 6)	V, B		DR, V, B, E, EL, EM, M	V, B, E, EL, EM, M
Current extinction, three-pulse group			V, B	V, B
Current extinction, six-pulse group			M, V, B	M, V, B
Loss of return path, monopolar operation or commutation failure			E, EL, EM	E, EL, EM
Earth faults and switching operations on a.c. side (node 1, a.c. line)	FA	FA	V, M, CB, A, FA E, EL, EM, FD, DR, C, B, T	V, B, A, E, EL, EM, FD
Lightning from a.c. system	A, FA			
Station shielding failure, pole bus	V, M, CB, C, B			

Event	**Fast-front and steep-front stresses**		**Slow-front and temporary overvoltage stresses**	
	Current	**Energy**	**Current**	**Energy**
(at nodes 9, 10, if applicable)				
Station shielding failure, pole bus (at nodes 8, if applicable)	E, EL, EM			
Some events may not need to be considered due to a too low probability of occurrence.				

Converter contingencies such as commutation failures or inverter blocking without by-pass pairs are not critical for determining protective levels and energy requirements of the HVDC converter station arresters. However, inverter blocking with current may be important for determining arrester energy requirements, unless if considered inconceivable (8.3.5.3.4). Some cases of commutation failures may be critical (e.g. giving rise to resonances, or in a situation involving the combination of the low neutral arrester protective level (E, EL, EM) and high impedance of a d.c. current return path).

9 Design procedure of insulation co-ordination

9.1 General

Because of the essential differences between a.c. and d.c. systems leading to some deviations in the process of insulation co-ordination as discussed in 6.2, it is useful in Clause 9 to define clearly the design objectives to be achieved as a result of the co-ordination procedures described in 9.2 to 9.7. This applies to some extent to the a.c. side of the HVDC converter station but to a greater extent to the d.c. side, particularly because several valve groups are normally connected in series. The valves and other equipment entirely separate from earth are therefore arranged to be protected by means of appropriate surge arresters as illustrated in Figures 1, 2 and 3.

The first design objective is thus to make a suitable choice of the locations of various arresters based on all the available or assembled necessary system details discussed in 10.3 not only for the d.c. converter scheme but also for the a.c. network, the d.c. and earth electrode lines and cables (if any), and the a.c. side of the HVDC converter station. The next important design objective is to plan and conduct studies for determining surge arrester requirements in sufficient detail as illustrated in 9.2. The studies are generally, but not necessarily, based on assessment and evaluation of various transient events affecting the stresses on different arresters using the methods and tools such as those discussed in Clause 10.

The main objective is the determination of the withstand voltages to achieve the desired reliability.

Subclauses 9.2 to 9.7 suggest some illustrative tables suitable both for itemizing the quantities which are to be the design objectives in a clear manner and as a possible means of presenting the design results.

9.2 Arrester requirements

Table 8 suggests for each of the arresters, such as referenced in Figure 3, the various requirements which should be the objectives of the insulation co-ordination design. The suggested (or similar) format on groups of arresters and individual items, should facilitate clear identification and presentation of the information.

Table 8 – Arrester requirements

Arrester identification – reference [a, b]	Continuous operating voltages			Arrester protective levels at co-ordination currents [a]						Energy absorption
	U_c, U_{ch}	CCOV	PCOV	SIPL		LIPL		STIPL [c]		Duty of arrester
(See Figures 1 and 3)	kV (r.m.s.)	kV (crest)	kV (peak)	kV (peak)	kA (peak)	kV (peak)	kA (peak)	kV (peak)	kA (peak)	kJ
I. AC section										
A		**N/A**	**N/A**					**N/A**	**N/A**	
FA1, FA2		**N/A**	**N/A**					**N/A**	**N/A**	
II. Converter circuit										
V	**N/A**									
T	**N/A**							**N/A**	**N/A**	
B	**N/A**							**N/A**	**N/A**	
M, MH, ML	**N/A**							**N/A**	**N/A**	
C, CH, CL, CB	**N/A**							**N/A**	**N/A**	
III. DC yard										
DB, DL, DC	**N/A**		**N/A**					**N/A**	**N/A**	
EB								**N/A**	**N/A**	
DR		**N/A**						**N/A**	**N/A**	
FD1, FD2		**N/A**	**N/A**					**N/A**	**N/A**	
E,EL, EM	**N/A**		**N/A**					**N/A**	**N/A**	

NOTE Refer to Clause 4 for abbreviations and Clause 3 for definitions.

[a] See 8.1 for general information on corresponding current impulse waveshapes.

[b] See Figure 1 for arrester references in a typical modern HVDC converter station. The actual arrangement is design specific.

[c] STIPL for valve arresters only.

9.3 Characteristics of insulation

As in a.c. substations there are two types of insulation used in HVDC converter stations, self-restoring, which applies to air, and non-self-restoring which applies to e.g. oil and paper. However, gases that may be used can fall under both types of insulation. In d.c. applications the composite effect of d.c., a.c. and impulse (also polarity reversal) voltages on the characteristics of the insulation shall be considered. The characteristics of the individual insulation are outside the scope of this standard.

9.4 Representative overvoltages (U_{rp})

The representative overvoltage as defined in IEC 60071-1 is equal to the maximum overvoltage of each class of overvoltages determined as described in Clause 10. This general concept applies to both a.c. and d.c. systems, but a particular application of this concept for d.c. systems is to consider that representative overvoltages are equal to protection levels of arresters for directly protected equipment.

The representative overvoltages, which may be presented as in Table 9, are determined by considering relevant faults and examining the results of the calculation to find out the representative type of overvoltage, i.e. slow-front, fast-front or steep-front. Once the type of overvoltage has been determined, the peak value of the waveform chosen may be adjusted to take into consideration the duration and shape of the overvoltage as per IEC 60071-2:1996, Clause 2. This adjustment can be considered to be taken into account when applying factors to the protective levels of arresters as per 9.6.

Table 9 – Representative overvoltages and required withstand voltages

Insulation location (Refer to Figure 3)	Representative overvoltages (U_{rp})			Required withstand voltages (U_{rw})		
	SIPL RSFO	LIPL RFFO	STIPL [a] RSTO [a]	RSIWV	RLIWV	RSTIWV
	kV	kV	kV	kV	kV	kV
I AC switchyard section						
AC busbars and conventional equipment, 1-N			**N/A**			**N/A**
Filter capacitors (a) HV side, 1-N, 3-N (b) Across, 1-2, 3-N (c) LV side, 2-N			**N/A**			**N/A**
Filter reactors (a) HV side, 2-N, 3-N (b) Across, 2-3, 3-N (c) LV side, 3-N			**N/A**			**N/A**
II Converter equipment						
Across a valve, 5-9, 7-5, 6-7, 6-8						
Across lower valve group, 7-8			**N/A**			**N/A**
Across upper valve group, 9-7			**N/A**			**N/A**
Phase-to-phase within a six-pulse bridge, 5a-5b, 5b-5c, 5c-5a 6a-6b, 6b-6c, 6c-6a			**N/A**			**N/A**
Mid-point to earth, 7-G			**N/A**			**N/A**
Each converter unit HV side, 9-G			**N/A**			**N/A**
Each converter unit LV side, 8-G			**N/A**			**N/A**
Converter HVDC bus, 9-G			**N/A**			**N/A**
DC neutral bus, 8-G			**N/A**			**N/A**

Insulation location	**Representative overvoltages (U_{rp})**			**Required withstand voltages (U_{rw})**		
(Refer to Figure 3)	**SIPL** **RSFO**	**LIPL** **RFFO**	**STIPL** [a] **RSTO** [a]	**RSIWV**	**RLIWV**	**RSTIWV**
	kV	kV	kV	kV	kV	kV
III DC side equipment						
Across d.c. reactor, 10-9			**N/A**			**N/A**
Filter capacitors (a) HV side, 10-G, 12-G (b) Across, 10-11, 12-8 (c) LV side, 11-G, 8-G			**N/A**			**N/A**
Filter reactors (a) HV side, 11-G, 12-G (b) Across, 11-12, 12-8 (b) LV side, 12-G, 8-G			**N/A**			**N/A**
HVDC Line/Cable, 10-G			**N/A**			**N/A**
DC line, 10-G			**N/A**			**N/A**
Earth electrode line, 8-G			**N/A**			**N/A**
IV Other equipment such as transformer, valve, windings (e.g. in oil)						
Star winding (a) phase-to-neutral, 5a-n, 5b-n, 5c-n (b) phase-to-phase, 5a-5b, 5b-5c, 5c-5a (c) neutral to earth, n-G (d) phase-to-earth, 5a-G, 5b-G, 5c-G			**N/A**			**N/A**
Delta winding (a) phase-to-phase, 6a-6b, 6b-6c, 6c-6a (b) phase-to-earth, 6a-G, 6b-G, 6c-G			**N/A**			**N/A**
Star-winding to delta winding, 5-6			**N/A**			**N/A**

[a] STIPL, RSTO and RSTIWV are applicable to valve arresters only.

9.5 Determination of the co-ordination withstand voltages (U_{cw})

The insulation co-ordination procedure recommended in IEC 60071-1 implies the application of a co-ordination factor (K_c) to the representative overvoltages (U_{rp}) to obtain the co-ordination withstand voltages (U_{cw}), which means: $U_{cw} = K_c \times U_{rp}$ (refer to IEC 60071-1:2006, 5.3).

For equipment on the d.c. side, the deterministic method (refer to IEC 60071-2:1996, 3.3) is actually used so that for such equipment this is the deterministic co-ordination factor K_{cd} (refer to IEC 60071-2:1996, 3.3.2.1) which is used instead of K_c. The co-ordination factor K_{cd} applied to the representative overvoltages includes:

- allowance for limitations in modelling and in data for calculating the overvoltages, and for the co-ordination currents taking into account the strong non-linearity of the arrester characteristics;
- allowance for shape and duration of overvoltages.

For d.c. applications if the calculated value of U_{rp} is the highest value for reasonable contingencies the value of U_{cw} may be taken to be equal to U_{rp}.

9.6 Determination of the required withstand voltages (U_{rw})

As with a.c. systems, equipment is classified into equipment with self-restoring and with non-self-restoring insulation according to IEC 60071-1. Self-restoring insulation consists primarily of air gaps and porcelain external insulation while non-self-restoring insulation consists primarily of oil and cellulose dielectric materials as used in converter transformers and reactors. Under certain circumstances the thyristor valve may be considered self-restoring. Redundant thyristor levels are provided to maintain the required withstand voltage even in the event of random failures of thyristor levels within the valve between maintenance periods.

Arresters are used to protect equipment insulation as in a.c. applications; however, the arresters are not necessarily directly connected to earth, but are also connected directly across equipment elevated from earth potential. For thyristor valves the arresters are located close to the valve in order to eliminate distance effects.

The essential difference compared with a.c. applications is that in HVDC applications the insulation is stressed by composite a.c., d.c. and impulse voltages. Composite voltages require consideration of both resistive and capacitive voltage distribution and may result in high-voltage stresses. These high-voltage stresses are, however, taken into account in the design and testing of the equipment.

The required withstand voltages (U_{rw}) for switching, lightning and steep-front are determined by multiplying the corresponding co-ordination withstand voltages (U_{cw}) with relevant multiplying factors. Based upon the withstand voltages, the test voltages for each equipment are determined according to the respective equipment standards. Referring to IEC 60071-1:2006, Figure 1, the required withstand voltages U_{rw} are obtained by applying to the co-ordination withstand voltage the altitude correction factor K_{a} for external insulation, and a safety factor K_{s} whose value depends on the type of insulation internal or external. The safety factor K_{s} includes:

- allowance for ageing of insulation;
- allowance for changes in arrester characteristics;
- allowance for dispersion in the product quality.

For HVDC converter stations, the deterministic method is applied and, for altitudes up to 1 000 m, experience has shown that the required withstand voltages of equipment can be obtained by applying a factor to the corresponding protective level of the arrester. Such a factor includes all the preceding ones discussed at the beginning of this subclause. Table 10 provides a set of indicative values for this factor which may be used as design objectives if not specified by the user or the relevant apparatus committees. In Table 10, all equipment is considered to be directly protected by an arrester. If this is not the case, e.g. for some of the equipment on the a.c. side, distance effect for fast and very-fast transients shall be taken into account and indicative ratios should be raised accordingly (refer to IEC 60071-1 and IEC 60071-2, co-ordination factor and co-ordination withstand voltages).

Table 10 – Indicative values of ratios of required impulse withstand voltage to impulse protective level

Type of equipment	Indicative values of required impulse withstand voltage/impulse protective level [a, c]		
	RSIWV/SIPL	RLIWV/LIPL	RSFIWV/STIPL [b]
AC switchyard – busbars, outdoor insulators, and other conventional equipment	1,20	1,25	1,25
AC filter components	1,15	1,25	1,25
Transformers (in oil)			
line side	1,20	1,25	1,25
valve side	1,15	1,20	1,25
Converter valves	1,15	1,15	1,20
DC valve hall equipment	1,15	1,15	1,25
DC switchyard equipment (outdoor) (including d.c. filters etc. and d.c. reactor)	1,15	1,20	1,25

[a] Indicated values are stated for general design objectives only. Appropriate final ratios (higher or lower) can be selected according to the chosen performance criteria.

[b] STIPL for valve arresters.

[c] Indicative ratios are on the basis that any equipment is directly protected with a surge arrester.

9.7 Determination of the specified withstand voltage (U_w)

The specified withstand voltages are values equal to or higher than the required withstand voltages. For a.c. equipment, the specified withstand voltages correspond to standard values as stated in IEC 60071-1.

For HVDC equipment, there are no standardized withstand voltage values and the specified withstand voltages are rounded up to convenient practical values.

10 Study tools and system modelling

10.1 General

Clause 10 discusses the overall methods and tools required to evaluate the overvoltage characteristics that may affect an HVDC converter station and to derive the required arrester characteristics. The objective of these studies, as further detailed in Clause 8, are as follows:

- determine stresses and protective levels of arresters in an HVDC converter station;
- form the basis for insulation co-ordination of HVDC converter stations;
- derive the specification of all the arresters involved.

10.2 Study approach and tools

In order to carry out the studies, the following information is required, as further detailed in 10.3:

- configuration of the HVDC station, as well as a.c. and d.c. system data;
- data of equipment connected on both the a.c. and d.c. side (e.g. transformers, lines, etc.);
- arrester characteristics appropriate to temporary overvoltages, slow-front, fast-front and steep-front impulses
- converter control and valve protection strategies, including response and/or delay in valve protecting firing circuit;
- operating conditions;

- valve protective strategies (response of valve protective firing).

The overvoltage study approach may consist of the following steps:

Step 1: Define the preliminary arrester configuration and determine the preliminary arrester parameters such as U_{c}, U_{ch}, PCOV and/or CCOV for each arrester.

