

BS EN 60099-5:2013



BSI Standards Publication

Surge arresters

Part 5: Selection and application
recommendations

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National foreword

This British Standard is the UK implementation of EN 60099-5:2013. It is identical to IEC 60099-5:2013. It supersedes BS EN 60099-5:1997 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee PEL/37, Surge Arresters - High Voltage.

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

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Anwendung
(IEC 60099-5:2013)

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Foreword

The text of document 37/405/FDIS, future edition 2 of IEC 60099-5, prepared by IEC/TC 37 "Surge arresters" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 60099-5:2013.

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) 2014-03-26
- latest date by which the national standards conflicting with the document have to be withdrawn (dow) 2016-06-26

This document supersedes EN 60099-5:1996 + A1:1999.

EN 60099-5:2013 includes the following significant technical changes with respect to EN 60099-5:1996 + A1:1999:

- a) Expanded discussion of different types of arresters and their application, including additions of discussion on
 - transmission of line arresters,
 - arresters for shunt capacitor switching,
 - arresters for series capacitor protection,
 - application of arresters between phases,
 - connecting arresters in parallel.
- b) Addition of section on asset management, including
 - managing surge arresters in the power grid,
 - arrester maintenance,
 - significantly expanded discussion of performance diagnostic tools,
 - end-of-life considerations.
- c) New annexes dealing with
 - arrester modelling for system studies,
 - example of data needed for specifying arresters.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC [and/or CEN] shall not be held responsible for identifying any or all such patent rights.

Endorsement notice

The text of the International Standard IEC 60099-5:2013 was approved by CENELEC as a European Standard without any modification.

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 When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

<u>Publication</u>	<u>Year</u>	<u>Title</u>	<u>EN/HD</u>	<u>Year</u>
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/TR 60071-4	-	Insulation co-ordination - Part 4: Computational guide to insulation co-ordination and modelling of electrical networks	-	-
IEC 60099-4 (mod) + A1 + A2	2004 2006 2009	Surge arresters - Part 4: Metal-oxide surge arresters without gaps for a.c. systems	EN 60099-4 + A1 + A2	2004 2006 2009
IEC 60099-6	2002	Surge arresters - Part 6: Surge arresters containing both series and parallel gapped structures - Rated 52 kV and less	-	-
IEC 60099-8	2011	Surge arresters - Part 8: Metal-oxide surge arresters with external series gap (EGLA) for overhead transmission and distribution lines of a.c. systems above 1 kV	EN 60099-8	2011
IEC 60507	-	Artificial pollution tests on high-voltage insulators to be used on a.c. systems	EN 60507	-
IEC/TS 60815-1	-	Selection and dimensioning of high-voltage insulators intended for use in polluted conditions - Part 1: Definitions, information and general principles	-	-
IEC/TS 60815-2	-	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	-	Selection and dimensioning of high-voltage insulators intended for use in polluted conditions - Part 3: Polymer insulators for a.c. systems	-	-
IEC 62271-1	-	High-voltage switchgear and controlgear - Part 1: Common specifications	EN 62271-1	-

<u>Publication</u>	<u>Year</u>	<u>Title</u>	<u>EN/HD</u>	<u>Year</u>
IEC 62271-200	-	High-voltage switchgear and controlgear - Part 200: AC metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV	EN 62271-200	-
IEC 62271-203	-	High-voltage switchgear and controlgear - Part 203: Gas-insulated metal-enclosed switchgear for rated voltages above 52 kV	EN 62271-203	-

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SURGE ARRESTERS –

Part 5: Selection and application recommendations

1 Scope

This part of IEC 60099 is not a mandatory standard but provides information, guidance, and recommendations for the selection and application of surge arresters to be used in three-phase systems with nominal voltages above 1 kV. It applies to gapless metal-oxide surge arresters as defined in IEC 60099-4, to surge arresters containing both series and parallel gapped structure – rated 52 kV and less as defined in IEC 60099-6 and metal-oxide surge arresters with external series gap for overhead transmission and distribution lines (EGLA) as defined in IEC 60099-8. In Annex H, some aspects regarding the old type of SiC gapped arresters are discussed.

The principle of insulation coordination for an electricity system is given in IEC 60071 and IEC 60071-2 standards. Basically the insulation coordination process is a risk management aiming to ensure the safe, reliable and economic design and operation of high voltage electricity networks and substations. The use of surge arrester helps to achieve a system and equipment insulation level and still maintaining an acceptable risk and the best economic of scale.

The introduction of analytical modelling and simulation of power system transients further optimise the equipment insulation level. The selection of surge arresters has become more and more important in the power system design and operation. It is worthwhile to note that the reliability of the power system and equipment is dependent on the safety margin adopted by the user in the design and selection of the equipments and surge arresters.

Surge arrester residual voltage is a major parameter of which most users have paid a lot of attention to when selecting the type and rating. The typical maximum surge arresters residual voltage are given in Annex F. It is likely, however, that for some systems, or in some countries, the system reliability requirements and design are sufficiently uniform that the recommendations of the present standard may lead to the definition of narrow ranges of arresters. The user of surge arresters will, in that case, not be required to apply the whole process introduced here to any new installation and the selection of characteristics resulting from prior practice may be continued.

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 60071-1:2006, *Insulation coordination – Part 1: Definitions, principles and rules*

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

IEC/TR 60071-4, *Insulation coordination – Part 4: Computational guide to insulation coordination and modelling of electrical networks*

IEC 60099-4:2009, *Surge arresters – Part 4: Metal-oxide surge arresters without gaps for a.c. systems*

IEC 60099-6:2002, *Surge arresters – Part 6: Surge arresters containing both series and parallel gapped structures – Rated 52 kV and less*

IEC 60099-8:2011, *Surge arresters – Part 8: Metal-oxide surge arresters with external series gap (EGLA) for overhead transmission and distribution lines of a.c. systems above 1 kV*

IEC 60507, *Artificial pollution tests on high-voltage insulators to be used on a.c. systems*

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

IEC/TS 60815-2, *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, *Selection and dimensioning of high-voltage insulators intended for use in polluted conditions – Part 3: Polymer insulators for a.c. systems*

IEC 62271-1, *High-voltage switchgear and controlgear – Part 1: Common specifications*

IEC 62271-200, *High-voltage switchgear and controlgear – Part 200: AC metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV*

IEC 62271-203, *High-voltage switchgear and controlgear – Part 203: Gas-insulated metal-enclosed switchgear for rated voltages above 52 kV*

3 Terms and definitions

For the purposes of this document, the following terms and abbreviations are used.

NOTE These terms follow standard definitions as close as possible, but are not in all cases exact citations of definitions in other IEC standards.

3.1

arrester – dead-front type, dead-front arrester

arrester assembled in a shielded housing providing system insulation and conductive earth shield, intended to be installed in an enclosure for the protection of underground and padmounted distribution equipment and circuits

Note 1 to entry: Most dead-front arresters are load-break arresters.

Note 2 to entry: The use of dead-front arresters is common in the USA.

3.2

arrester disconnecter

device for disconnecting an arrester from the system in the event of arrester failure, to prevent a persistent fault on the system and to give visible indication of the failed arrester

Note 1 to entry: Clearing of the fault current through the arrester during disconnection generally is not a function of the device.

3.3

arrester – liquid-immersed type

arrester designed to be immersed in an insulating liquid

3.4

arrester – separable type, separable arrester

arrester assembled in an insulated or screened housing providing system insulation, intended to be installed in an enclosure for the protection of distribution equipment and systems.

Electrical connection may be made by sliding contact or by bolted devices; however, all separable arresters are dead-break arresters

Note 1 to entry: The use of separable arresters is common in Europe.

3.5

back flashover rate

BFOR

characteristics of an overhead line or system with respect to the number of back flashovers typically given per 100 km and year

3.6

bending moment

horizontal force acting on the arrester housing multiplied by the vertical distance between the mounting base (lower level of the flange) of the arrester housing and the point of application of the force

3.7

continuous current of an arrester

current flowing through the arrester when energized at the continuous operating voltage

Note 1 to entry: The continuous current, which consists of a resistive and a capacitive component, may vary with temperature, stray capacitance and external pollution effects. The continuous current of a test sample may, therefore, not be the same as the continuous current of a complete arrester.