Step 2: Study the cases producing the highest current and energy stresses. At this stage, the minimum number of arrester columns and their ratings are defined, considering the arrester stresses and contingencies.

Step 3: Check for fast-front and steep-front overvoltages to ensure that with the arrester arrangement defined in steps 1 and 2, the whole HVDC station is adequately protected. Additional arresters may be required due to distance effects.

Step 4: Establish the arrester duties (co-ordination current/voltage/energy) based on the study results and determine the arrester specification (see Clause 8).

Step 5: Establish the maximum overvoltages and withstand voltages at various locations (see 9.4).

For arrester duties, the general principles consist in considering the minimum V-I protection characteristics for energy consumption and the maximum V-I protection characteristics for the protection level.

Although there are many tools available for the calculation of overvoltages and arrester stresses, it is important to consider the validity of each tool for the proper representation of power system components to obtain the required characteristics of the models for the study undertaken. To obtain meaningful results the components need to be properly modelled with regard to the frequency range of interest and other characteristics of the network components. (For guidance on model representations, see the Bibliography). Typically digital computer programs employing numerical transient analysis methods are used for these calculations.

Study tools using real time digital simulation techniques are available. These tools under the present conditions may not be suitable to study the high-frequency overvoltages due to time step limitations.

10.3 System details

10.3.1 Modelling and system representation

For insulation co-ordination studies, models of network components valid in the range d.c. to 50 MHz may be required. A representation valid for the complete frequency range is difficult to achieve for all network components. Various parameters have different influences on the correct representation of components within the frequency range of interest at which the model should be representative of the system characteristics.

Transient phenomena appear during transitions from one steady state condition to another. The primary causes of such disturbances in a system are closing or opening of a breaker or another switching equipment, short-circuits, earth faults or lightning strikes. The consequential electromagnetic phenomena are travelling waves on lines, cables or busbar sections and oscillations between inductances and capacitances of the system. The frequencies of oscillations are determined by the surge impedances and travel times of the connecting lines.

Table 11 gives an overview on the various origins of such transients and their frequency ranges. These frequency ranges are needed for modelling.

Table 11 – Origin of overvoltages and associated frequency ranges

Group	Frequency range for representation	Representation mainly for	Origin
I	0,1 Hz to 3 kHz	Temporary overvoltages	• Transformer energization (ferroresonance) • Load rejection • Fault clearing or initiation, line energization
II	50 Hz to 20 kHz	Slow-front overvoltages	• Terminal faults • Short line faults • Closing/reclosing
III	10 kHz to 3 MHz	Fast-front overvoltages	• Fast-front overvoltages • Circuit breaker restrikes • Faults in substations
IV	1 MHz t0 50 MHz	Steep-front overvoltages	• Disconnector switching • Faults in GIS – substations • Flashover

The overall system configuration is schematically represented in Figure 8. From an insulation co-ordination point of view, it is convenient to divide an HVDC converter station, including the connected a.c. and d.c. lines, into different parts with regard to the overvoltages generated. These parts or subsystems comprise:

a) the a.c. network;

b) the a.c. part of the HVDC converter station including the a.c. filters and any other reactive power source, circuit breakers and line side of converter transformer;

c) the converter bridges, the valve side of the converter transformer, the d.c. reactor, the d.c. filter and the neutral bus;

d) the d.c. line/cable and earth electrode line/cable.

These parts or subsystems should be considered in defining the study model, which could be either detailed or suitably simplified without losing the validity of the study results.

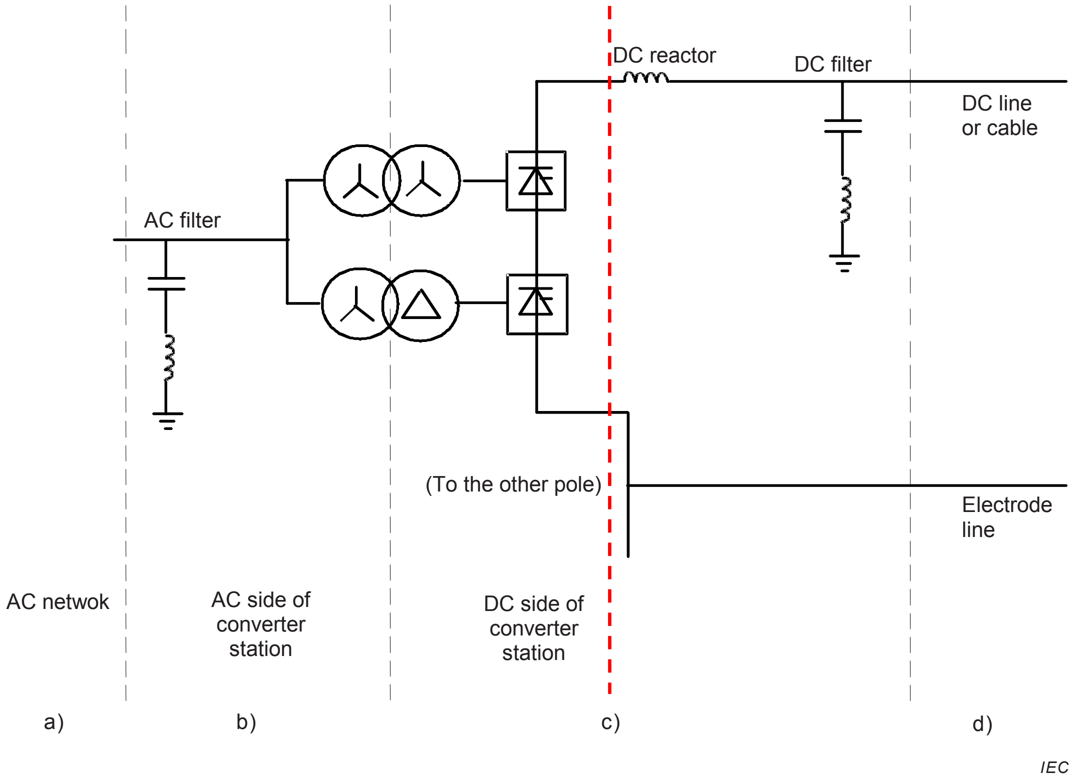


Figure 8 – One pole of an HVDC converter station

10.3.2 AC network and a.c. side of the HVDC converter station

10.3.2.1 Temporary and slow-front overvoltages

Details about the a.c. network and a.c. side equipment, and the modelling adequate for slow-front and temporary overvoltages are dealt with in this subclause.

a) Detailed three-phase modelling or adequate equivalents for the a.c. network near the HVDC converter station. Lines leaving the station and nearby transformers including their saturation characteristics are represented as well as converters electrically close to the plant. Network equivalents should be used for the main part of the a.c. systems, and the damping effect of the loads which affect the overall damping at resonance frequencies as seen from the HVDC station is taken into account.

b) Representation of the equipment installed on the a.c. side of the HVDC converter station. This includes any reactive power source and the converter transformers. The saturation of the converter transformer is a key parameter.

c) Representation of a.c. bus and filter arrester characteristics in the frequency range of some hundreds of Hz.

10.3.2.2 Fast-front and steep-front overvoltages

Details about the a.c. network and a.c. side equipment, and the modelling adequate for fast-front and steep-front overvoltages are dealt with in this subclause.

An adequate high frequency parameter model should be used for a.c. lines, busbars, etc.

a) AC filter components shall be represented including stray inductance and capacitance.

b) AC lines of length such that the travelling time exceeds the time frame of the studied event can be represented by their surge impedance.

c) All stray capacitances of equipment made up of windings can be represented by lumped equivalents, both to earth and across the equipment.

d) Arrester characteristics shall be considered for the appropriate frequency range as given in Table 11.

e) There shall be an adequate model for the earthing system, the earth connection and the flashover arc.

10.3.3 DC overhead line/cable and earth electrode line details

10.3.3.1 Temporary and slow-front overvoltages

Details about the d.c. overhead line/cable and electrode line, and the modelling adequate for slow-front and temporary overvoltages are dealt with in this subclause.

a) DC and earth electrode lines shall be represented from d.c. up to about the 20 kHz frequency range according to Table 11.

b) Representation of d.c. and neutral bus arresters characteristics in the frequency range of some hundreds of Hz.

10.3.3.2 Fast-front and steep-front overvoltages

Details about the d.c. overhead line/cable and electrode line, and the modelling adequate for fast-front and steep-front overvoltages are dealt with in this subclause.

a) Adequate high-frequency parameters should be used for d.c. and earth electrode lines as well as buses. Also short lines can be represented by their surge impedances as long as the reflection from their far end does not intercept with the studied event. The 50 % flashover voltages of the line insulators are decisive for the maximum stresses.

b) DC and neutral bus arresters characteristics should be considered for the appropriate frequency range as given in Table 10.

c) There shall be an adequate model for the earth connection and flashover arc.

10.3.4 DC side of an HVDC converter station details

10.3.4.1 Temporary and slow-front overvoltages

Details about the converter station equipment on the d.c. side, and the modelling adequate for slow-front and temporary overvoltages are dealt with in this subclause.

a) DC side station equipment (d.c. reactor, valves, d.c. filter and neutral bus arresters and capacitor, etc.) is represented.

b) Representation of d.c. side arresters in the frequency range of some hundreds of Hz.

c) If applicable, control and protection actions shall be considered, particularly for temporary overvoltages.

10.3.4.2 Fast-front and steep-front overvoltages

Details about the converter station equipment on the d.c. side, and the modelling adequate for fast-front and steep-front overvoltages are dealt with in this subclause.

a) DC side equipment (d.c. reactor, d.c. filters, valves etc.), shall be represented including stray inductances and capacitances.

b) All stray capacitances of equipment made up of windings can be represented by lumped equivalents, both to earth and across equipment.

c) Arrester characteristics for the appropriate frequency range shall be indicated.

d) Control and protection actions do not need to be considered since they will not respond to these fast transients.

11 Creepage distances

11.1 General

The creepage distance on the insulators is one of the factors that dictates the performance of external insulations at continuous operating voltages (a.c., d.c. or mixed). When wetted, contamination on the insulators reduces their ability to support the operating voltages. Rain, snow, dew or fog are some of the weather conditions that can initiate this process. The withstand capability of contaminated insulators is also affected by other factors such as the shed profile, the orientation angle and the diameter of the insulators. In the case of bushings, d.c. current measuring devices, d.c. voltage dividers and other similar equipment, the internal construction of the core impacts both the internal and external voltage distribution. All these factors should be considered in determining the type and shape of the insulators suitable for the applications.

There have been cases of bushing flashover on various operating d.c. schemes where contamination deposits have been lightly wetted by dew, fog or rain. In addition, flashovers have occurred due to unequal wetting of external insulators, such as horizontally mounted bushings, although this phenomenon is independent of the creepage distance.

11.2 Base voltage for creepage distance

The base voltage across the insulation used together with the unified specific creepage distance is as follows:

a) for the phase-to-earth insulation on the a.c. side of the converter (a.c. equipment): the highest continuous r.m.s. value of the phase-to-earth operating voltage;

b) for the phase-to-phase insulation on the a.c. side of the converter (a.c. equipment): the highest r.m.s. value of the phase-to-phase operating voltage;

c) for the insulation of the d.c. equipment subjected to a pure d.c. voltage: the maximum continuous d.c. voltage across the equipment;

d) for the case of mixed voltage waveforms composed of d.c. fundamental and harmonics: the r.m.s. value of the voltage (e.g. valves and d.c. filter components);

e) for the case of mixed voltage waveforms composed of a .c. fundamental frequency and harmonics: the highest r.m.s. value of the voltage (e.g. a.c. filter components).

The required creepage distances are defined based on IEC TS 60815-1:2008, 8.3, which, for the purposes of standardization, includes five classes of pollution characterizing site pollution severity (SPS).

11.3 Creepage distance for outdoor insulation under d.c. voltage

The trend in the industry for several years has been to use larger specific creepage distances in HVDC applications under polluted operating conditions of around 60 mm/kV for porcelain insulators.

Several mitigation techniques have been used on existing HVDC systems to solve this problem. Although the application of silicone grease has been successful in avoiding flashovers, the frequency of reapplying the grease coating is high under polluted conditions. An alternative method involves the application of room temperature vulcanized rubber (RTV) on the surface of the insulators. Technological advances in this area have resulted in improved performance.

The application of booster sheds has also been successful in avoiding bushing flashovers.

The use of composite housings for bushings and other devices have been successfully applied in solving the flashovers in HVDC stations, even with smaller specific creepage distances. Operating experience of composite insulator and bushings shows that around 75 % of the creepage associated with an equivalent porcelain insulator is found to result in satisfactory performance. The hydrophobicity of composite material makes it suitable in applications involving unequal wetting as well. Of late, composite insulators and bushings have been satisfactorily used, especially, at 500 kV and above.

11.4 Creepage distance for indoor insulation under d.c. or mixed voltage

For an indoor clean and controlled (valve hall) environment with humidity control, a minimum specific creepage distance of about 14 mm/kV (based on the appropriate base voltage as calculated in 11.2) has been widely used and has not experienced any flashover. The creepage path, in any case, may not be an especially suitable parameter to define the converter valve internal insulation and the arcing distance may be more appropriate.

For indoor HVDC installations (indoor DC yard) with uncontrolled environment, satisfactory performance has been demonstrated for creepage distance between 20 mm/kV to 30 mm/kV under the assumption that condensation is avoided.

11.5 Creepage distance of a.c. insulators

IEC TS 60815-2 for ceramic and glass insulators and IEC TS 60815-3 for polymer insulators give the user the means to:

- determine the reference unified specific creepage distance (RUSCD) from the site pollution severity (SPS) class (IEC TS 60815-2:2008, Figure 1, and IEC TS 60815-3:2008, Figure 1);
- evaluate the suitability of different insulator profiles;
- determine the necessary USCD by applying corrections for insulator shape, size, position, etc. to the RUSCD;
- if required, determine the appropriate test methods and parameters to verify the performance of the selected insulators.

12 Clearances in air

Details concerning the required clearances in the air to assure a specified impulse voltage insulation for a.c. applications are presented in IEC 60071-2, while IEC 60071-2:1996, Annex A, gives the correlations between impulse withstand voltages and minimum air clearances. The clearances in d.c. applications are based on the insulation levels of equipment which are determined to provide the appropriate margin over the protective level of the arresters rather than on standard equipment levels.

The critical (50 %) withstand voltage (U_{50}) used for outdoor clearance calculations shall be calculated with at least 2σ in accordance with the following formula:

$$U_\mathrm{w} = U_{50}\ (1\text{-}2\ \sigma)$$

where:

U_w is the impulse withstand voltage, kV;

U_{50} is the 50 % flashover voltage for the appropriate voltage waveshape, kV;

σ is the standard deviation.

The U_{50} value shall be based on the value of the gap factor appropriate to the electrode shape.

In calculating U_w atmospheric correction factors shall be applied for non-standard atmospheric conditions in accordance with IEC 60060-1.

The minimum clearance is selected as the larger clearance determined from the switching and lightning impulse withstand of the equipment.

For the equipment inside the valve hall, the U_{50} value should be at least 2σ above the equipment withstand voltage (U_w), by taking into consideration:

- the maximum valve hall temperature in calculating the atmospheric correction factor;
- the appropriate electrode configuration in applying the gap factor;
- the actual complex waveshape of the service voltage including a.c., d.c., and transient components.

In HVDC applications the presence of composite a.c., d.c. and impulse voltages shall be considered [7].

Annex A
(informative)

Example of insulation co-ordination for conventional HVDC converters

A.1 General

Annex A gives a description and method of calculation for the insulation co-ordination of a conventional HVDC converter station with a d.c. cable with earth return. This example is intended to be informative and tutorial and is very schematic. It mainly summarizes steps leading to chosen arrester ratings and specified insulation levels, based on procedures explained in the main text.

The results presented in Annex A are based on the study approach and the described procedures in Clause 10 and in Clause 8. Because there are no standard withstand voltages for HVDC, calculated values for SIWV, LIWV and SSFIWV are rounded up to convenient practical values.

A.2 Arrester protective scheme

Figure A.1 shows the arrester protective schemes for the HVDC converter station. All arresters are of the metal-oxide type without gap.

A.3 Arrester stresses, protection and insulation levels

A.3.1 General

The following main data are used for the basic design of the HVDC converter station:

AC side: strong a.c. system

DC side:

DC voltage	kV	500	(rectifier)
DC current	A	1 500	
Smoothing reactor	mH	225	
Firing angles	degree (°)	15/17	(rectifier/inverter)

Converter transformer

Rating (three-phase, six-pulse)	MVA	459
Short-circuit impedance	p.u.	0,12
Valve side voltage	kV r.m.s.	204
Tap-changer range		±5 %
Inductance per phase (valve side)	mH	35

AC bus arrester (A)

The following data are given for the HVDC converters:

Parameters		Bus 1 (A)
Nominal system voltage	kV r.m.s	400
Highest system voltage (U_s)	kV r.m.s	420
Continuous operating voltage, phase-to-earth	kV r.m.s	243
SIPL (at 1,5 kA)	kV	632
LIPL (at 10 kA)	kV	713
Maximum slow-front overvoltage transferred to valve side (between two phases)	kV	549
Number of parallel arrester columns	–	2
Arrester energy capability	MJ	3,2

Valve arrester type (V1) and (V2)

The following values are valid for both converter stations:

CCOV	kV	$208 \times \sqrt{2}$	
Number of parallel columns		8	for arrester (V1)
		2	for arrester (V2)
Energy capability	MJ	16,2	for arrester (V1)
	MJ	2,6	for arrester (V2)

The stresses of the valve arresters are determined by computer studies for the following cases.

A.3.2 Slow-front overvoltages transferred from the a.c. side

The highest stresses are expected if the transferred slow-front overvoltage appears between two phases (e.g. R and S), where only one valve is conducting (Figure A.2). The value of the transferred slow-front overvoltage is dependent on the maximum protective level of the a.c. bus arrester (A) on the line side of the converter transformer.

Figure A.3 show the results for the HVDC converters if only one arrester in the circuit is conducting. This fault case is decisive for the design of all lower valve arresters of type (V2).

Results (valid for valve arrester (V2)):

The switching impulse protective level (SIPL) of the valve arrester (V2) is given by

SIPL = 500 kV at 1 027 A (see Figure A.3)

RSIWV = 1,15 × 500 kV = 575 kV => $\boxed{\text{SIWV = 575 kV}}$

A.3.3 Earth fault between valve and upper bridge transformer bushing

This fault case gives the highest stresses for the valve arresters protecting the three-pulse commutating group on the highest potential. The equivalent circuit for this case is shown in Figure A.4. The stresses for the upper valve arresters are also dependent on the fault insertion time. To determine the maximum values, the fault insertion time is varied from zero electrical degree to 360 electrical degrees.

The results of the maximum stresses are shown in Figure A.5.

This fault case is decisive for the design of all upper valve arresters (V1) if the slow-front overvoltage (A.3.2) does not result in higher arrester stresses.

Results (valid for valve arrester (V1)):

The switching impulse protective level (SIPL) of the valve arrester (V1) is given by

SIPL = 499,8 kV at 4 230 A (see Figure A.5)
RSIWV = 1,15 × 499,8 kV = 575 kV => $\boxed{\text{SIWV = 575 kV}}$

Converter group arrester (C)

The following values are valid for both converter stations:

CCOV: 558 kV
Number of parallel columns: 1
Energy capability: 2,5 MJ

The stresses of the group arresters are determined by computer studies transferred slow-front overvoltages from the a.c. side. The magnitude of the transferred slow-front overvoltage voltage is twice the value given for the valve arresters. It is assumed that during normal operation, when four thyristor valves are conducting, a slow-front overvoltage will be transferred between the phases.

For the design of the converter group arrester (C) the following values for the co-ordination currents are chosen:

SIPL = 930 kV at 0,5 kA
LIPL = 1 048 kV at 2,5 kA
RSIWV = 1,15 × 930 kV = 1 070 kV => $\boxed{\text{SIWV = 1 175 kV}}$
RLIWV = 1,20 × 1 048 kV = 1 258 kV => $\boxed{\text{LIWV = 1 300 kV}}$

DC bus arrester (DB)

The following values are valid for both converter stations:

CCOV: 515 kV
Number of parallel columns: 1
Energy capability: 2,2 MJ

For the design of the d.c. bus arrester (DB) the following values for the co-ordination currents are chosen:

SIPL = 866 kV at 1 kA
LIPL = 977 kV at 5 kA
RSIWV = 1,15 × 866 kV = 996 kV => $\boxed{\text{SIWV = 1 050 kV}}$
RLIWV = 1,2 × 977 kV = 1 173 kV => $\boxed{\text{LIWV = 1 300 kV}}$

DC line/cable arrester (DL)

The following values are valid for both ends of the d.c. line/cable arrester (DL):

CCOV: 515 kV
Number of parallel columns: 8
Energy capability: 17,0 MJ

For the design of the d.c. line/cable arresters (DL) the following values for the co-ordination currents are chosen:

SIPL = 807 kV at 1 kA
LIPL = 872 kV at 5 kA
RSIWV = 1,15 × 807 kV = 928 kV => $\boxed{\text{SIWV} = 950\ \text{kV}}$
RLIWV = 1,20 × 872 kV = 1 046 kV => $\boxed{\text{LIWV} = 1\,050\ \text{kV}}$

Neutral bus arrester (E)

The following values are valid for both converter stations comprising all neutral bus arresters:

CCOV: 30 kV
Number of parallel columns: 12
Energy capability: 2,4 MJ

For the design of all neutral bus arresters (E) the following values for the co-ordination currents are chosen:

SIPL = 78 kV at 2 kA
LIPL = 88 kV at 10 kA
RSIWV = 1,15 × 78 kV = 90 kV => $\boxed{\text{SIWV} = 125\ \text{kV}}$
RLIWV = 1,20 × 88 kV = 106 kV => $\boxed{\text{LIWV} = 125\ \text{kV}}$

AC filter arrester (FA)

The operating voltage for the arresters consists of fundamental and harmonic voltages.

The rating of the arresters is determined by the stresses during earth faults followed by recovery overvoltages on the a.c. bus.

AC filter arrester (FA1)

U_{ch}: 60 kV
Number of parallel columns: 2
Energy capability: 1,0 MJ

For the design of the arrester (FA1) the following values for the co-ordination currents are chosen:

SIPL = 158 kV at 2 kA
LIPL = 192 kV at 40 kA
RSIWV = 1,15 × 158 kV = 182 kV => $\boxed{\text{SIWV} = 200\ \text{kV}}$
RLIWV = 1,20 × 192 kV = 230 kV => $\boxed{\text{LIWV} = 250\ \text{kV}}$

AC filter arrester (FA2)

U_{ch}:	30 kV
Number of parallel columns:	2
Energy capability:	0,5 MJ

For the design of the arrester (FA2) the following values for the co-ordination currents are chosen:

SIPL = 104 kV at 2 kA
LIPL = 120 kV at 10 kA
RSIWV = 1,15 × 104 kV = 120 kV => $\boxed{\text{SIWV} = 150\ \text{kV}}$
RLIWV = 1,20 × 120 kV = 144 kV => $\boxed{\text{LIWV} = 150\ \text{kV}}$

DC filter arrester (FD)

The operating voltage for the arresters consists mainly of harmonic voltages.

The rating of the arresters is determined by the stresses during transferred slow-front overvoltage with a subsequent earth fault on the d.c. bus.

DC filter arrester (FD1)

U_{ch}:	5 kV
Number of parallel columns:	2
Energy capability:	0,8 MJ

For the design of the arrester (FD1) the following values for the co-ordination currents are chosen:

SIPL = 136 kV at 2 kA
LIPL = 184 kV at 40 kA
RSIWV = 1,15 × 136 kV = 156 kV => $\boxed{\text{SIWV} = 200\ \text{kV}}$
RLIWV = 1,20 × 184 kV = 221 kV => $\boxed{\text{LIWV} = 250\ \text{kV}}$

DC filter arrester (FD2)

U_{ch}:	5 kV
Number of parallel columns:	2
Energy capability:	0,5 MJ

For the design of the arrester (FD2) the following values for the co-ordination currents are chosen:

SIPL = 104 kV at 2 kA
LIPL = 120 kV at 10 kA
RSIWV = 1,15 × 104 kV = 120 kV => $\boxed{\text{SIWV} = 150\ \text{kV}}$
RLIWV = 1,20 × 120 kV = 144 kV => $\boxed{\text{LIWV} = 150\ \text{kV}}$

A.4 Transformer valve side withstand voltages

A.4.1 Phase-to-phase

Since the converter transformer valve windings are not directly protected by a single arrester, the following two cases are considered:

- when the valves are conducting, the phase-to-phase insulation of the converter transformer valve side is protected by one valve arrester (V);
- when the valves are blocked, two valve arresters (V) are connected in series, phase-to-phase. During this event, the full transferred slow-front overvoltage will determine the maximum slow-front overvoltage.

SIPL = 550 kV
RSIWL = 1,15 × SIPL
SIWV = 650 kV
The selected specified lightning withstand voltage is:
LIWV = 750 kV

If the two phases are in separate transformer units (single-phase, three-winding transformers), and under the assumption that the voltages are not equally shared, the specified insulation levels for the star-winding have been selected to be:

SIWV = 550 kV
LIWV = 650 kV

A.4.2 Upper bridge transformer phase-to-earth (star)

The phase-to-earth insulation of the transformer and converters is determined by additive slow-front overvoltages between the transformer phases during the conducting status. These slow-front overvoltages originating from the a.c. side are limited by the arrester (A) on the primary side of the converter transformer. This additive method is not possible in the non-conducting status of the thyristor valves. Therefore only the 'conducting' status needs to be considered.

SIPL = 1 000 kV (2 × SIPL of arrester (V2) at 1 025 A, assuming no current in the neutral arrester)
RSIWV = 1,15 × SIPL => SIWV = 1 175 kV
The selected specified lightning withstand voltage is: LIWV = 1 300 kV

A.4.3 Lower bridge transformer phase-to-earth (delta)

The insulation levels are the same as phase-to-phase, assuming no current in the neutral arrester.

SIWV = 650 kV
The selected specified lightning withstand voltage is: LIWV = 750 kV

A.5 Air-insulated smoothing reactors withstand voltages

A.5.1 Terminal-to-terminal slow-front overvoltages

The worst case for the stresses between the terminals of smoothing reactors is given by the slow-front overvoltages on the d.c. side, which is limited by the arrester (DL). Assuming opposite polarity to the d.c. voltage, the total voltage will be:

SIPL of arrester (DL):	866 kV
Maximum d.c. voltage:	500 kV
Sum of both voltages:	1 366 kV
Smoothing reactors:	225 mH
Transformer inductances (four phases):	140 mH (4 × 35 mH)
Total inductance:	365 mH
Voltage between terminals:	1 366 kV × (225 mH/365 mH) = 842 kV

SIPL = 842 kV
RSIWV = 1,15 × 842 kV = 968 kV => SIWV = 1 175 kV

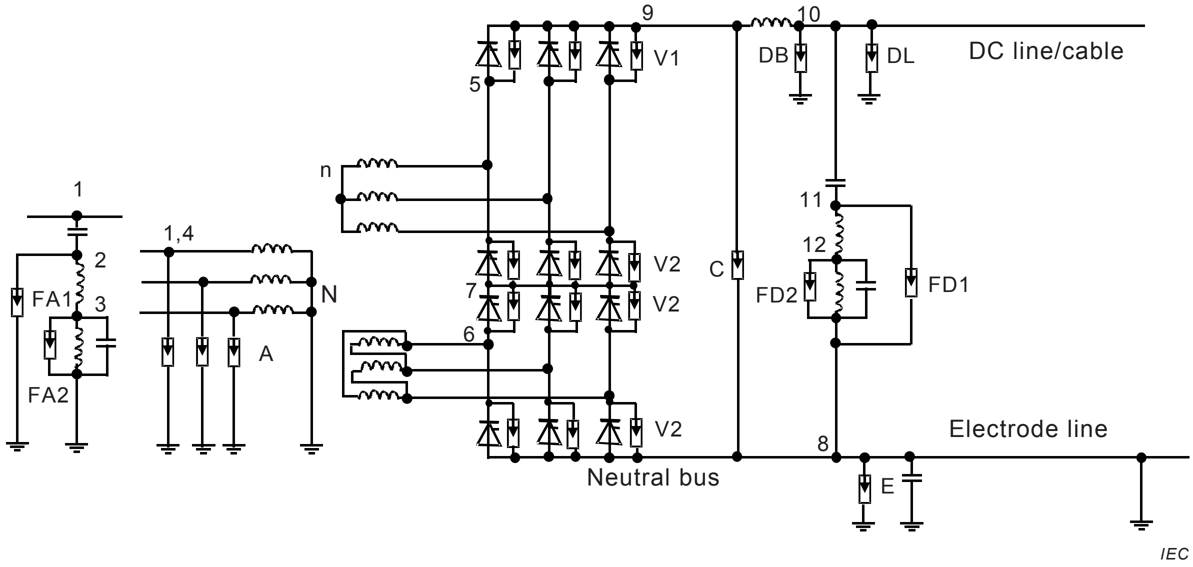
The maximum fast-front overvoltages between terminals are determined by the relative ratio of the capacitance across the reactor to the capacitance to earth on the valve side of the reactor. The specified lightning withstand voltage is: LIWV = 1 300 kV

A.5.2 Terminal-to-earth

The insulation levels are the same as for the arresters (C) or (DL).