Note 2 to entry: The continuous current is, for comparison purposes, expressed either by its r.m.s. or peak value.

3.8

continuous operating voltage of an arrester

U_c

designated permissible r.m.s. value of power-frequency voltage that may be applied continuously between the arrester terminals in accordance with IEC 60099-4 and 60099-6

3.9

dead-break arrester

arrester which can be connected and disconnected from the circuit only when the circuit is de-energized

3.10

discharge current of an arrester

impulse current which flows through the arrester

3.11

disruptive discharge

phenomenon associated with the failure of insulation under electric stress, which include a collapse of voltage and the passage of current

Note 1 to entry: The term applies to electrical breakdowns in solid, liquid and gaseous dielectric, and combinations of these.

Note 2 to entry: A disruptive discharge in a solid dielectric produces permanent loss of electric strength. In a liquid or gaseous dielectric the loss may be only temporary.

3.12

externally gapped line arresters

EGLA

a line surge arrester designed with an external spark gap in series with a SVU part to protect the insulator assembly from lightning caused fast-front overvoltages only

Note 1 to entry: This is accomplished by raising the sparkover level of the external series gap to a level that isolates the arrester from power frequency overvoltages and from the worst case slow-front overvoltages due to switching and fault events expected on the line to which it is applied.

3.13
fast-front overvoltage
FFO

transient overvoltage usually unidirectional, with time to peak between 0,1 μ s to 20 μ s, and tail duration < 300 μ s

3.14
fault indicator

device intended to provide an indication that the arrester is faulty and which does not disconnect the arrester from the system

3.15
flashover

disruptive discharge over a solid surface

3.16
flashover rate
FOR

characteristics of an overhead line or system with respect to total number of flashovers typically given per 100 km and year

3.17
follow current

the current immediately following an impulse through an EGLA with the power frequency voltage as the source

Note 1 to entry: The external series gap shall be able to interrupt follow current due to external leakage current on a polluted SVU as well as due to internal resistive current through the non-linear metal oxide resistors; that is, the performance of the EGLA under polluted conditions is introduced by the gap resealing performance under wet and polluted condition, and it is verified by the follow current interruption test.

3.18
follow current of an arrester

the current from the connected power source which flows through an arrester following the passage of discharge current

3.19
gas-insulated metal enclosed surge arrester
GIS-arrester

gas-insulated metal-enclosed metal-oxide surge arrester without any integrated series or parallel spark gaps, filled with gas other than air and used in gas-insulated switchgears

Note 1 to entry: The gas pressure is normally higher than 1 bar = 10^5 Pa.

3.20
grading current

current flowing through the arrester while a power frequency voltage is applied

3.21
grading ring of an arrester

metal part, usually circular in shape, mounted to modify electro-statically the voltage distribution along the arrester

3.22
high current impulse

peak value of discharge current having a 4/10 or 2/20 impulse shape, which is used to test the withstand capability of the SVU on extreme lightning occasions

3.23**highest voltage for equipment** U_m

highest value of the phase-to-phase voltage (r.m.s. value) for which the equipment is designed in respect of its insulation as well as other characteristics which relate to this voltage in the relevant equipment Standards. Under normal service conditions specified by the relevant apparatus committee this voltage can be applied continuously to the equipment

3.24**highest voltage of a system** U_s

highest value of the phase-to-phase operating voltage (r.m.s. value) which occurs under normal operating conditions at any time and at any point in the system

3.25**impulse protective levels of an arrester tested in accordance with IEC 60099-6 – fast-front protective level**

highest of either the steep current residual voltage or the front-of-wave impulse sparkover voltage at I_n

3.26**impulse protective levels of an arrester tested in accordance with IEC 60099-6 – standard lightning impulse protective level**

highest of the residual voltage at nominal discharge current or 1,2/50 lightning impulse sparkover voltage at I_n

3.27**impulse protective levels of an arrester tested in accordance with IEC 60099-6 – switching impulse protective level**

highest of either the maximum residual voltage for the specified switching current or the specified switching impulse sparkover voltage

3.28**impulse**

unidirectional wave of voltage or current which, without appreciable oscillations, rises rapidly to a maximum value and falls, usually less rapidly, to zero with small, if any, excursions of opposite polarity

Note 1 to entry: The parameters which define a voltage or current impulse are polarity, peak value, front time and time to half-value on the tail.

3.29**impulse sparkover voltage-time curve**

a curve which relates the impulse sparkover of the voltage to the time to sparkover

3.30**insulation coordination**

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

3.31**lightning current impulse**

8/20 current impulse with limits on the adjustment of equipment such that the measured values are from 7 μs to 9 μs for the virtual front time and from 18 μs to 22 μs for the time to half-value on the tail

Note 1 to entry: The time to half-value on the tail is not critical and may have any tolerance during the residual voltage type tests (see IEC 60099-4:2009, 8.3).

3.32**lightning [or switching] impulse protective level** U_{pl} (LIPL) [or U_{ps} (SIPL)]

maximum peak voltage on the terminals of a surge arrester subjected to lightning [or switching] impulses under specific conditions

3.33**lightning impulse withstand voltage**

LIWV

Standard rated lightning impulse withstand voltage of an equipment or insulation configuration

3.34**line surge arresters**

LSA

a type of arrester that is applied to overhead lines of power systems to reduce the risk of insulator flashover during lightning overvoltages. It is not generally used to protect the insulator from other types of transients such as switching surges

3.35**load-break arrester**

arrester which can be connected and disconnected when the circuit is energized

3.36**mean breaking load**

MBL

the average breaking load for porcelain or cast resin-housed arresters determined from tests

3.37**metal-oxide surge arrester with gapped structures**

an arrester having non-linear metal-oxide resistors connected in series and/or in parallel with any internal series or shunt spark gaps

3.38**nominal discharge current of an arrester** I_n

peak value of lightning current impulse which is used to classify an arrester in IEC 60099-4, 60099-6, and 60099-8

3.39**nominal voltage of a system** U_n

suitable approximate value of voltage used to identify a system

3.40**non gapped line arresters**

NGLA

a line surge arrester designed without any external gapped structures to protect the line insulator assembly from lightning caused fast-front overvoltages

Note 1 to entry: It may also protect the line insulators against switching surges if so selected.

Note 2 to entry: NGLA are generally equipped with a disconnecter device that facilitates fast reclosing in case of an arrester overloading.

3.41**non-linear metal-oxide resistor**

part of the surge arrester which, by its non-linear voltage versus current characteristics, acts as a low resistance to overvoltages, thus limiting the voltage across the arrester terminals, and as a high resistance at normal power-frequency voltage

3.42**polymer-housed arrester**

arrester using polymeric and composite materials for housing, with fittings

Note 1 to entry: Designs with an enclosed gas volume are possible. Sealing may be accomplished by use of the polymeric material itself or by a separate sealing system.

3.43**porcelain-housed arrester**

arrester using porcelain as housing material, with fittings and sealing systems

3.44**power-frequency withstand voltage versus time characteristic of an arrester**

power-frequency withstand voltage versus time characteristic shows the maximum time durations for which corresponding power-frequency voltages may be applied to arresters without causing damage or thermal instability, under specified conditions in accordance with IEC 60099-4

3.45**protective characteristics of an arrester tested in accordance with IEC 60099-4**

the combination of the following:

- a) residual voltage for steep current impulse according to 8.3.1;
- b) residual voltage versus discharge current characteristic for lightning impulses according to 8.3.2;

Note 1 to entry: The lightning impulse protection level of the arrester is the maximum residual voltage for the nominal discharge current.

- c) residual voltage for switching impulse according to 8.3.3

Note 2 to entry: The switching impulse protection level of the arrester is the maximum residual voltage at the specified switching impulse currents.