SIWV = 1 175 kV
LIWV = 1 300 kV

A.6 Results



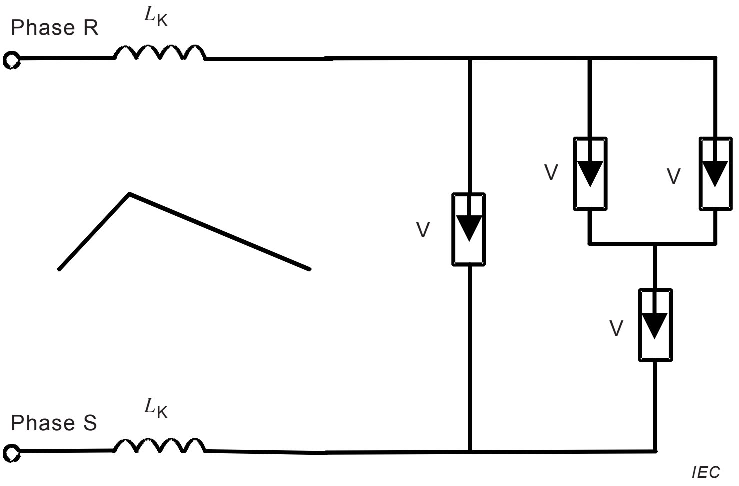
Arrester type		A	V1	V2	C	DB	DL	E	FD1	FD2	FA1	FA2
U_{ch} or CCOV	kV	243 r.m.s.	294 crest	294 crest	558 crest	515 d.c.	515 d.c.	30 d.c.	5 d.c.	5 d.c.	60 r.m.s.	30 r.m.s.
Lightning:												
– protection level	KV	713	–	–	1 048	977	872	88	184	120	192	120
– at current	KA	10	–	–	2,5	5	5	10	40	10	40	10
Switching:												
– protection level	KV	632	499,8	500	930	866	807	78	136	104	158	104
– at current	KA	1,5	4,23	1,025	0,5	1,0	1,0	6,0	2,0	2,0	2,0	2,0
No. of columns	–	2	8	2	1	1	8	2	2	2	2	2
Energy capability	MJ	9,2	10,4	2,6	2,5	2,2	17,0	0,4	0,8	0,5	1,0	0,5

Protection location	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
U_{ch} (kV)	243	60	30	243	558	294	294	30	558	515	15	15
LIPL = RFFO (kV)	713	192	120	713	–	–	–	88	1 048	977	184	120
SIPL = RSFO (kV)	632	158	104	632	1 000	550	550	78	930	866	136	104
LIWV (kV)	1 425	250	150	1 425	1 300	750	750	125	1 300	1 300	250	150
SIWV (kV)	1 050	200	150	1 050	1 175	650	650	125	1 175	1 175	200	150

Protection location	**1-2**	**2-3**		**5 and 6 ph-ph**	**5-6**	**8-9**	**9-10**	**10-11**	**11-12**	**Valves V1 and V2**
LIPL = RFFO (kV)	825	192		–	–	1048	–	977	184	–
SIPL = RSFO (kV)	747	158		550	1 000	930	842	866	136	500
LIWV (kV)	1 300	250		750	1 300	1 300	1 300	1 300	250	–
SIWV (kV)	1 050	200		650	1 175	1 175	1 175	1 175	200	575

NOTE Specified withstand voltages on the a.c. side are in line with recommended standard withstand values in IEC 60071-1 for 420 kV a.c. standard voltage class.

Figure A.1 – AC and d.c. arresters



NOTE The stray capacitances are not shown, but they are design dependent.

Figure A.2 – Valve arrester stresses for slow-front overvoltages from a.c. side

Stresses on arrester:

$U_{max.}$ = 500 kV $I_{max.}$ = 1,03 kA Energy = 698 kJ

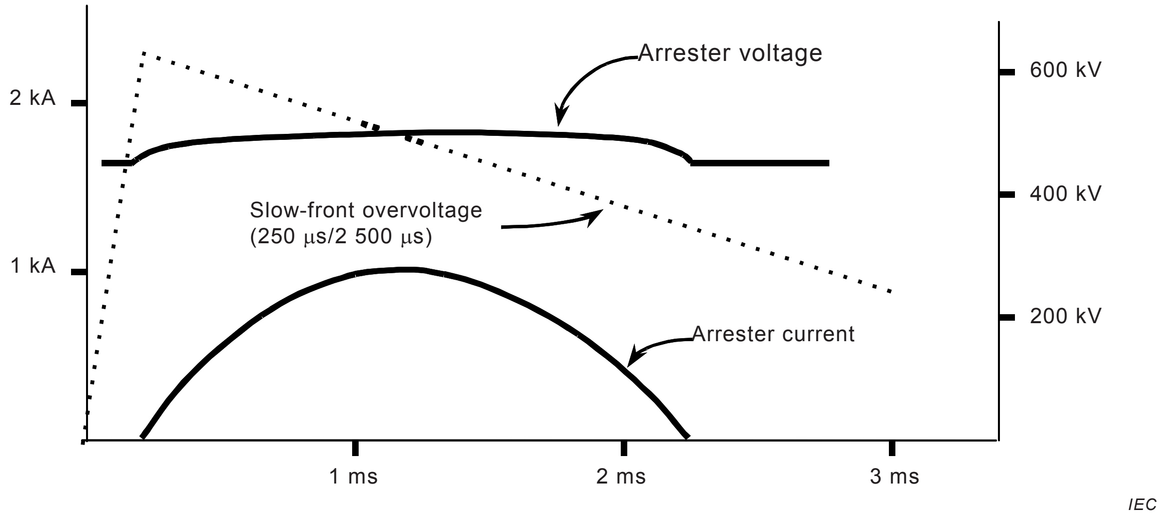
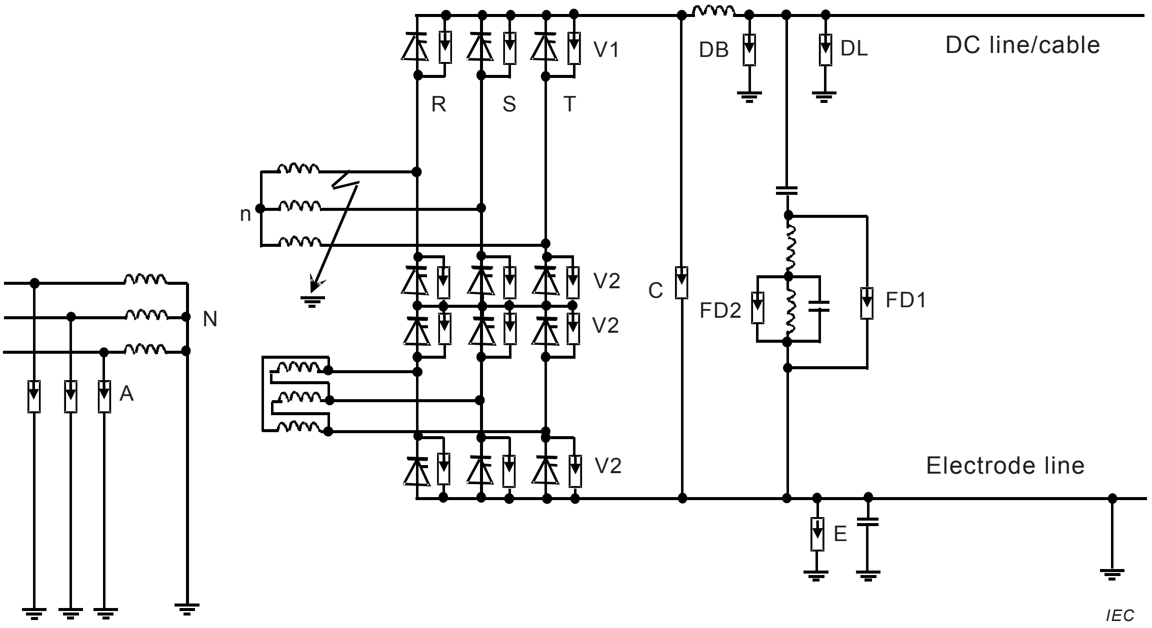


Figure A.3 – Arrester V2 stress for slow-front overvoltage from a.c. side



NOTE The stray capacitances are not shown, and are design dependent.

Figure A.4 – Valve arrester stresses for earth fault between valve and upper bridge transformer bushing

Stresses on arrester:

$U_{\text{max.}}$ = 500 kV $I_{\text{max.}}$ = 4,2 kA Energy = 16 189 kJ

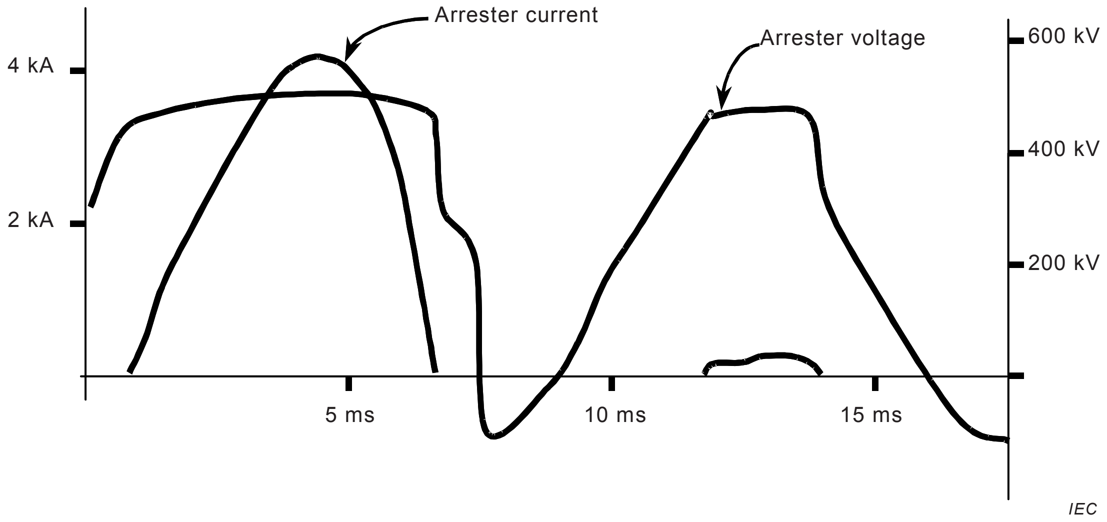


Figure A.5 – Arrester V1 stress for earth fault between valve and upper bridge transformer bushing

Annex B
(informative)

Example of insulation co-ordination for capacitor commutated converters (CCC) and controlled series capacitor converters (CSCC)

B.1 General

Annex B gives a description and method of calculation for the insulation co-ordination of CSCC and CCC converter stations with a d.c. cable with earth return. This example is intended to be informative and tutorial and is very schematic. It mainly summarizes steps leading to chosen arrester ratings and specified insulation levels, based on procedures explained in the main text.

The results presented are based on the study approach and procedures described in Clause 10 and Clause 8. Because there are no standard withstand voltages for HVDC, calculated values for SIWV, LIWV and SSFIWV are rounded up to convenient practical values.

B.2 Arrester protective scheme

Figures B.1a) and B.1b) show the arrester protective schemes for the CSCC and CCC converter station. All arresters are of the metal-oxide type without gap.

B.3 Arrester stresses, protection and insulation levels

B.3.1 General

The following main data are used for the basic design of the converter station:

AC side: strong a.c. system

DC side:

DC voltage	500	kV	(rectifier)
DC current	1 590	A	
Smoothing reactor	225	mH	
Firing angles	15/17	degree (°)	(rectifier/inverter)

CCC/CSCC capacitors		CCC converter	CSCC converter
Capacitance	μF	118	43
U_{ch}	kV r.m.s.	45	136

Converter transformer

Rating (three-phase, six-pulse)	MVA	419	459
Short-circuit impedance	p.u.	0,12	0,12
Secondary voltage (valve side)	kV	186,4	204
tap-changer range	r.m.s.	± 5 %	± 5 %
Inductance per phase (valve side)	mH	32	35

AC bus arresters (A1) and (A4)

The following data are given for the CCC and CSCC converters:

		CCC/CSCC	CSCC
Parameters		Bus 1 (A1)	Bus 4 (A4)
Nominal system voltage	kV r.m.s.	400	400
Highest system voltage (U_s)	kV r.m.s.	420	420
Continuous operating voltage, phase-to-earth	kV r.m.s.	243	256
SIPL (at 1,5 kA)	kV	632	690
LIPL (at 10 kA)	kV	713	790
Maximum slow-front overvoltage transferred to valve side (between two phases)	kV	512/560	N.A.
Number of parallel columns	-	2	2
Arrester energy capability	MJ	3.2	3.4

Valve arrester type (V1) and (V2)

The following values are valid for both converter stations:

		CCC	CSCC	
CCOV	kV	218 × √2	208 × √2	
Number of parallel columns		4	4	for arrester (V1)
		2	2	for arrester (V2)
Energy capability	MJ	5,4	5,2	for arrester (V1)
	MJ	2,7	2,6	for arrester (V2)

The stresses on the valve arresters are determined by computer studies for the following cases.

B.3.2 Transferred slow-front overvoltages from the a.c. side

The highest stresses are expected if the transferred slow-front overvoltage appears between the phases (e.g. R and S), where only one valve is conducting (Figures B.2a) and B.2b)). The value of the transferred slow-front overvoltage is dependent on the maximum protective level of the a.c. bus arrester (A) on the primary side of the converter transformer.

Figures B.3a) and B.3b) show the results for CCC and CSCC converters if only one arrester in the circuit is conducting. This fault case is decisive for the design of all lower valve arresters (V2).

Results valid for valve arrester (V2):

The switching impulse protective level (SIPL) of the valve arrester (V2) is given by:

SIPL 488,1 kV at 40 A (see Figure B.3a) for CCC converters)
480,8 kV at 466 A (see Figure B.3b) for CSCC converters)

$$\text{RSIWV} = 1{,}15 \times 488{,}1\ \text{kV} = 561{,}3\ \text{kV} \Rightarrow \boxed{\text{SIWV} = 605\ \text{kV}}$$

$$= 1{,}15 \times 480{,}8\ \text{kV} = 553\ \text{kV} \Rightarrow \boxed{\text{SIWV} = 605\ \text{kV}}$$

for both CCC and CSCC converters.

B.3.3 Earth fault between valve and upper bridge transformer bushing

This fault case gives the highest stresses for the valve arresters protecting the three-pulse commutating group on the highest potential. The equivalent circuit for this case is shown in Figures B.4a) and B.4b). The stresses for the upper valve arresters are also dependent on the fault insertion time. To determine the maximum values, the fault insertion time is varied from zeroelectrical degree to 360 electrical degrees.

The results of the maximum stresses are shown in Figures B.5a) and B.5b) for both CCC and CSCC converters.

This fault case is decisive for the design of all upper valve arresters (V1) if the slow-front overvoltage (B.3.2) doesn't result in higher arrester stresses.