3.46**protective characteristics of an arrester tested in accordance with IEC 60099-6**

the combination of the following:

- a) residual voltage for steep current impulse and front-of-wave spark-over according to 7.3.1 and 8.3.6.2;
- b) residual voltage versus discharge current characteristic for lightning impulses and the 1,2/50 impulse spark-over according to 7.3.2 and 8.3.7.2;
- c) residual voltage for switching impulse and the switching impulse sparkover according to 7.3.3 and 8.3.8.2

3.47**rated frequency of an arrester**

frequency of the power system on which the arrester is designed to be used

3.48**rated voltage of an arrester**

U_r

The maximum permissible r.m.s. value of power frequency voltage between its terminals at which it is designed to operate correctly under temporary overvoltage conditions as established in the operating duty tests of IEC 60099-4 and 60099-6

Note 1 to entry: The rated voltage is used as a reference parameter for the specification of operating characteristics.

3.49

reference current of an arrester

peak value (the higher peak value of the two polarities if the current is asymmetrical) of the resistive component of a power-frequency current used to determine the reference voltage of the arrester

Note 1 to entry: The reference current will be high enough to make the effects of stray capacitances at the measured reference voltage of the arrester units (with designed grading system) negligible and is to be specified by the manufacturer.

Note 2 to entry: Depending on the nominal discharge current and/or line discharge class of the arrester, the reference current will be typically in the range of 0,05 mA to 1,0 mA per square centimetre of disc area for single column arresters.

3.50

reference voltage of an arrester

U_{ref}
peak value of power-frequency voltage divided by $\sqrt{2}$ which is applied to the arrester to obtain the reference current

Note 1 to entry: The reference voltage of a multi-unit arrester is the sum of the reference voltages of the individual units.

3.51

residual voltage of an arrester

U_{res}
peak value of voltage that appears between the terminals of an arrester during the passage of discharge current

Note 1 to entry: The term "discharge voltage" is used in some countries.

3.52

residual voltage of EGLA

peak value of voltage that appears across the terminal-to-terminal length of the EGLA including the series gaps and connection leads during the passage of discharge current

3.53

routine tests

tests made on each arrester, or on parts and materials, as required, ensuring that the product meets the design specifications

3.54

self-restoring insulation

insulation which, after a short time, completely recovers its insulating properties after a disruptive discharge during test

3.55

series gap

Intentional gap(s), between spaced electrodes in series with one or more metal-oxide resistors, across which all or part of the imparted terminal voltage appears

3.56

series varistor unit

SVU

non-linear metal oxide resistor part, contained in a housing, which must be connected with an external series gap to construct a complete EGLA; the SVU may include several units

3.57**shielding failure flashover rate****SFFOR**

characteristics of an overhead line with respect to the number of shielding failures leading to flashover typically given per 100 km and year

3.58**shielding failure rate****SFR**

characteristics of an overhead line with respect to the number of shielding failures typically given per 100 km and year

3.59**shunt gap**

intentional gap(s), between spaced electrodes, that is electrically in parallel with one or SVUe main metal-oxide resistors

3.60**slow-front overvoltage****SFO**

transient overvoltage usually unidirectional, with time to peak between 20 μs to 5 000 μs , and tail duration ≤ 20 ms

3.61**sparkover of an arrester**

a disruptive discharge between the electrodes of the gaps of an arrester

3.62**specified long-term load****SLL**

force perpendicular to the longitudinal axis of an arrester, allowed to be continuously applied during service without causing any mechanical damage to the arrester

3.63**specified short-term load****SSL**

greatest force perpendicular to the longitudinal axis of an arrester, allowed to be applied during service for short periods and for relatively rare events (for example, short-circuit current loads, very high wind loads or seismic loads) without causing any mechanical damage to the arrester

Note 1 to entry: For seismic load an even higher load than the SSL may be considered.

3.64**steep current impulse**

current impulse with a virtual front time of 1 μs with limits in the adjustment of equipment such that the measured values are from 0,9 μs to 1,1 μs and the virtual time to half-value on the tail is not longer than 20 μs

3.65**surface current of SVU**

current that flows on the surface of the SVU

3.66**switching impulse withstand voltage****SIWV**

Standard rated switching impulse withstand voltage of an equipment or insulation configuration

3.67**switching surge flashover rate**
SSFOR

characteristics of an overhead line with respect to the number of switching surges leading to flashover typically given per 100 km and year

3.68**temporary overvoltage**
TOV

power frequency overvoltage of relatively long duration

Note 1 to entry: The overvoltage may be undamped or weakly damped. In some cases its frequency may be several times lower or higher than power frequency.

3.69**terminal line force**

force perpendicular to the longitudinal axis of the arrester measured at the centre line of the arrester

3.70**thermal runaway of an arrester**

situation when the sustained power loss of an arrester exceeds the thermal dissipation capability of the housing and connections, leading to a cumulative increase in the temperature of the resistor elements culminating in failure

3.71**thermal stability of an arrester**

arrester is thermally stable if, after an operating duty causing temperature rise, the temperature of the resistor elements decreases with time when the arrester is energized at specified continuous operating voltage and at specified ambient conditions

3.72**time to sparkover of an arrester**

the time interval between virtual origin and the instant of sparkover of the arrester expressed in microseconds

3.73**torsional loading**

each horizontal force at the top of a vertical mounted arrester housing which is not applied to the longitudinal axis of the arrester

3.74**transient overvoltage**

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

Note 1 to entry: Transient overvoltages may be immediately followed by temporary overvoltages. In such cases the two overvoltages are considered as separate events.

3.75**type tests****design tests**

tests which are made upon the completion of the development of a new arrester design to establish representative performance and to demonstrate compliance with the relevant standard

Note 1 to entry: Once made, these tests need not be repeated unless the design is changed so as to modify its performance. In such a case, only the relevant tests need be repeated.

3.76**unit of an arrester**

completely housed part of an arrester which may be connected in series and/or in parallel with other units to construct an arrester of higher voltage and/or current rating

3.77**very-fast-front overvoltage****VFFO**

transient overvoltage usually unidirectional, with time to peak $\leq 0,1 \mu\text{s}$, and with or without superimposed oscillations at frequency $30 \text{ kHz} < f < 100 \text{ MHz}$

4 General principles for the application of surge arresters

IEC 60071 specifies withstand voltages for two ranges of highest voltages for equipment:

- range I: above 1 kV to 245 kV included
- range II: above 245 kV

In addition this guide uses:

- distribution voltage up to 52 kV
- UHV above and 800 kV included

NOTE Insulation coordination refers both to U_m (highest voltage for equipment) U_s (highest system voltage), whereas the dimensioning of arresters is usually based exclusively on U_s .

For range I systems containing overhead lines, the main risk to equipment arises from induced and direct lightning strikes to the connected overhead lines. In cable systems not connected to overhead lines, overvoltages due to faults or switching operations are most likely to occur. In rare cases, however, lightning induced overvoltages may also be generated. In systems of range II, in addition to range I factors, switching overvoltages become important, increasing with higher system voltages. Overvoltages may cause flashovers and serious damage to the equipment and thereby jeopardize the supply of power to users. It is essential to prevent this by proper coordination of surge arresters with the insulation. Therefore, it is recommended to use surge arresters if there are possibilities of lightning overvoltages or high switching overvoltages, which may be dangerous to the equipment.

The surge arresters should constitute a reliable part of the system. They are designed to withstand the voltages and the resulting currents through them with a sufficiently high reliability taking into account pollution and other site matters. In each system, such voltage stresses are (see IEC 60071):

- operating voltage;
- temporary overvoltages;
- slow-front overvoltages;
- fast-front overvoltages;
- very-fast-front (GIS applications)

where the slow-front overvoltages due to switching are of particular importance for arresters protecting range II equipment.

As a general principle, the best protection of equipment and high surge arrester rated voltages are contradicting requirements. Thus the selection of an adequate arrester constitutes an optimization process, which has to consider a great number of system and equipment parameters. These are further explained in Clause 6, insulation coordination and surge arrester application.

5 Surge arrester fundamentals and applications issues

5.1 Evolution of surge protection equipment

The metal-oxide (also called MO, or sometimes ZnO) surge arrester was introduced in the mid to late 1970s and proved to be a solution to the problems which could not be solved with the gapped silicon carbide (SiC) arrester technology [19] [20] [21]¹. The protection level of a surge arrester was no longer a statistical parameter, but could be accurately given. The protective function was no longer dependant on the installation or vicinity to other apparatus – as compared to SiC arresters, where the sparkover voltage could be affected by surrounding electrical fields. The MO surge arrester could be designed to meet virtually any energy requirements by connecting MO resistor elements in parallel (even though the technique to ensure a sufficiently good current sharing, and thus energy sharing, between the columns is sophisticated). The possibility to design protective equipment that could handle extremely high-energy stresses also opened up new application areas, protection of series capacitors, for example, where the arrester is a huge arrester bank made of tens to hundreds of individual MO resistor columns connected in parallel.

Some of the first MO surge arresters utilised spark gaps in series with the varistor elements or in parallel with sections of the varistor column (shunt gaps). These designs reflected, to some extent, a concern for the long-term stability of the MO resistor material. Using spark gaps in series or parallel consequently made it possible to decrease the continuous voltage stress on the MO resistors and still maintain a low protection level. Another reason was to obtain protective levels better than for the most qualified SiC gapped arresters at that time with active spark gaps and low protection levels [18].

These designs are not found on the market any longer for HV applications. With experience, the elimination of gaps permitted the design of very compact, reliable, low profile arresters compared to what was possible with the old technology.

On the other hand MO surge arresters with external series spark gap (externally gapped line arresters: EGLA) are still found on the market, with even increasing tendency. These arresters are used for protection of overhead transmission and distribution lines against lightning related fast-front overvoltages only. The arresters, therefore, are designed not to operate for slow-front and temporary overvoltages.

The MO resistor technology was developed further during the 1980s and 1990s through to the present day, towards uncritical aging behaviour, lower protection levels, higher permissible voltage stresses on the material, greater specific energy absorption capabilities and better current withstand strengths [8] [9] [10] [11] [12] [13] [22] [23] [24] [26] [27] [39].

New polymeric materials, superseding the traditional porcelain housings, started to be used in the mid 1980s for distribution arresters. By the end of the 1980s, polymer-housed arresters were available up to 145 kV system voltages, and today polymer-housed arresters are accepted for all voltage ranges including 800 kV and the emerging UHV levels (1 100 kV, 1200 kV) [21].

Many of the early polymeric designs utilized EPDM rubber as an insulator material, but during the 1990s more and more manufacturers changed to silicone rubber (SIR), which has an outstanding performance under polluted conditions due to its hydrophobicity (ability to repel water), which is even transferred to pollution layers. SIR insulation is therefore considered less affected by environmental conditions, including UV radiation and pollution.

¹ Numbers in square brackets refer to the Bibliography.

5.2 Different types and designs and their electrical and mechanical characteristics

5.2.1 General

Surge arresters may first of all be distinguished by their types of applied non-linear resistors: SiC or MO, where the latter is today practically always based on ZnO. Another way of differentiation is with or without gaps. The gaps may be arranged internally and externally, and internal gaps may be series connected to all or shunt connected to part of the non-linear resistors. Another important attribute is the applied housing technology. Air insulated substation (AIS) surge arresters are available with porcelain housings or with polymeric housings, with a wide variety of different designs and polymeric materials. Gas insulated substation (GIS) surge arresters make use of metal enclosures, filled with sulphur hexafluoride (SF₆) at high operating pressures. Furthermore, there exist some other very specific housing technologies for distribution applications.

These different surge arrester technologies are covered by the following standards of the IEC 60099 series:

- SiC surge arresters with internal series gaps, porcelain-housed: 60099-1;
- MO surge arresters without gaps, all housing technologies: 60099-4;
- MO distribution surge arresters of 52 kV rated voltage or less, with internal series gaps, porcelain or polymer-housed: 60099-6;
- externally gapped line arresters (EGLA) for application in distribution or transmission overhead lines, porcelain or polymer-housed: 60099-8.

SiC arresters are still in service in huge quantities, but are not available on the market any more. This application guide will address MO surge arresters only. However, in Annex H some aspects of SiC gapped arresters are discussed.

The majority of newly installed surge arresters today are MO surge arresters without gaps. In distribution applications, polymeric housings are predominant. In transmission systems, porcelain housings are still common, but polymeric housings have an increasing market share.

Most of all surge arresters are outdoor types for air insulated substations (AIS), whereas GIS surge arresters are limited to protect gas insulated substations or parts of them.

Traditionally, arresters have mainly protected substation equipment such as power transformers, instrument transformers or in some cases circuit breakers of incoming lines. A comparatively new application (with an exceptionally long tradition in Japan, however) are line arresters which prevent insulator flashovers caused by lightning strikes to unshielded lines or to shielded lines after shielding failures, or due to high footing impedances in case of strikes to the shield wire or pole/tower (back flashovers). Further applications have become possible by the high energy handling capability of modern MO surge arresters, which can easily be extended by parallel connections of many (sometimes more than one hundred) individual MO resistor columns. Special designs are compatible to cable plug systems and can thus simply be integrated in existing distribution switchgear, and others are directly installed in transformer tanks and operated under oil.

5.2.2 Metal-oxide arresters without gaps according to IEC 60099-4

5.2.2.1 Different types and designs

IEC 60099-4 covers the following types of MO surge arresters without gaps:

- porcelain-housed arresters;
- polymer-housed arresters;
- gas-insulated metal enclosed arresters (GIS arresters);

- separable and deadfront arresters;
- liquid immersed arresters.

These different types of arresters are explained in the 5.2.2.2 to 5.2.2.6.

5.2.2.2 Porcelain-housed arresters

The active part of a porcelain-housed MO surge arrester consists of a column of stacked MO resistor elements, mechanically supported by different kinds of structures. MO resistors exhibit a characteristic that is approximated by the equation $I = k \times U^\alpha$, where α is the coefficient of non-linearity, having a value dependent upon the material and on the actual region of the voltage-current ($U-I$) characteristic. It can take values from 5 to 50. MO resistor elements for surge arrester applications are usually of cylindrical shape, with diameters in the range from about 20 mm to about 110 mm and heights of up to about 45 mm. Several MO resistor columns may be connected in parallel within one housing in order to increase energy handling capability (by an increased volume and thus heat capacity) or to reduce the protective level (by a decreased current density at a given current impulse level).

The gap between active part and inner wall of the housing may be completely or partly filled with gas or by a solid or semi-solid material (e.g. silicone rubber). The surrounding gas in these arresters typically is nitrogen or (synthetic) air. If other gases, e.g. SF₆, are used it should be checked that all relevant tests as per 60099-4 are made with the actual filling medium in the arresters and that possible leakage is considered. This is in particular important for the short-circuit test since the type of gas probably has a significant effect on the performance of the arrester under short-circuit. To perform the test with air or nitrogen inside the arrester is therefore not representative if other gases are used.

Usually pressure relief devices are provided which ensure that the housing will not fail violently after puncture or flashover of the active part due to energetic overload. It must be noted, however, that designs without pressure relief devices do exist on the market, and special care about safety considerations has then to be taken by the user.

The porcelain housing protects the active part from the environment. The housing has to fulfil many different requirements with regard to

- mechanical strength,
- flashover distance,
- creepage distance,
- performance under polluted conditions,
- sealing against moisture ingress,
- pressure relief under overload conditions.

For surge arrester housings in general (i.e. not limited to porcelain), the requirements on dielectric strength are different from those of all other equipment in electrical power systems. Note that the standard insulation levels of the insulation coordination standard IEC 60071:2006 (Tables 1 and 2) are not relevant, but lower values shall be applied instead as an arrester housing represents the best protected insulation in a power system. In order to avoid any flashover under impulse residual voltage stress during arrester operation, the minimum requirements for surge arrester housings, according to IEC 60099-4, are (abbreviations in line with IEC 60071):

- LIWV = 1,3 times the lightning impulse protection level (U_{pl}) of the arrester
- SIWV = 1,25 times the switching impulse protection level (U_{ps}) of the arrester for 10 kA and 20 kA arresters with ratings of 200 kV and above
- ACWV (peak value) = 1,06 times the switching impulse protection level (U_{ps}) of the arrester for 10 kA and 20 kA arresters with ratings of less than 200 kV

- ACWV (peak value) = 0,88 times the lightning impulse protection level (U_{pl}) of the arrester for 1,5 kA, 2,5 kA, 5 kA and high lightning duty arresters (in accordance with Annex C of IEC 60099-4:2009)

The applied factors take into account increased residual voltages for discharge currents higher than the nominal values and atmospheric correction for altitude of erection of 1 000 m above sea level (which means that an altitude correction for altitudes up to 1 000 m is always included, and only for higher altitudes of installation further corrections have to be applied as defined by IEC 60071-2).