Results (valid for valve arrester (V1)):

The switching impulse protective level (SIPL) of the valve arrester (V1) is given by:

SIPL = 523,6 kV at 1 776 A (see Figure B.5)a for CCC converter)
498,9 kV at 2 244 A (see Figure B.5b) for CSCC converter)
RSIWV = 1,15 × 523,6 kV = 602,1 kV => SIWV = 605 kV
= 1,15 × 498,9 kV = 574 kV =>

for both CCC and CSCC converters.

CCC and CSCC capacitor arresters (C_{cc}/C_{sc})

		CCC converter	CSCC converter
CCOV	kV	45	136
Number of parallel columns		8	6
Energy capability[2]	MJ	4,0	4.0
SIPL	kV	149	207
at co-ordination current	kA	7,8	8,8
		(Figure B.6a))	(Figure B.6b))
LIPL	kV	172	250
at co-ordination current	kA	10	10
RSIWV = 1,15×SIPL	kV	200	250
RLIWV = 1,20×LIPL	kV	250	300

Converter group arrester (C)

The following values are valid for both converter stations:

CCOV: 558 kV

Number of parallel columns: 1

Energy capability: 2,5 MJ

The stresses of the group arresters are determined by computer studies transferred slow-front overvoltages from the a.c. side. The magnitude of the transferred slow-front overvoltage is twice the value given for the valve arresters. It is assumed that during normal operation, when four thyristor valves are conducting, a slow-front overvoltage will be transferred between the phases.

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[2] This is based on the earth fault on the HV bushing of the converter transformer.

For the design of the converter group arrester (C) the following values for the co-ordination currents are chosen:

SIPL = 930 kV at 0,5 kA
LIPL = 1 048 kV at 2,5 kA
RSIWV = 1,15 × 930 kV = 1 070 kV => SIWV = 1 175 kV
RLIWV = 1,20 × 1048 kV = 1 258 kV => LIWV = 1 300 kV

DC bus arrester (DB)

The following values are valid for both converter stations:

CCOV: 515 kV
Number of parallel columns: 1
Energy capability: 2,2 MJ

For the design of the d.c. bus arrester (DB) the following values for the co-ordination currents are chosen:

SIPL = 866 kV at 1 kA
LIPL = 977 kV at 5 kA
RSIWV = 1,15 × 866 kV = 996 kV => SIWV = 1 050 kV
RLIWV = 1,2 × 977 kV = 1 173 kV => LIWV = 1 300 kV

DC line/cable arrester (DL)

The following values are valid for both ends of the d.c. line/cable:

CCOV: 515 kV
Number of parallel columns: 8
Energy capability: 17,0 MJ

For the design of the d.c. line/cable arresters (DL) the following values for the co-ordination currents are chosen:

SIPL = 807 kV at 1 kA
LIPL = 872 kV at 5 kA
RSIWV = 1,15 × 807 kV = 928 kV => SIWV = 950 kV
RLIWV = 1,20 × 872 kV = 1046 kV => LIWV = 1 050 kV

Neutral bus arrester (E)

The following values are valid for both converter stations comprising all neutral bus arresters:

CCOV: 30 kV
Number of parallel columns: 12
Energy capability: 2,4 MJ

For the design of all neutral bus arresters (E) the following values for the co-ordination currents are chosen:

SIPL = 78 kV at 2 kA
LIPL = 88 kV at 10 kA
RSIWV = 1,15 × 78 kV = 90 kV => SIWV = 125 kV
RLIWV = 1,20 × 88 kV = 106 kV => LIWV = 125 kV

AC filter arrester (FA)

The operating voltage for the arresters consists of fundamental and harmonic voltages.

The rating of the arresters is determined by the stresses during earth faults followed by recovery overvoltages on the a.c. bus.

AC filter arrester (FA1)

U_{ch}: 60 kV
Number of parallel columns: 2
Energy capability: 1,0 MJ

For the design of the arrester (FA1) the following values for the co-ordination currents are chosen:

SIPL = 158 kV at 2 kA
LIPL = 192 kV at 20 kA
RSIWV = 1,15 × 158 kV = 182 kV => SIWV = 200 kV
RLIWV = 1,20 × 192 kV = 230 kV => LIWV = 250 kV

AC filter arrester (FA2)

U_{ch}: 30 kV
Number of parallel columns: 2
Energy capability: 0,5 MJ

SIPL = 104 kV at 2 kA
LIPL = 120 kV at 10 kA
RSIWV = 1,15 × 104 kV = 120 kV => SIWV = 150 kV
RLIWV = 1,20 × 120 kV = 144 kV => LIWV = 150 kV

DC filter arrester (FD)

The operating voltage for the arresters consists mainly of harmonic voltages.

The rating of the arresters is determined by the stresses during transferred slow-front overvoltage with a subsequent earth fault on the d.c. bus.

DC filter arrester (FD1)

U_{ch}: 5 kV
Number of parallel columns: 2
Energy capability: 0,8 MJ

For the design of the arrester (FD1) the following values for the co-ordination currents are chosen:

SIPL = 136 kV at 2 kA
LIPL = 184 kV at 40 kA
RSIWV = 1,15 × 136 kV = 156 kV => SIWV = 200 kV
RLIWV = 1,20 × 184 kV = 221 kV => LIWV = 250 kV

DC filter arrester (FD2)

U_{ch}:	5 kV
Number of parallel columns:	2
Energy capability:	0,5 MJ

For the design of the arrester (FD2) the following values for the co-ordination currents are chosen:

SIPL = 104 kV at 2 kA
LIPL = 120 kV at 10 kA
RSIWV = 1,15 × 104 kV = 120 kV => SIWV = 150 kV
RLIWV = 1,20 × 120 kV = 144 kV => LIWV = 150 kV

B.4 Transformer valve side withstand voltages

B.4.1 Phase-to-phase

Since the converter transformer valve windings are not directly protected by a single arrester, the following two cases are considered:

- when the valves are conducting, the phase-to-phase insulation of the converter transformer valve side is protected by one valve arrester (V);
- when the valves are blocked, two valve arresters (V) are connected in series, phase-to-phase. During this event, the full transferred slow-front overvoltage will determine the maximum slow-front overvoltage.

SIPL = 512 kV (transferred slow-front voltage for CCC)
560 kV (transferred slow-front voltage for CSCC)
RSIWL = 1,15 × SIPL

SIWV = 650 kV
LIWV = 750 kV

If the two phases are in separate transformer units (single-phase, three-winding transformers) and under the assumption that the voltages are not equally shared, the specified insulation levels for the star-winding have been selected to be:

SIWV = 550 kV
LIWV = 650 kV

B.4.2 Upper bridge transformer phase-to-earth (star)

The phase-to-earth insulation of the transformer and converters are determined by additive slow-front overvoltages between the transformer phases during the conducting status. Thus, slow-front overvoltages originating from the a.c. side are limited by the arrester (A) on the primary side of the converter transformer. This additive method is not possible in the non-conducting status of the thyristor valves. Therefore only the 'conducting' status needs to be considered.

SIPL = 976 kV for CCC (2 × SIPL of arrester (V2), see Figure B.3a) assuming no current in the neutral arrester)
962 kV for CSCC (2 × SIPL of arrester (V2), see Figure B.3b) assuming no current in the neutral arrester)
RSIWV = 1,15 × SIPL => SIWV = 1 175 kV
LIWV = 1 300 kV

B.4.3 Lower bridge transformer phase-to-earth (delta)

The specified insulation levels are the same as phase-to-phase, assuming no current in the neutral arrester.

SIWV = 650 kV
LIWV = 750 kV

B.5 Air-insulated smoothing reactors withstand voltages

B.5.1 Slow-front terminal-to-terminal overvoltages

The worst case for the stresses between the terminals of smoothing reactors is given by the slow-front overvoltages on the d.c. side, which is limited by the arrester (DL). Assuming opposite polarity to the d.c. voltage, the total voltage will be:

SIPL of arrester (DL):	866 kV	
Maximum d.c. voltage:	500 kV	
Sum of both voltages:	1 366 kV	
Smoothing reactors:	225 mH	
Transformer inductances (four phases):	140 mH	(4 × 35 mH)
Total inductance:	365 mH	

One 225 mH smoothing reactor
Voltage between terminals: 1 366 kV × (225 mH/365 mH) = 842 kV

SIPL = 842 kV
RSIWV = 1,15 × 842 kV = 968 kV =>

The maximum fast-front overvoltages between terminals are determined by the relative ratio of the capacitance across the reactor to the capacitance to earth on the valve side of the reactor. The specified lightning withstand voltage is:

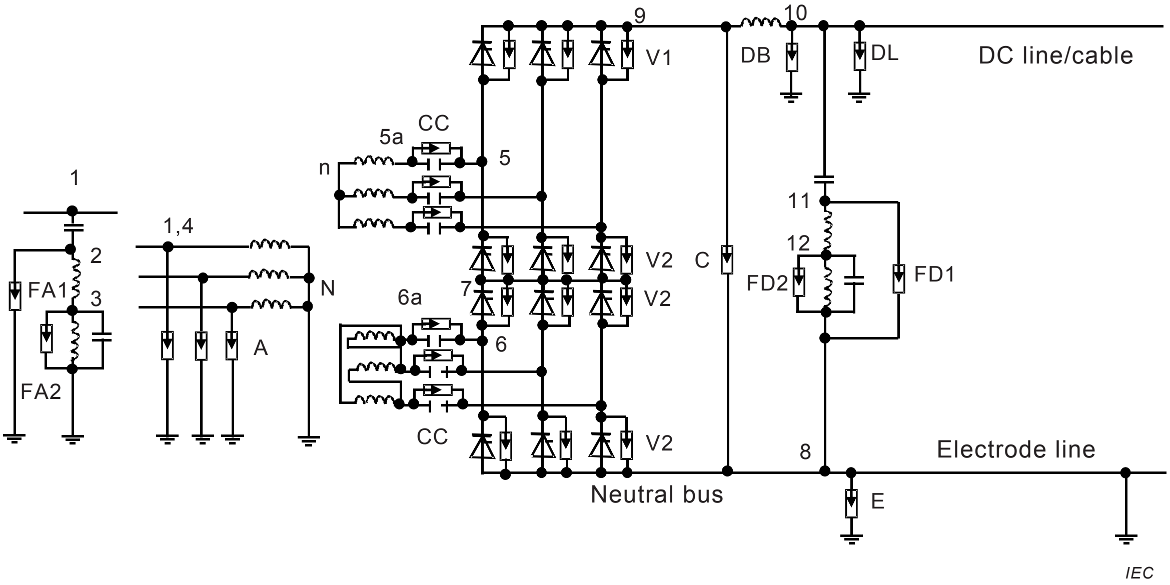
SIWV = 1 175 kV
LIWV = 1 300 kV

B.5.2 Terminal-to-earth

The specified insulation levels are the same as for the arresters (C) or (DL):

SIWV = 1 175 kV
LIWV = 1 300 kV

B.6 Results

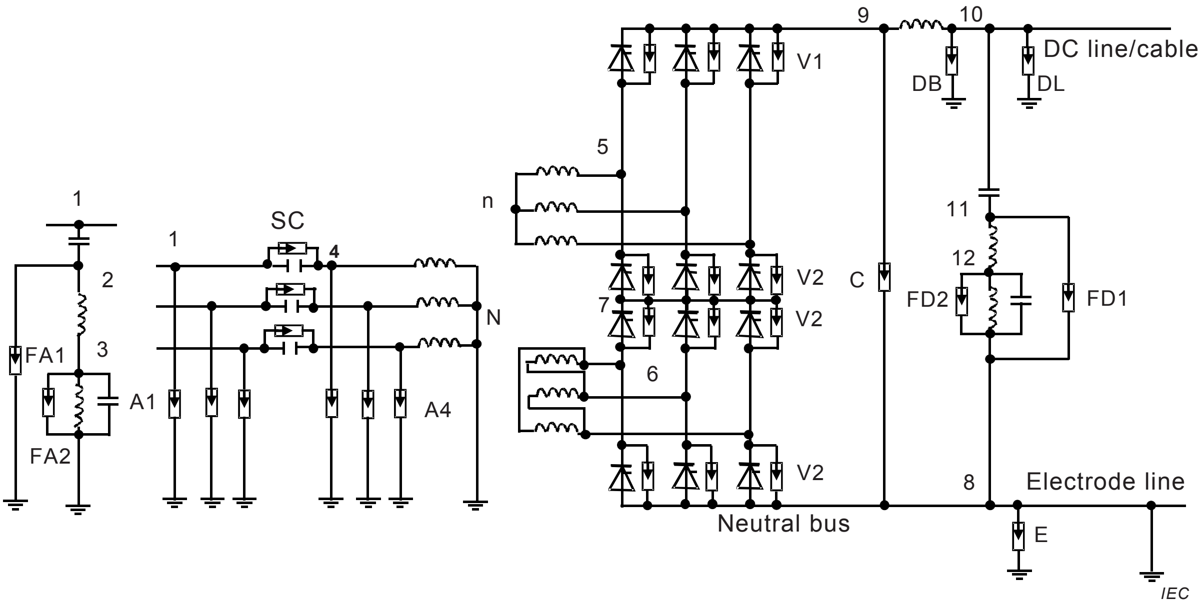


Arrester type		A	V1	V2	C	DB	DL	E	FD1	FD2	FA1	FA2	CC
U_{ch} or CCOV	kV	243 r.m.s.	308 peak	308 peak	558 d.c.	515 d.c.	515 d.c.	30 d.c.	5 d.c.	5 d.c.	60 r.m.s.	30 r.m.s.	60 peak
Lightning													
– protection level	kV	713	-	-	1 048	977	872	88	184	120	192	120	172
– at current	kA	10	-	-	2,5	5	5	10	40	10	20	10	10
Switching													
– protection level	kV	632	523	488	930	866	807	78	136	104	158	104	149
– at current	kA	1,5	1,8	0,1	0,5	1,0	1,0	2,0	2,0	2,0	2,0	2,0	7,8
Number of columns	-	2	4	2	1	1	8	2	2	2	2	2	8
Energy capability	MJ	9,2	5,2	2,6	2,5	2,2	17,0	0,4	0,8	0,5	1,0	0,5	4,0

Protection location	1	2	3	4	5	6	7	8	9	10	11	12
U_{ch} (kV)	243	60	30	243	558	308	308	30	558	515	15	15
LIPL = RFFO (kV)	713	192	120	713	-	-	-	88	1 048	977	184	120
SIPL = RSFO (kV)	632	158	104	632	976	523	523	78	930	866	136	104
LIWV (kV)	1 425	250	150	1 425	1 300	750	750	150	1 300	1 300	250	150
SIWV (kV)	1 050	200	150	1 050	1 175	650	650	150	1 175	1 175	200	150