The following example explains the different withstand voltage requirements:

Highest voltage for equipment $U_m = 420$ kV

- required LIWV for equipment other than surge arrester housings (IEC 60071:2006, Table 3): LIWV = 1 425 kV
- required SIWV for equipment other than surge arrester housings (IEC 60071:2006, Table 3): SIWV = 1 050 kV

Typical arrester's lightning impulse protection level $U_{pl} = 825$ kV

Typical arrester's switching impulse protection level $U_{ps} = 700$ kV

- required LIWV for surge arrester housing: LIWV = $1,3 \times 825$ kV = 1 073 kV
- required SIWV for surge arrester housing: SIWV = $1,25 \times 700$ kV = 875 kV

Often users are not aware of this special situation for surge arresters and would require the standard values of IEC 60071. This leads to unnecessarily tall arrester housings, which is not only a problem of geometrical dimensions but also leads to an adverse axial voltage distribution and possibly to a more critical performance under polluted conditions. There may be special situations, such as extreme environmental conditions, that require higher impulse withstand ratings, but in general only the requirements of IEC 60099-4 should be applied.

For arresters the sealing system is critical and this is not only the case for porcelain-housed arresters. Moisture ingress on porcelain-housed arresters is one of the main reasons – if not the only one – for a limited lifetime of MO surge arresters. It should be noted that the electrical aging of the MO resistor elements, i.e. a non-reversible change of the voltage-current-characteristic in the leakage current range, plays only a minor role with respect to surge arrester lifetime and is not a consideration, if verified in accordance with IEC 60099-4.

The length of a single arrester unit usually is limited to less than two meters for mechanical reasons. Therefore, arresters for system voltages higher than 245 kV usually comprise more than one unit in series. Also beginning from a length of about 1,5 m to 2 m, external grading rings have to be applied, which serve for controlling the uneven axial voltage distribution caused by stray capacitances to earth. Though these rings are often considered as undesirable from a station layout perspective they must not be omitted during installation, because the arrester would then fail within short time by a thermal runaway (i.e. electrical power losses exceed thermal heat dissipation capability).

Currently, IEC 60099-4 allows performing dielectric testing of the housing on individual units and without the external grading system. However it is quite evident that this will not result in correct withstand values for multi-unit EHV and UHV arresters. It is therefore suggested that, for 800 kV surge arresters and above, complete arresters are tested but with the MO resistors replaced by grading components.

5.2.2.3 Polymer-housed arresters

Polymer-housed arresters appeared on the market in the mid 1980s (distribution) and late 1980s (transmission). In distribution, they represent state of the art today and porcelain-housed distribution arresters are hardly available these days. In transmission, the market

share of polymer-housed arresters is smaller, but with increasing tendency. A variety of different designs has been developed especially for distribution arresters, but all existing designs can be assigned to one of only few basic design principles that are listed below [49]. It should be noted that, from a mechanical point of view, IEC 60099-4 considers any design of an arrester that uses a pure epoxy-resin housing as a porcelain-housed arrester, because epoxy resin is a brittle material and will, without doubt, mechanically behave like a porcelain housing.

"Tube design": This is an arrester using a housing with an intended included gas volume (similar to a porcelain housing). It must consequently have a sealing and a pressure relief system. The housing is usually a non-ceramic composite housing, formed e.g. from a tube of fibre glass reinforced plastic (FRP), covered by outer weather sheds. The outer weather sheds may be directly moulded to the tube or drawn as individual parts in different possible processes. The internal design and surrounding medium in these arresters is normally similar to porcelain-housed arresters.

All other existing designs use housings which are directly applied to the stack of MO resistor elements, without an intended gas volume included.

"Wrapped design": The mechanically supporting part of the housing is formed by a wrapped FRP structure. This may be implemented by epoxy resin soaked glass rovings or pre-impregnated mats or bands that are wound around the MO resistor stack and then cured in an oven. The resulting tube, surrounding the varistor stack, may be completely closed (sometimes with prepared weakened areas that support opening of the housing under overload conditions) or have some open "windows". The wrap may also consist of a prefabricated FRP tube which is pushed over the stack of MO resistor elements, and where the gap between MO resistors and FRP tube is then filled by some elastic material.

"Cage design": The stack of MO resistor elements is clamped by FRP loops or rods or bands at extremely high mechanical tension forces. The MO resistor elements themselves thus act as part of the mechanically supporting structure, and the FRP elements form an open cage. Additional bands may be wound around this cage of FRP elements in order to increase mechanical strength and to improve short-circuit performance. The outer weather sheds have to be directly moulded to the modules, usually making use of silicone rubber.

Though this classification has turned out to be quite practical, another classification with a different background has been adopted by IEC 60099-4, in order to classify designs with regard to different procedures in the short-circuit tests. During short-circuit testing, it makes a difference if the "pressure relief" behaviour of a closed housing with included gas volume shall be verified, or the short-circuit performance of a housing directly attached to the MO resistor stack. These two basic design principles require different approaches in testing. For instance, in order to reflect worst case conditions, in the first case an internal arc has to be initiated by melting a fuse wire located in parallel to the varistor stack and thus representing an internal flashover, whereas in the latter case only energetic overloading (by application of excess voltage) of the arrester will result in a representative failure scenario, as it may not be excluded that individual failed MO resistor elements will break and thus mechanically damage the housing. Therefore, the following has been introduced to IEC 60099-4 with regard to short-circuit performance:

"Design A" arresters have a design in which a gas channel runs along the entire length of the arrester unit and fills $\geq 50\%$ of the internal volume not occupied by the internal active parts.

"Design B" arresters are of a solid design with no enclosed volume of gas or having an internal gas volume filling $< 50\%$ of the internal volume not occupied by the internal active parts.

Notes in IEC 60099-4 give further explanation:

"Typically, 'Design A' arresters are porcelain-housed arresters, or polymer-housed arresters with a composite hollow insulator which are equipped either with pressure relief devices, or with prefabricated weak spots in the composite housing which burst or flip open at a specified pressure, thereby decreasing the internal pressure."

"Typically, 'Design B' arresters do not have any pressure relief device and are of a solid type with no enclosed volume of gas. If the resistors fail electrically, an arc is established within the arrester. This arc causes heavy evaporation and possibly burning of the housing and/or internal material. These arresters' short-circuit performance is determined by their ability to control the cracking or tearing open of the housing due to the arc effects, thereby avoiding a violent shattering."

In other words, "Design A" defines an arrester where the probability of a failure initiated in the gas volume is much higher than in the solid material, and "Design B" defines a design with a higher probability of failure initiated in the solid material. This classification is optimized with regard to test requirements, though many cases will remain where a differentiation between both designs will be problematical, but it is not possible to differentiate in detail between the different makes of actual arresters on the market. Thus both classifications cited above may co-exist.

The outer part of a polymeric housing, which is exposed to the environment, may be made from different kinds of materials, such as EPDM (ethylene-polyene-diene-monomer), EVA (ethylene-vinyl-acetate) or SIR (silicone rubber), the latter subdivided into RTV (room temperature vulcanizing), HTV (high temperature vulcanizing) and LSR (liquid silicone rubber). These are only generic names, and many sub-variants exist. In most cases, these polymeric materials are doped by chemicals or filled by fillers such as ATH (aluminium tri-hydrate) in order to provide sufficient resistance to environmental impact. Most important characteristics are hydrophobicity (the ability to repel water) and its dynamic behaviour (temporary loss under long-lasting humidification and recovery in following drying periods), and tracking and erosion resistance. It is therefore important and required in IEC 60099-4 that all polymer-housed arresters without gaps are exposed to a weather aging test as part of the type tests.

The performance of the sealing system of a polymer-housed arrester without included gas volume is tested by a water immersion test (boiling for 42 hours).

When applying polymer-housed arresters the user should be aware that, different from porcelain-housed arresters, even designs of extremely high mechanical strength may be deflected under mechanical cantilever loads. This has to be considered in the station layout, e.g. in case of extremely low clearances to neighboured equipment.

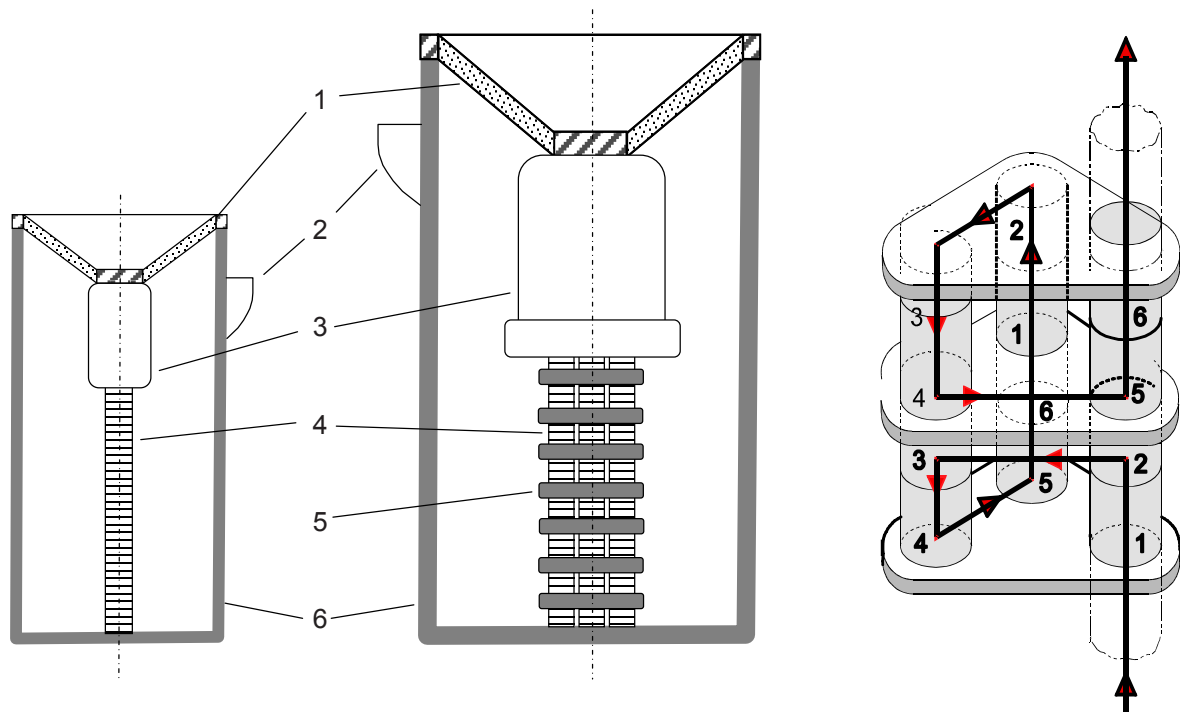
One different variant of polymer-housed arresters are series-parallel connected designs [48]. These are made up e.g. from distribution system modules, connected in series to meet the required voltage rating and in parallel to meet energy handling and protection level requirements. IEC 60099-4 is not well-prepared to cover all particular aspects of this design (e.g. with regard to short-circuit and mechanical testing), and the user must therefore be aware that the performance of the completely assembled device may deviate from the performance verified in type tests on the individual modules only.

5.2.2.4 Gas-insulated metal enclosed arresters (GIS arresters)

Gas-insulated metal enclosed arresters (GIS arresters) are arresters, which can be directly connected to a GIS. Their metal enclosure is usually made from aluminium or steel. As the interfaces of the gas compartments are manufacturer specific and not standardized, the same applies to the GIS arresters. Therefore, GIS manufacturers usually have their own GIS arrester designs. But with the help of adaptor flanges it is basically possible, though not very common, to connect any GIS arrester to any GIS on the market.

GIS arrester designs may first of all be distinguished by the number of phases in one common metal enclosure. For system voltages 170 kV and below, three-phase designs are common. For higher system voltages, one-phase designs are usually applied.

GIS arresters more than AIS arresters are exposed to the strong influence of earth capacitances affecting the MO resistor column and leading to an extremely non-uniform voltage distribution along the active part if no countermeasures are taken. The internal voltage grading system is therefore more complex than the grading ring system of AIS arresters. Furthermore, for system voltages above 170 kV the internal design of the active part is a mechanically staggered three-column arrangement but electrically a one-column design, the purpose being to reduce the geometrical length of the stack (Figure 1). Insulating plates of extremely high electric strength have to be applied in order to insulate the layers of MO resistors from each other. These arresters require special dielectric withstand tests in 11.8.2.5 of IEC 60099-4:2009.



Key

- 1 Cone insulator
- 2 Pressure relief vent
- 3 Grading hood
- 4 MO resistor stack(s)
- 5 Floor separation insulators
- 6 Metal enclosure (tank)

IEC 1010/13

Figure 1 – GIS arresters of three mechanical/one electrical column (middle) and one column (left) design and current path of the three mechanical/one electrical column design (right)

Recent developments have been that, even for EHV systems, arresters of mechanical and electrical single column design are used, which make use of high voltage gradient MO resistors (i.e. MO resistors of more "volts per millimetre length"), and UHV arresters with extremely low protection levels by connecting four MO resistor columns electrically in parallel, leading to a staggered active part of twelve parallel MO columns.

In general, the requirements on insulation strength are the same as for AIS arresters (LIWV = 1,3 times U_{pl} , SIWV = 1,25 times U_{ps} , ACWV = 1,06 times U_{ps}) though there is no need for

any atmospheric correction: the gas density inside the enclosure remains always the same as long as there is no gas leakage. This is justified by a demand for higher safety margins, because a dielectric failure of a GIS would have much more severe consequences (power arc inside the metal enclosure). For three-phase designs, the phase-to-phase withstand voltages have also to be verified.

The coaxial cylinder configuration is the reason for a much lower self inductance of a GIS arrester compared to an AIS arrester. Typically, for GIS arresters a value of $0,3 \mu\text{H/m}$ length is assumed, while the value for AIS arresters is $1 \mu\text{H/m}$ (see also Annex C). Therefore, the protection level of a GIS arrester under steep current impulse stress is lower than that of a comparable AIS arrester.

If a GIS arrester uses metal enclosures that have been tested according to IEC 62271-200 or 62271-203 and if it has no additional internal pressure relief system, no short-circuit test has to be performed during type tests. Otherwise, the internal pressure relief system has to be tested in a short-circuit test.

Special care must be taken during commissioning tests on GIS if they include GIS arresters. Arresters cannot withstand the required power-frequency withstand voltage levels of the required dielectric tests. Most of the failures reported on GIS arresters occurred during commissioning testing. GIS arresters have to be removed during these tests, or the integrated disconnectors, which are incorporated in some arrester designs, have to be opened [16] [50] [51] [52].

5.2.2.5 Separable and deadfront arresters

Separable and deadfront arresters are two different designs of arresters, which have in common that they are not fixed installations and permanently connected to the system by fixed conductors but can be installed and removed by sliding contacts and plugs, respectively. Usually, they are intended for installation in enclosures, such as distribution switchgear, but also outdoor applications have been reported. Some basic differences exist between separable and deadfront arresters.

Separable arresters may be manufactured in either insulated (polymeric) or screened (metallic or electrically conducting polymeric) housings. In all cases, they are dead-break arresters, which mean that the power system has to be de-energized before the arrester may be connected or removed. The use of separable arresters is common in Europe.

Deadfront arresters sometimes called elbow arresters, common in the USA, always have shielded housings, as shown in Figure 2. They are usually installed in underground and padmounted distribution equipment and circuits, and they are always of the load-break type, i.e. they can be installed and removed under voltage.