Protection location	1-2	2-3	5-5a CCC	5 and 6 ph-ph	5-6	8-9	9-10	10-11	11-12	Valves V1 and V2
LIPL = RFFO (kV)	825	192	172	-	-	1 048	-	977	184	-
SIPL = RSFO (kV)	747	158	149	523	976	930	842	866	136	523
LIWV (kV)	1 300	250	250	750	1 300	1 300	1 300	1 300	250	-
SIWV (kV)	1 050	200	200	650	1 175	1 175	1 175	1 175	200	605

a) AC and d.c. arresters for CCC



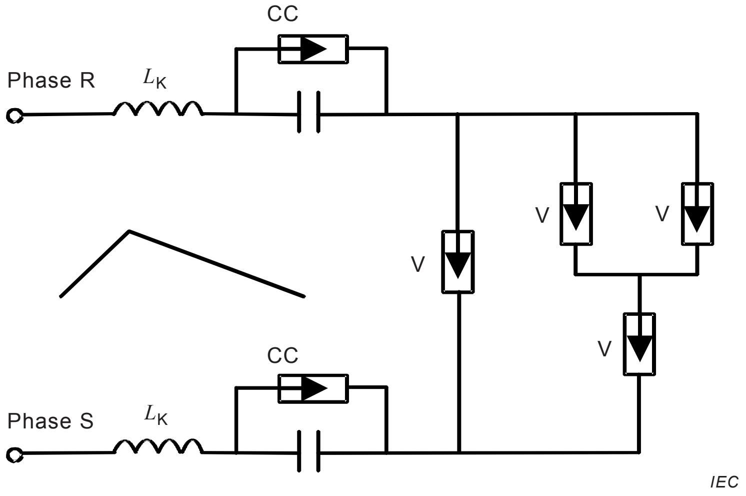
Arrester type		A	V1	V2	C	DB	DL	E	FD1	FD2	FA1	FA2	CSC	A4
U_{ch} or CCOV	kV	243 r.m.s.	294 peak	294 peak	558 d.c.	515 d.c.	515 d.c.	30 d.c.	5 d.c.	5 d.c.	60 r.m.s.	30 r.m.s.	96 r.m.s.	256 r.m.s.
Lightning														
- protection level	kV	713	-	-	1 048	977	872	88	184	120	192	120	250	790
- at current	kA	10	-	-	2,5	5	5	10	40	10	20	10	10	10
Switching														
- protection level	kV	632	499	481	930	866	807	78	136	104	158	104	207	690
- at current	kA	1,5	2,2	0,5	0,5	1,0	1,0	2,0	2,0	2,0	2,0	2,0	8,8	1,5
No. of columns	-	2	4	2	1	1	8	2	2	2	2	2	6	2
Energy capability	MJ	9,2	5,2	2,6	2,5	2,2	17,0	0,4	0,8	0,5	1,0	0,5	4,0	3,4

Protection location	1	2	3	4	5	6	7	8	9	10	11	12
U_{ch} (kV)	243	60	30	256	558	294	294	30	558	515	15	15
LIPL = RFFO (kV)	713	192	120	790	-	-	-	88	1 048	977	184	120
SIPL= RSFO (kV)	632	158	104	690	962	499	499	78	930	866	136	104
LIWV (kV)	1 425	250	150	1 425	1 300	750	750	150	1 300	1 300	250	150
SIWV (kV)	1 050	200	150	1 050	1 175	650	650	150	1 175	1 175	200	150

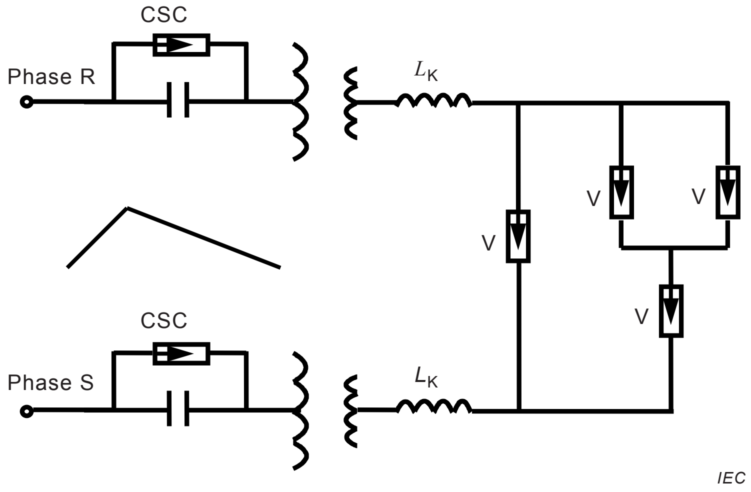
Protection location	1 – 2	2 – 3	1-4 CSC	5 and 6 ph-ph	5-6	8-9	9-10	10-11	11-12	Valves V1 and V2
LIPL = RFFO (kV)	825	192	250	-	-	1 048	-	977	184	-
SIPL= RSFO (kV)	747	158	207	523	962	930	842	866	136	523
LIWV (kV)	1 300	250	300	750	1 300	1 300	1 300	1 300	250	-
SIWV (kV)	1 050	200	250	650	1 175	1 175	1 175	1 175	200	605

b) AC and d.c. arresters for CSCC

Figure B.1 – AC and d.c. arresters for CCC and CSCC converters



a) Valve arrester stresses for slow-front overvoltages from a.c. side (CCC converter)

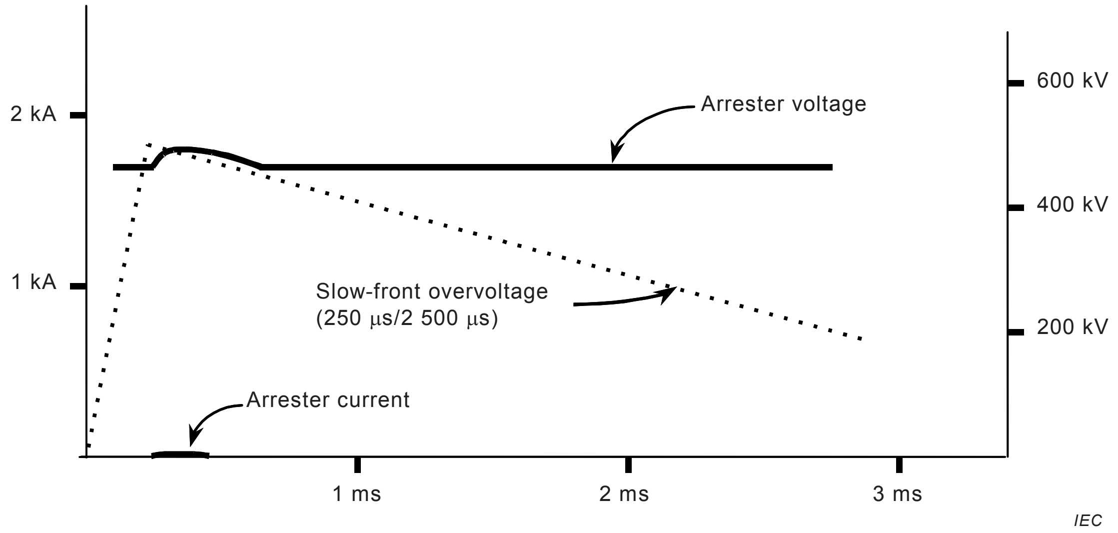


b) Valve arrester stresses for slow-front overvoltages from a.c. side (CSCC converter)

Figure B.2 – Valve arrester stresses for slow-front overvoltages from a.c. side

Stresses on arrester:

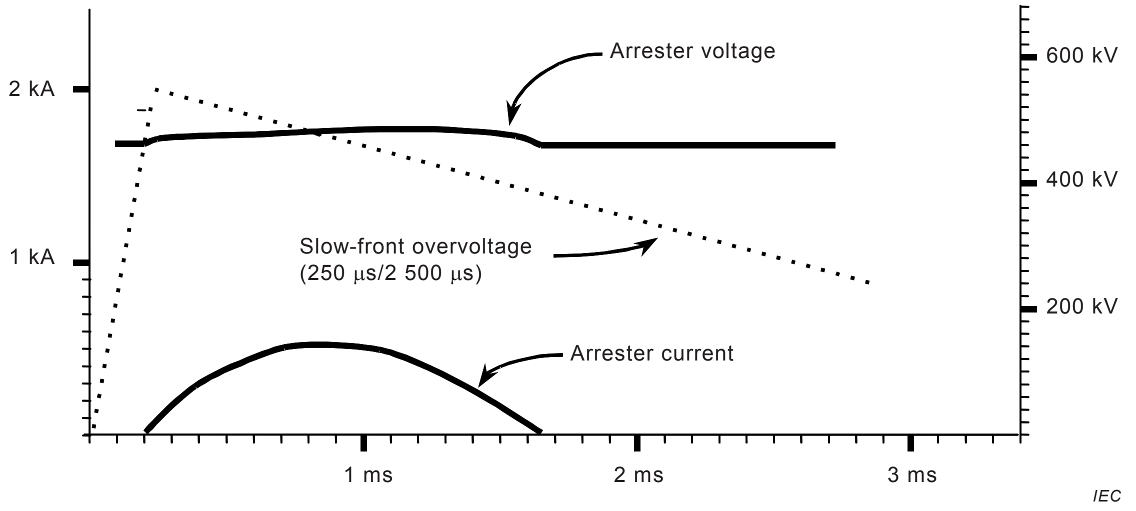
$U_{max.}$ = 488 kV $I_{max.}$ = 0,04 kA Energy = 1,9 kJ



a) Arrester V2 stress for slow-front overvoltage from a.c. side (CCC converter)

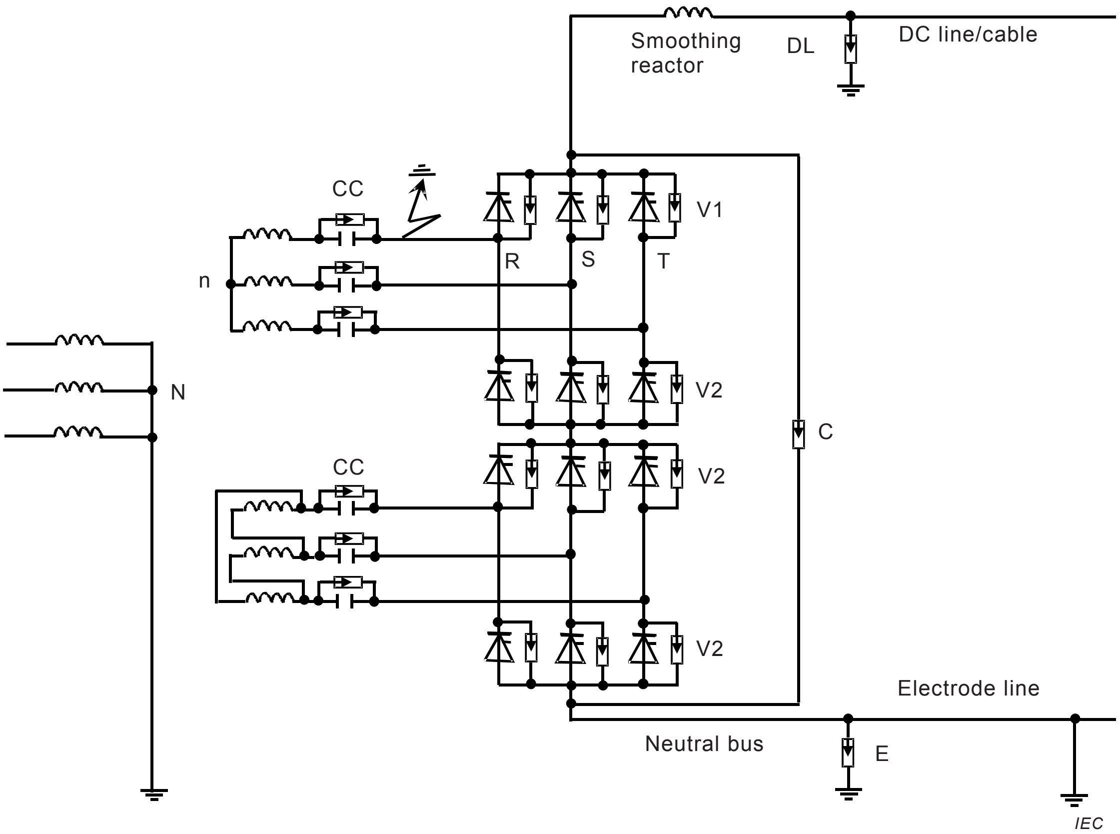
Stresses on arrester:

$U_{max.}$ = 481 kV $I_{max.}$ = 0,47 kA Energy = 223 kJ



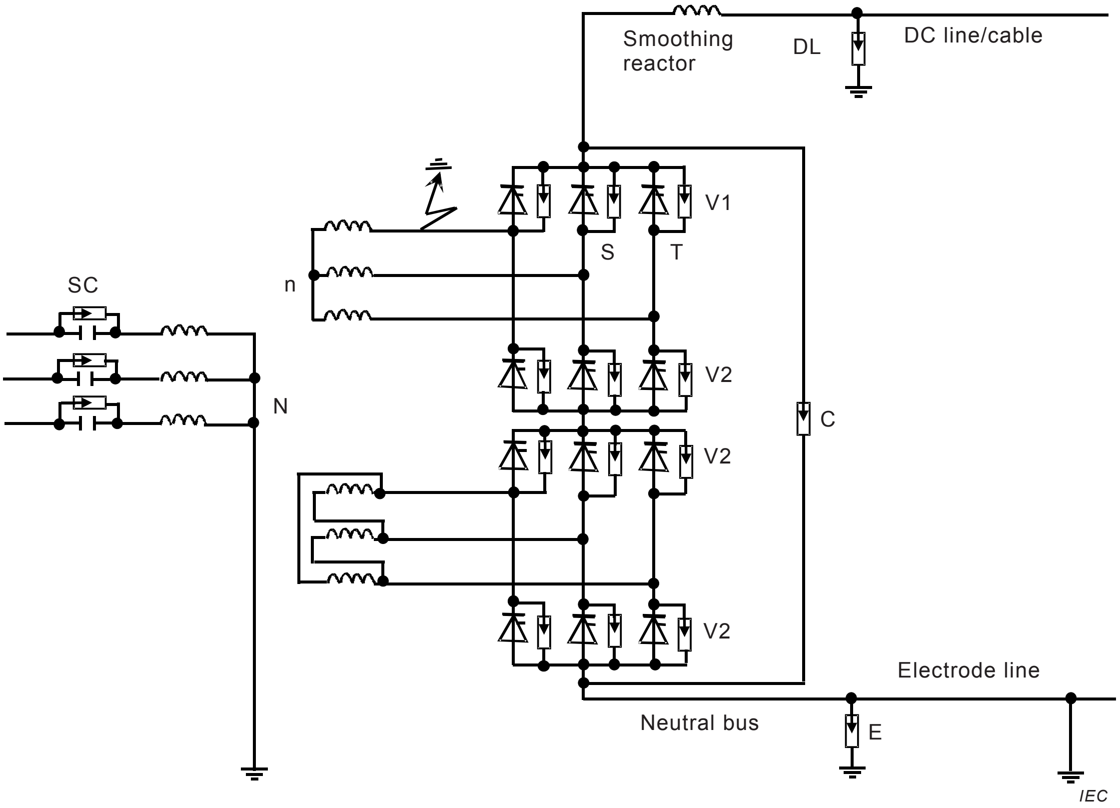
b) Arrester V2 stress for slow-front overvoltage from a.c. side (CSCC converter)