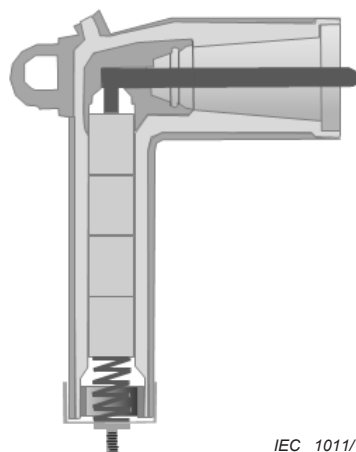


Figure 2 – Typical deadfront arrester

The requirements on insulation withstand are different from those of standard AIS arresters, and they are different for designs with insulating or shielded/screened housings. The requirements arise from those of IEC 60071 and IEC 60694 in case of unscreened separable arresters and from IEEE C62.11 in case of screened separable and dead-front arresters (see 12.8.2 of IEC 60099-4:2009).

Further requirements different from those on standard AIS arresters apply for the short-circuit behaviour and related test conditions and evaluation. The user should be aware that separable and dead-front arresters may in case of overload eject arrester parts through the body of the housing by release of a bottom cap or through other parts specifically designed for this purpose. The method of installation should take this possibility into account.

5.2.2.6 Liquid immersed arresters

Although IEC 60099-4 addresses arresters in insulation liquids in general, the only implemented solutions are arresters under oil, which are installed directly in the transformer tank in close proximity to the winding to be protected. They have been applied in huge quantities in the USA since 1980 and in Japan since 1985. In other parts of the world this technology has not generally been accepted and adopted.

Only arresters which directly protect the transformer windings and which are therefore permanently stressed by the operating voltage are covered by the standard, but not, for example, MO resistor elements that protect tap changers.

Advantages of liquid immersed arresters are an optimized protective performance as the arrester is installed as close as possible to the winding, thus avoiding separation effects due to travelling wave phenomena, and the perfect protection of the arrester from the environment.

One problem that has to be solved is the operation under hot oil. For this reason the accelerated aging test (part of the operating duty test) has to be performed for 7 000 hours (this time may be reduced to not less than 2 000 hours after agreement between manufacturer and user), which however does not give the same confidence on lifetime prediction as a 1 000 hours test on MO resistor elements for standard applications (see Annex K of IEC 60099-4:2009 for further explanation).

Another issue is short-circuit performance. Liquid-immersed arresters may be designed as either “fail-open” or “fail-short”, but it has to be realized that a fail-open design arrester will not always fail in an open-circuit mode for fault currents below its fail-open rating, and that a fail-short design arrester will not always fail in a short-circuit mode for actual fault currents above its fail-short rating. Also, the term “fail-open” should not be taken as implying that the arrester will break the circuit. It only means that, after other devices have cleared the fault, a fail-open arrester allows re-energization of the protected equipment with of course no overvoltage protection. The two basically different approaches of short-circuit behaviour require test procedures and evaluation criteria different from those of all other arrester designs (see 13.8.7 of IEC 60099-4:2009). [53], [54]

5.2.2.7 Electrical and mechanical characteristic data

5.2.2.7.1 General

Basic electrical characteristics of metal-oxide surge arresters are the continuous operating voltage, the rated voltage, the nominal discharge current and the residual voltages at nominal discharge current, at switching impulse current and at steep front current, see Figure 15. For given continuous operating and rated voltages, different types of arresters, and therefore different protection levels, exist. Further characteristics which have to be considered in a particular application are line discharge class, rated short-circuit current and pollution withstand capability. Mechanical characteristic data are the specified long-term load and the specified short-term load.

5.2.2.7.2 Continuous operating voltage, U_c

The continuous operating voltage U_c is the maximum permissible value of a sinusoidal power frequency voltage, which may be continuously applied between the arrester terminals. The continuous operating voltage of the complete arrester may be lower per section than that used in the operating duty test, for the ageing procedure, and for verifying thermal stability. The lower continuous operating voltage may be due to the pollution strength of the arrester housing or to large non-linearities in the voltage distribution along the MO resistor stack due to less effective grading caused by proximity effects of other objects. Smaller grading rings and proximity to earthed objects are other reasons.

5.2.2.7.3 Rated voltage, U_r

The rated voltage U_r is the maximum power frequency voltage that is applied in the operating duty test for ten seconds (see 8.5 of IEC 60099-4:2009). It is, furthermore, the reference parameter to establish the power frequency voltage versus time characteristic of the arrester, and for defining the test requirements for the line discharge test.

Standard rated voltages are defined in steps of 1 to 24 kV according to IEC 60099-4:2009, Table 2. Other values are acceptable, provided they are multiples of six.

5.2.2.7.4 Nominal discharge current, I_n

The nominal discharge current I_n is used for the surge arrester classification. Five standard nominal discharge currents exist according to IEC 60099-4:2009, Table 1, with an increasing number indicating increased duties and requirements (1 500 A, 2 500 A, 5 000 A, 10 000 A, 20 000 A). Though the IEC standard gives these values in A, it is common practice to specify the nominal discharge current in kA (i.e. 1,5 kA, 2,5 kA, 5 kA, 10 kA, 20 kA). The nominal discharge current is the main parameter for the protective characteristics and the energy absorption capability of the arrester. Its choice has also an impact on the whole procedure of insulation coordination.

5.2.2.7.5 Protective (or protection) levels, U_{pl} and U_{ps}

The lightning impulse protective level, LIPL (according to IEC 60071-1) or U_{pl} (according to IEC 60099-4) of an arrester is the maximum residual voltage at nominal discharge current. It is applicable to the protection of equipment from fast-front overvoltages.

The switching impulse protective level, SIPL or U_{ps} is the maximum residual voltage at the specified switching impulse currents. It is applicable to the protection of equipment from slow-front overvoltages.

For the protection performance of metal-oxide surge arresters for very-fast-front overvoltages the residual voltage is tested in the steep current impulse test.

5.2.2.7.6 Line discharge (LD) class

A number related to the energy absorption capability of 10 kA and 20 kA arresters for the discharge of long transmission lines. Five classes exist according to IEC 60099-4:2009, Table 5, with an increasing number indicating increased energy absorption capability. Required energies for UHV arresters may not be covered by existing LD classes.

For arresters with LD class 2 and above, the resulting discharge current is used in the operating duty test to verify thermal stability after energy absorption. System events causing arrester currents with different shapes may be evaluated by comparison with energy and current of an equivalent line discharge. However, energy handling capability of an arrester is not a fixed value but depends on current density and time duration of the energy injection. In general, energy handling capability increases with higher current densities and shorter time durations. This matter is still under investigation [38] [41] [55].

NOTE A change of energy classification system is under consideration for IEC 60099-4:2009.

5.2.2.7.7 Rated short-circuit current, I_s

The rated short-circuit current I_s is an internal fault current after failure of the arrester's active part which the arrester is able to withstand for 200 ms without violent shattering of the housing and risk of maintaining fire. In the short-circuit type test, also the short-circuit performance at lower currents, approximately 50 % and 25 % of the rated short-circuit current, as well as at a current of only 600 A for one second has to be verified. The reason for testing also at lower currents is that due to the design lower currents may be more critical. This is in particular the case for long units of porcelain-housed arresters.

5.2.2.7.8 Pollution withstand characteristics

The pollution withstand capability of an arrester concerns three aspects:

- a) The arrester housing has to withstand the pollution stresses without flashover. This can be verified according to IEC 60507 or is assured by a design according to the IEC 60815 series.
- b) The arrester has to withstand the possible temperature increase due to the transient changes in voltage distribution caused by the pollution activity on the surface of the housing. Consideration should be given to the pollution level and the frequency and amplitude of overvoltages caused by faults and reclosing operations during polluted conditions. A suitable test procedure for multi-unit porcelain-housed arresters is given in Annex F of IEC 60099-4:2009. For polymer-housed arresters, no similar test procedure has been specified so far.
- c) The arrester has to withstand internal partial discharges from high radial fields caused by disturbed voltage grading on the housing due to pollution, without damage to the varistors or to the internal mounting elements. No related test procedure exists so far [42].