Figure B.3 – Arrester V2 stress for slow-front overvoltage from a.c. side



NOTE The stray capacitances are not shown, but they are design dependent.

a) Valve arrester stresses for earth fault between valve and upper bridge transformer bushing (CCC converter)



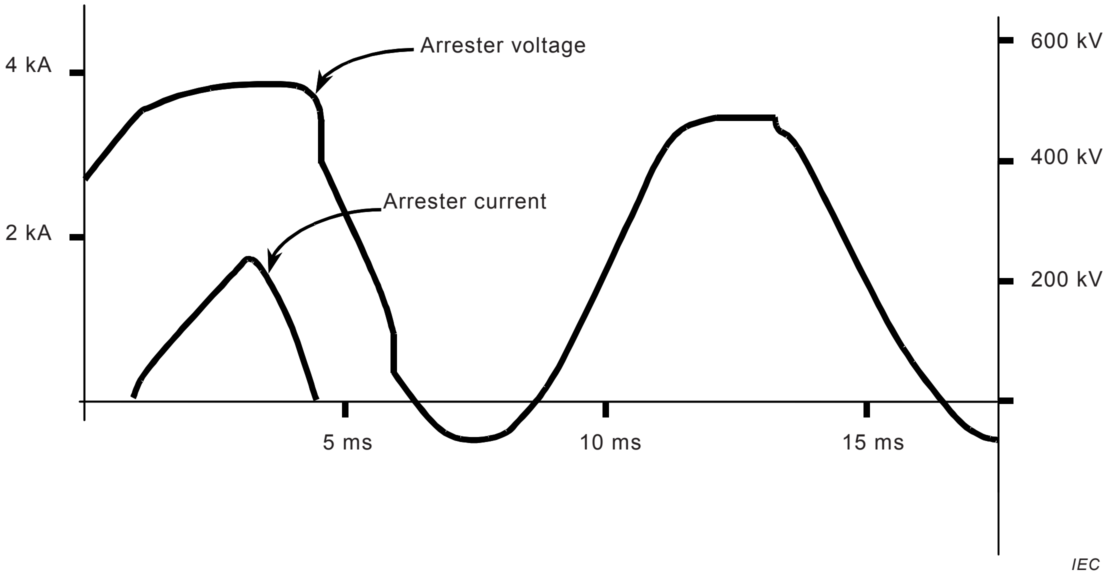
NOTE The stray capacitances are not shown, but they are design dependent.

b) Valve arrester stresses for earth fault between valve and upper bridge transformer bushing (CSCC converter)

Figure B.4 – Valve arrester stresses for earth fault between valve and upper bridge transformer bushing

Stresses on arrester:

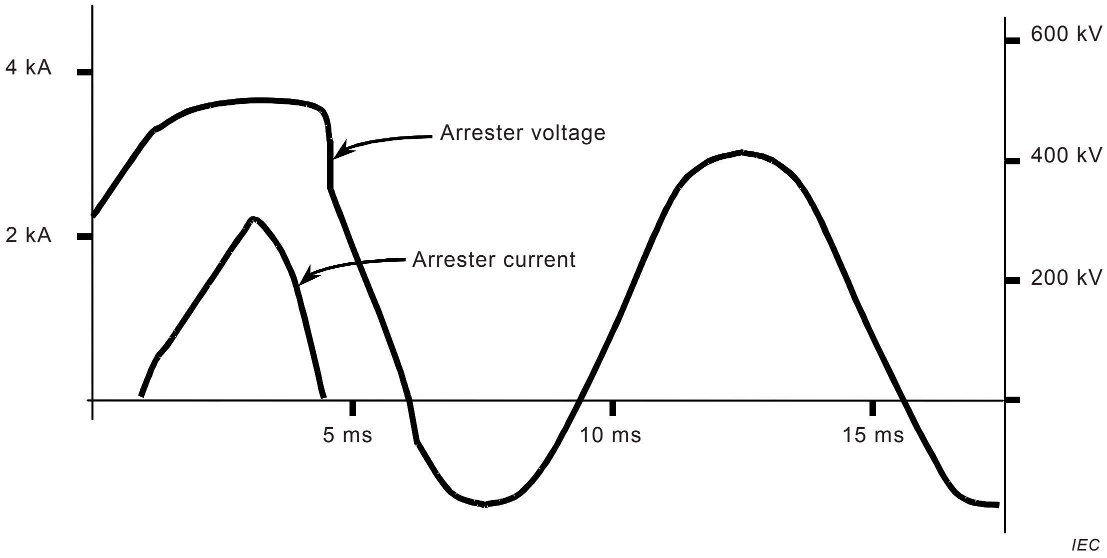
$U_{max.}$ = 524 kV $I_{max.}$ = 1,78 kA Energy = 3 690 kJ



a) Arrester V1 stress for earth fault between valve and upper bridge transformer bushing (CCC converter)

Stresses on arrester:

$U_{max.}$ = 499 kV $I_{max.}$ = 2,24 kA Energy = 4 309 kJ

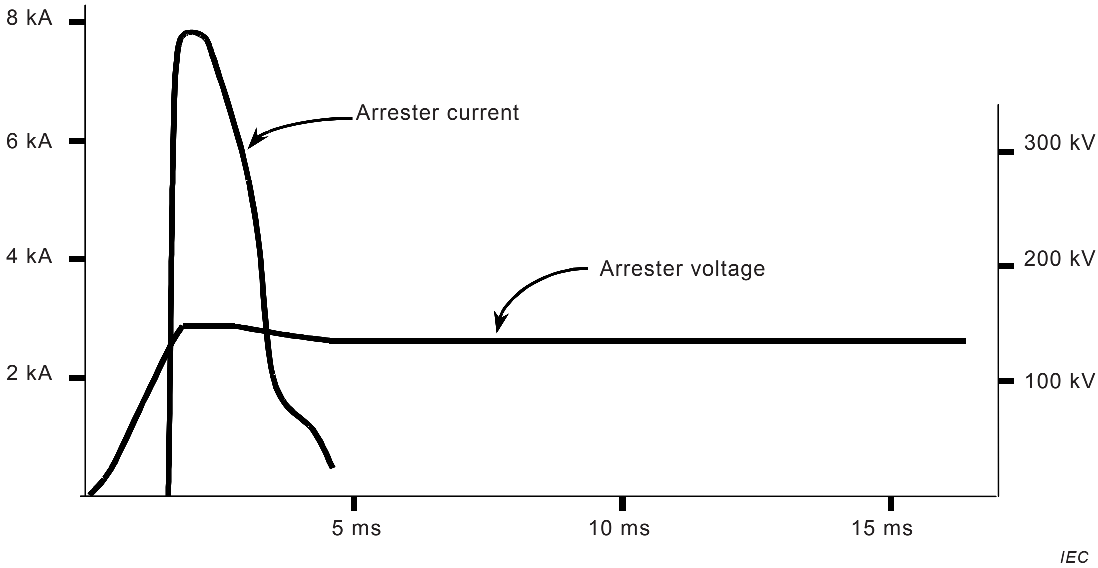


b) Arrester V1 stress for earth fault between valve and upper bridge transformer bushing (CSCC converter)

Figure B.5 – Arrester V1 stress for earth fault between valve and upper bridge transformer bushing

Stresses on arrester:

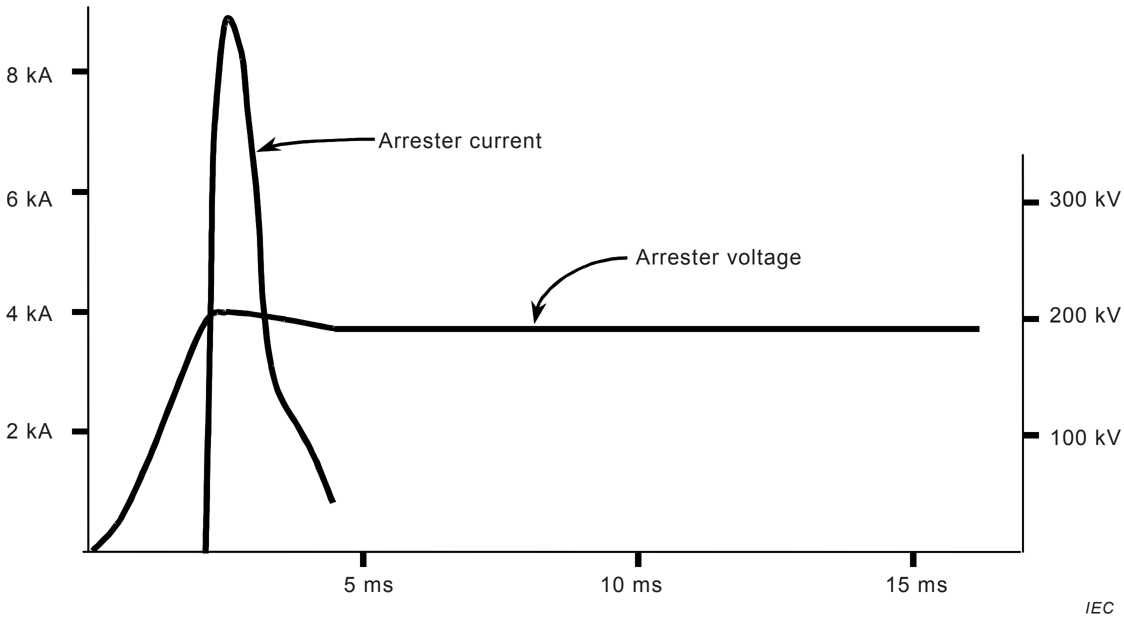
$U_{\text{max.}}$ = 149 kV $I_{\text{max.}}$ = 7,81 kA Energy = 3 687 kJ



a) CCC capacitor arrester stress C_{CC} during earth fault between valve and upper bridge transformer bushing (CCC converter)

Stresses on arrester:

$U_{\text{max.}}$ = 207 kV $I_{\text{max.}}$ = 8,84 kA Energy = 3 866 kJ



b) CSCC capacitor arrester stress C_{SC} during earth fault between valve and upper bridge transformer bushing (CSCC converter)

Figure B.6 – Stresses on capacitor arresters C_{cc} and C_{sc} during earth fault between valve and upper bridge transformer bushing

Annex C
(informative)

Considerations for insulation co-ordination of some special converter configurations

C.1 Procedure for insulation co-ordination of back-to-back type of HVDC links

In back-to-back d.c. links the two converter terminals (rectifier and inverter) are located in the same station, with all the valves accommodated in one building. The procedures for insulation co-ordination of this type of d.c. link are, however, similar to those for the schemes involving d.c. line or cable. The influence of one converter terminal on the other should be taken into account in evaluating the arrester requirements, maximum overvoltages and other aspects for the various fault events as discussed in Clause 8.

For this evaluation, appropriate parts of both terminals should be included when necessary in the circuits being modeled for the studies.

The effects of any transfer of overvoltages due to fast-front and steep-front overvoltages from one terminal to the other should similarly be included in the studies, taking account of the inductance and capacitance of the smoothing reactor, if present. These effects have been found to be small in existing back-to-back schemes, whether the smoothing reactor is absent or present, because the effective d.c. circuit between the valve windings of the two terminals includes the effect of presence of the inductances and capacitances of these transformer windings.

C.2 Procedure for insulation co-ordination of parallel valve groups

C.2.1 General

Parallel valve groups are encountered when new converter stations are being designed, or if an existing converter station is being expanded by the addition of a second valve group to be connected in parallel. The procedure to be followed in insulation co-ordination of such converter stations, shown in Figure C.1, follows the method explained for the conventional single valve group stations as explained in Clause 8.

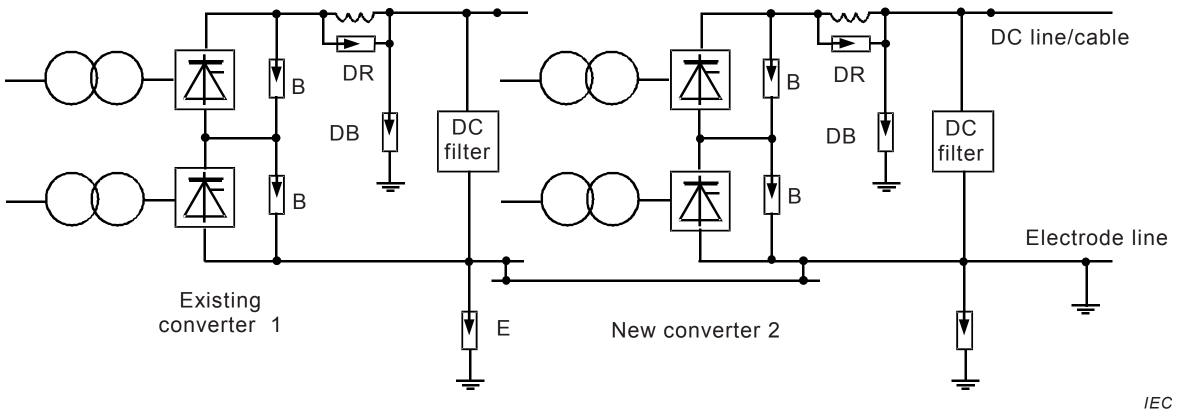


Figure C.1 – Expanded HVDC converter with parallel valve groups

All arresters, including possible arresters across the smoothing reactors, shall be co-ordinated with the arresters of converter 2. In C.2.2 to C.2.12, different aspects are addressed for the different arresters when an existing station is expanded by the addition of a parallel converter 2.

C.2.2 AC bus arrester (A)

The protective level of the expansion a.c. bus arresters shall be lower than the existing one with sufficient safety margin. In this case, the existing a.c. bus arresters will not be overstressed. However, the new a.c. bus arrester shall be designed for the worst case of fault clearing, followed by the recovery saturation overvoltages and overvoltages due to load rejection. In some cases, the best technical solution can be to replace the existing a.c. bus arrester in order to obtain better energy sharing on both existing and expansion schemes.

C.2.3 AC filter arrester (FA)

Where low order filters are used in the existing schemes, the arresters of these filters may be overstressed due to higher magnitudes of the low order harmonics during parallel operation. These arresters may be replaced, otherwise no impact on existing arresters is expected.

C.2.4 Valve arrester (V)

The most critical case for the valve arrester during parallel operation is the earth fault on the valve side converter transformer of the bridge with the highest d.c. potential. In this case, the current supplied for the other healthy parallel converter group will increase the stresses of the valve arrester. Protective actions may be needed to avoid overstresses of the valve arrester. This is valid only for the valve arresters protecting the three-pulse commutating group on the highest potential. All other valve arresters may be designed as described in subclause 8.3.5.

C.2.5 Bridge arrester (B) and converter unit arrester (C)

These arresters may be overstressed during earth faults on the existing converter pole. In this case, they may need to be replaced.

C.2.6 Mid-point arrester (M)

This arrester may be overstressed during by-pass operation of the valve group above this arrester. In this case it may need to be replaced.

C.2.7 Converter unit d.c. bus arrester (CB)

The existing arrester is not affected by the parallel operation.

C.2.8 DC bus and d.c. line/cable arrester (DB and DL)

The existing arresters are not affected by the parallel operation.

C.2.9 Neutral bus arrester (E)

The protection level of the new neutral bus arrester shall be lower than the existing one. In this case the existing neutral bus arrester will not be overstressed. However, the new neutral bus arrester shall be designed for all fault cases given in 8.3.11 at this lower protective level.

C.2.10 DC reactor arrester (DR)

If used, the reactor arrester will be affected during earth faults due to higher fault currents. However, this will only influence the protective level for the existing reactor and not the energy. This increase may be covered by the protective margins of this reactor.

C.2.11 DC filter arrester (FD)

Where existing d.c. filters are to be retained, the insulation co-ordination of the existing d.c. filter shall be checked, particularly during earth faults within the d.c. filter branches. The new d.c. filter arrester may be designed according to 8.3.13.

C.2.12 New converter stations with parallel valve groups

The above considerations apply even if the existing converter is equipped with gapped arresters and is to be connected in parallel with a new one employing metal-oxide arresters.

The same considerations also apply if both converter stations are being newly designed.

C.3 Procedure for insulation co-ordination of upgrading existing systems with series-connected valve groups

C.3.1 General

The insulation co-ordination of converter stations with two 12-pulse series connected valve groups follows the general procedure explained in Clause 8 for the conventional single 12-pulse valve group station; however, special precautions apply for the by-pass operation in the inverter (7.4.3 and 7.5.3).

The insulation co-ordination of an existing station to be upgraded with the addition of a series valve group as illustrated in Figure C.2 is outlined below.

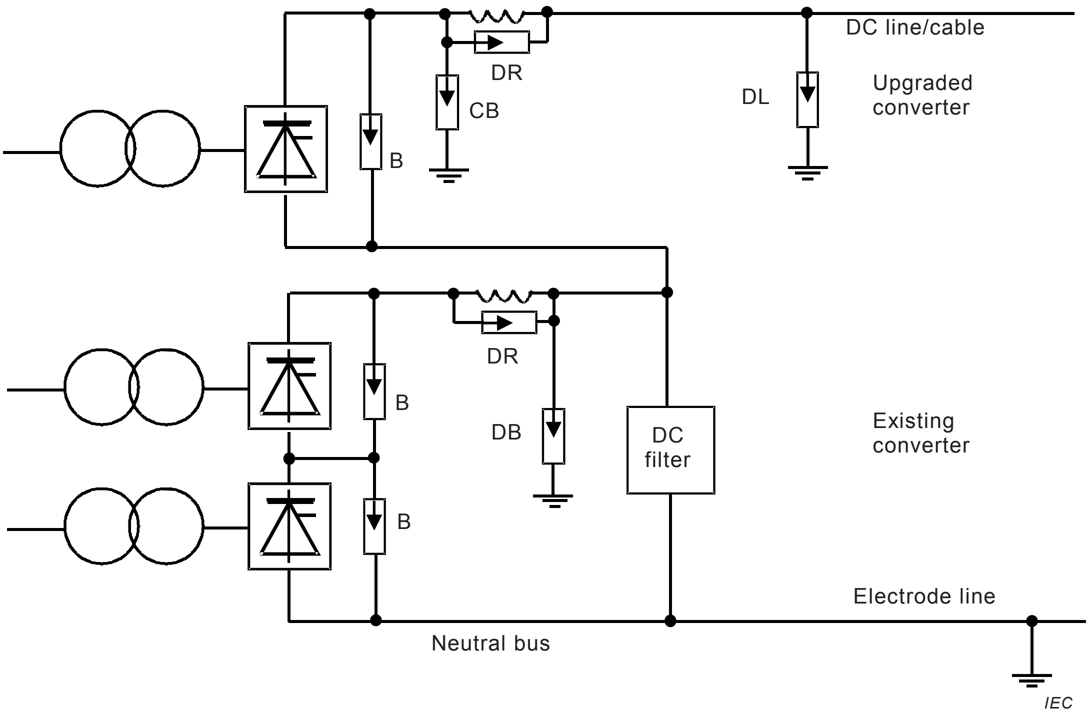


Figure C.2 – Upgraded HVDC converter with series valve group

All arresters of the new converters shall be co-ordinated with all arresters of the existing converters. In C.3.2 to C.3.10, different aspects are addressed for the new arresters as well as for the impact on the existing arresters. If any of the existing pole equipment is to be retained, the adequacy of its insulation shall be evaluated.

C.3.2 AC bus arrester (A)

The protective level of the new a.c. bus arresters shall be lower than the existing one with a sufficient safety margin. In this case, the existing a.c. bus arresters will not be overstressed. However, the new a.c. bus arrester shall be designed for the worst case of fault clearing, followed by the recovery saturation overvoltages and overvoltages due to load rejection. In some cases the best technical solution can be to replace the existing a.c. bus arrester in order to obtain better energy sharing on both the existing and the new converter.

C.3.3 AC filter arrester (FA)

Where low order filters are used in the existing schemes, the arresters of these filters may be overstressed due to higher magnitudes of the low order harmonics. These arresters may be replaced, otherwise no impact on existing a.c. filter arresters is expected.

C.3.4 Valve arrester (V)

For the existing valve arrester no impact is expected. The valve arresters of the new converter may be designed as described in 8.3.5.

C.3.5 Bridge arrester (B) and converter unit arrester (C)

These arresters may be overstressed during earth faults on the existing converter pole. In this case, they may need to be replaced.

C.3.6 Mid-point arrester (M)

This arrester may be overstressed during by-pass operation of the valve group above this arrester. In this case it may need to be replaced.

C.3.7 Converter unit d.c. bus arrester (CB), d.c. bus and d.c. line/cable arrester (DB and DL)

The existing arrester may be overstressed during by-pass operation of the new converter unit. In this case, the arresters shall be replaced. New arresters designed according to 8.3.9 and 8.3.10 should be placed on the upgraded d.c. bus.

C.3.8 Neutral bus arrester (E)

The existing arrester may need to be replaced due to the higher stresses at upgrading. The new neutral bus arrester should be designed for all fault cases given in 8.3.11.

C.3.9 DC reactor arrester (DR)

If used, the reactor arrester will be affected during earth faults due to higher fault currents. However, this will influence only the protective level for the existing reactor and not the energy. This increase may be covered by the protective margins of this reactor.

C.3.10 DC filter arrester (FD)

Where existing d.c. filters are to be retained, the insulation co-ordination of the existing d.c. filter shall be checked, particularly during earth faults within the d.c. filter branches. The new d.c. filter arrester may be designed according to 8.3.13.

Procedure for insulation co-ordination of a.c. side in cases where a.c. filters are on a tertiary winding of the converter transformer

In some schemes, particularly in back-to-back links, all or part of the a.c. line side filters are connected to a tertiary low-voltage winding of the converter transformer in order to permit less expensive, lower voltage filtering equipment and associated circuit breakers or switches to be employed. The procedures for insulation co-ordination are no different for this case compared with the case where all the filters are on the a.c. line side of the transformer. System studies should include suitable models of the transformer, including its saturation; moreover, fault events and arresters on the tertiary winding should be included in the studies. When tertiary winding is delta-connected, tertiary-side arresters connected phase-to-phase as well as phase-to-earth may be incorporated in the arrester scheme, but these are readily studied and selected using similar procedures as for the a.c. line side filters. In some schemes the arresters may also be employed as temporary over-voltage limiters after full or partial load rejection until the filters are disconnected and the arresters are then assigned appropriate ratings based on studies.

C.4 Overvoltages in the a.c. network due to closely coupled HVDC links

HVDC links may be closely coupled when there are multiple d.c. infeeds at the same a.c. station or when converter terminals of two different d.c. schemes are connected to a.c. substations located a short distance apart, e.g. 20 km or 30 km.

Disturbances in one d.c. scheme, including full or partial load rejection, can produce overvoltages experienced at the converter station of the other d.c. scheme. AC system fault events can, in such cases, produce overvoltages at both stations which, even for the same a.c. system conditions, are more severe than when only one d.c. scheme is operating. The arresters on the a.c. line side of such adjacent converter terminals, their protective levels and corresponding co-ordination current, should then be co-ordinated so that their duties are shared appropriately. The saturation characteristics and parameters of all transformers connected to the a.c. busbars at both converter stations, together with the appropriate minimum short-circuit power of the a.c. network, should be modeled adequately for the worst possible event. The detailed procedures for insulation co-ordination, however, remain the same as in the case of a single d.c. scheme.

C.5 Effect of gas-insulated switchgear on insulation co-ordination of HVDC converter stations

Some HVDC converter stations are located near the seashore for connection with the route of submarine cables. For those stations, countermeasures for salt contamination should be taken into special consideration. Rapid and heavy salt contamination caused by storms or typhoons may also need to be taken into account. For some other HVDC converter stations, it is difficult to obtain sufficient space to install station equipment. Application of gas-insulated switchgear (GIS) for the HVDC converter station can be effective to help solve the pollution problems, to make the equipment compact and to reduce the converter station area.

The GIS can be used on the a.c. side and/or d.c. side of the converter. The GIS on the a.c. side (AC-GIS) is substantially identical with the GIS for the ordinary a.c. substation; the AC-GIS usually involves circuit breakers, line switches, a.c. bus arresters and voltage and current transducers.

The typical GIS on the d.c. side (DC-GIS) is composed of disconnecting switches for the d.c. main bus, circuit breakers as by-pass pair switches and for metallic neutral bus protection, d.c. bus arresters and voltage and current transducers. For the DC-GIS, countermeasures for levitation of conductive particles from the inner surface of the enclosure and charge accumulation on the surface of the insulating spacer, both caused by the d.c. electric field, are usually taken into consideration.

The waveshape, peak value and duration of the overvoltages generated in the HVDC converter station with the GIS are usually not different from those in the station with the air-insulated switchgear. In general, special consideration of the effect of the GIS on the insulation co-ordination of the station is not necessary.

In a GIS-equipped HVDC converter station, when the gas-insulated disconnecting switch is closed, an oscillating voltage with a high frequency of several hundred kilohertz to several megahertz may be generated from the GIS. In particular, the oscillating voltage may transfer directly to the converter with little attenuation. This type of voltage has a certain low peak value, and in this sense, is not an “overvoltage”. However, special consideration should be taken because its dv/dt rate may exceed the tolerable value for the thyristor valves. The typical countermeasure is to provide a resistor for the disconnecting switch, and to insert the resistor before closing the disconnecting switch.

The voltage and current characteristic of the arrester in a GIS is usually not different from that of the arrester in air. The characteristic of the arrester in the SF_6 gas may have little deterioration, unlike the arrester installed in the air which may be affected by the pollution on the surface of the bushing.

In order to determine the test voltage of the DC-GIS, the dielectric performance in the SF_6 gas for various types of overvoltages should be taken into consideration. The characteristic relating the peak withstand voltage in air versus the time to reach the peak value has generally a steep negative dv/dt rate in the time range corresponding to the lightning impulse, while the characteristic in the SF_6 gas is relatively flat in all time ranges. The overvoltages with DC-GIS can be obtained by the same study tools, for example, numerical transient analysis programs. For the DC-GIS, d.c. overvoltage, d.c. overvoltage with polarity reversal, as well as fast-front, slow-front and other overvoltages should be taken into account.

Annex D
(informative)

Typical arrester characteristics

Figure D.1 presents a typical gapless metal oxide arrester characteristics used in insulation co-ordination studies. The x-axis represent the co-ordinating current in amperes and the y-axis presents the protective voltage in p.u. of the 10 kA fast-front protective value.

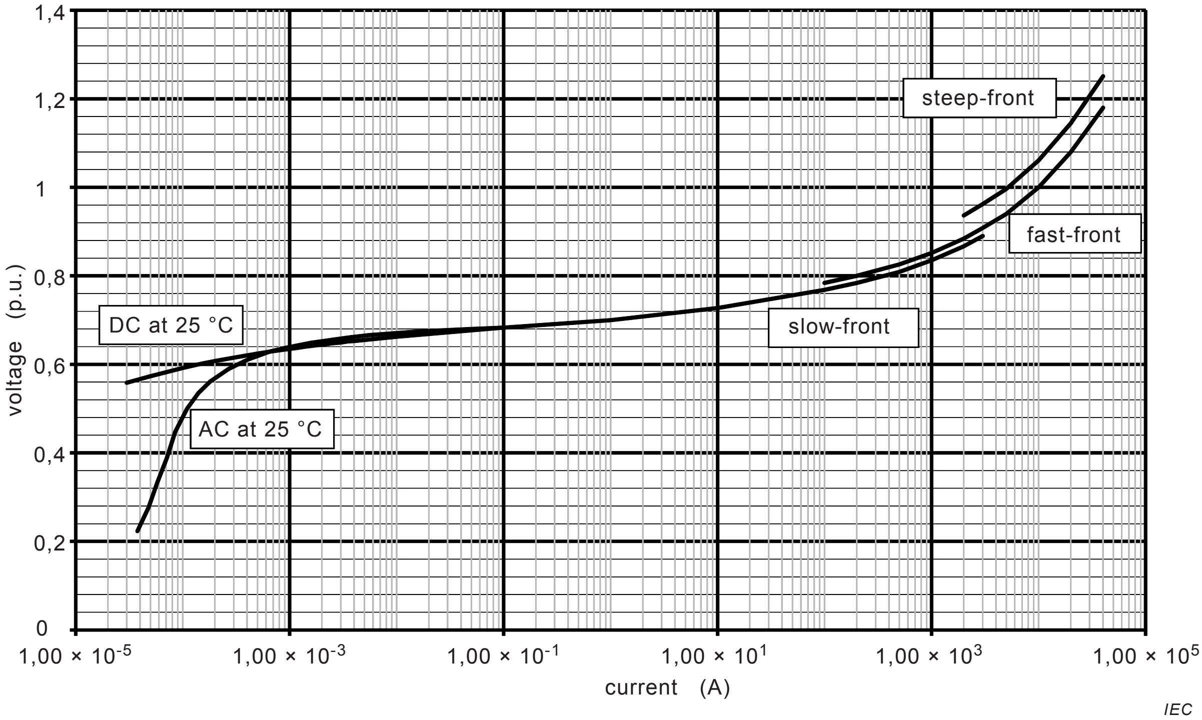


Figure D.1 – Typical arrester V-I characteristics

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