5.2.2.7.9 Resistance of polymeric housings to environmental impact

For arresters with polymeric housings the long term performance and resistance to environmental impact, such as light pollution, rain, electrical surface discharges and solar (UV) radiation has to be demonstrated in a "weather aging test". This test may be either a 1 000 hours salt fog test (named "series A") or a 5 000 hours cyclic test (named "series B"). The former is the standard test requirement, and it is a test with permanent exposure to salt fog of a given salt mass concentration under applied continuous operating voltage. The latter shall be applied in case of heavy or very heavy pollution conditions and after agreement between the manufacturer and the user only, and this is a test with cyclic exposure to rain, salt fog, humidity, dry heat and UV radiation. As a fundamental requirement, the longest electrical unit of the design has to be tested in order to also demonstrate that there is no impact (puncture of the housing, internal partial discharges) from the radial field stress that may be imposed by the permanently changing potential distribution on the housing. This requirement may be in conflict with available test possibilities, because only few laboratories will be able to perform such a 5 000 hours cyclic test on a high-voltage arrester unit. Therefore, if a user requires the 5 000 hours cyclic test on a high-voltage arrester, the standard allows performance of this test on a short arrester section, and the 1 000 hours salt fog test has then to be performed on the longest electrical unit of the design in addition.

5.2.2.7.10 Specified long-term load, SLL

The specified long-term load SLL is a force perpendicular to the longitudinal axis of an arrester, allowed to be continuously applied during service without causing any mechanical damage to the arrester. It can be given in terms of force (in N) or bending moment (in Nm); where in the latter case the related force can be calculated by dividing the bending moment value with the arrester length (in m). For high-voltage polymer-housed arresters, the SLL is verified by a cyclic load test, followed by evaluation tests that include a leakage seal test (water immersion test) against moisture ingress. Short arresters, i.e. arresters for system voltages not exceeding 52 kV, do not need to be type tested in a cyclic manner but by a simple bending test. The same applies to porcelain-housed arresters in general, where due to

the fact that they are not deflected under mechanical loads a simple bending test is considered sufficient as well.

5.2.2.7.11 Specified short-term load, SSL

The specified short-term load SSL is the greatest force perpendicular to the longitudinal axis of an arrester, allowed to be applied during service for short periods and for relatively rare events (for example, short-circuit current loads or extreme wind gusts) without causing any mechanical damage to the arrester. As for the SLL, it is given in terms of force (in N) or bending moment (in Nm). The SSL is a load that the arrester could be subjected to even after many years in service, which is taken into consideration by the related type test procedure (the SSL test follows the SLL test). It is important to note that SSL does not cover any seismic loads which may require much higher SSL values than usually applied for normal service conditions and which therefore need special consideration by tests according to IEC/TR 62271-300.

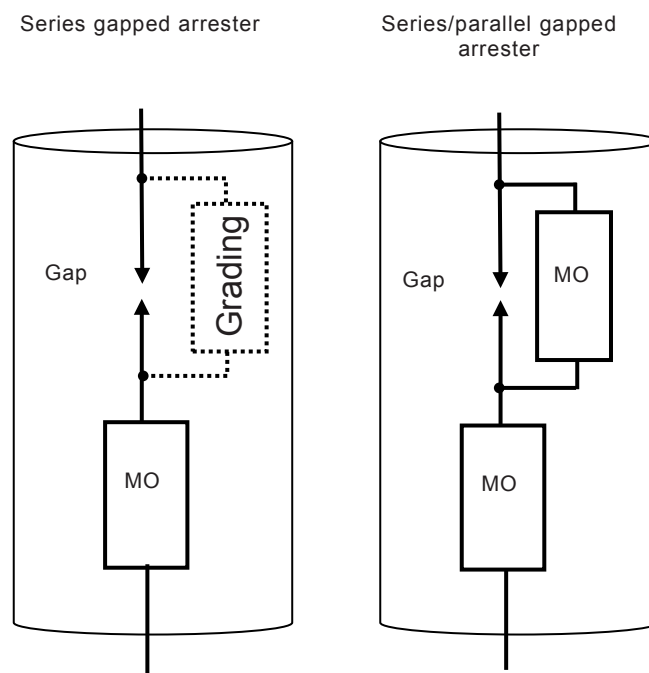
5.2.3 Metal-oxide surge arresters with internal series gaps according to IEC 60099-6

5.2.3.1 General

This standard is limited to MO surge arresters with internal series spark gaps designed to limit voltage surges in a.c. distribution systems (rated voltages 52 kV and below), housed in either porcelain or polymeric housings.

5.2.3.2 Different types and designs

IEC 60099-6 covers series gapped MO surge arresters. Figure 3 shows an example of this design. The internally series gap design has been in use since the late 1970s in Japan and USA. The internally gapped arrester is a type of arrester that combines the characteristics of the oldest arrester design component, a series gap, and the newest arrester design component, a MO resistor stack [18].



IEC 1012/13

Figure 3 – Internally gapped metal-oxide surge arrester designs

The internally gapped MO arrester has two basic components as shown in Figure 3, the MO resistor part(s) and the gap. The MO resistor part is a non-linear MO resistor stack. It has roughly the same characteristics as a standard MO arrester. The gap is generally an air gap in series with the varistor stack and sometimes in parallel with grading elements or another MO resistor part. The gap section may be a single unit, or several units. This is the same for the MO resistor part, it may be a single MO resistor element or a plurality of such elements.

Each component of the series gapped MO arrester is significantly different from the earlier gapped SiC arresters. In the earlier generation SiC arrester designs, the gap section functioned as the switch that turned on at the moment of the surge, and turned off when the voltage across the gap was near zero. The gap was used for both turning the arrester on and turning it off in a sense. The gap of the series gapped MO arrester is used only for initiating an operation, but not for ending it. The MO resistor part has assumed the function of ending the surge operation of this design. Due to the extreme nonlinear characteristic of the MO element there is no follow current through the arrester and gaps, as there was with the silicone carbide gapped arrester. The elimination of follow current also eliminates the degradation of the gaps.

Because the internal gap withstands most of the voltage across the arrester (if not all), the MO portion of the arrester can contain fewer MO resistor elements than an ungapped arrester. The MO resistor element voltage need only be high enough to fulfil its function to switch off the arrester after the surge has passed. This means the turn on voltage of the arrester can be just a few percent above the system voltage that will be applied to it during a surge. A lower reference voltage translates directly into fewer MO resistor elements or at least less MO material.

5.2.3.3 Electrical and mechanical characteristic data

5.2.3.3.1 Rated voltage and continuous operating voltage

Unless otherwise stated by the manufacturer, the rated voltage (U_r) of arresters tested and designed according to IEC 60099-6 is derived by the same means as U_r for arresters tested and designed according to IEC 60099-4. The continuous operating voltage (U_c) is also derived by the same means and can be considered identical in definition and usage as an MO arrester without gaps as designed and tested per IEC 60099-4.

5.2.3.3.2 Arrester class and energy handling requirements

Arresters covered in IEC 60099-6:2002 are of LD class 1 only. The energy absorbed by this arrester is generally lower than that of an arrester without gaps in the same application because generally there are fewer MO resistor elements in a comparably rated gapped arrester. But charge transfer and current carrying capabilities of this arrester are similar to the gapless arrester.

5.2.3.3.3 Insulation coordination considerations

The protective characteristics of arresters designed and tested according to IEC 60099-6 are as follows:

- a) residual voltage for steep current impulse and front-of-wave sparkover according to 7.3.2 and 7.3.6.2 of IEC 60099-6:2002;
- b) residual voltage versus discharge current characteristic for lightning impulses and the 1,2/50 impulse sparkover according to 7.3.3 and 7.3.7.2 of IEC 60099-6:2002;
- c) residual voltage for switching impulse and the switching impulse sparkover according to 7.3.4 and 7.3.8.2 of IEC 60099-6:2002.

In all cases, the higher of the two values is reported as the protective characteristic. This maximum value has to be used in the insulation coordination procedure. The insulation coordination must also take into account a larger spread in the protection level for this type of arresters, due to the sparkover of the gaps.

5.2.3.3.4 Temporary overvoltage considerations

The temporary overvoltage (TOV) characteristics of arresters designed and tested per IEC 60099-6 can be considered in the same manner as arresters designed and tested per IEC 60099-4.

5.2.4 Externally gapped line arresters (EGLA) according to IEC 60099-8:2011

5.2.4.1 Different types and designs

The purpose of most line surge arresters (LSA) is to prevent insulator flashovers due to direct lightning strikes to the conductor of an unshielded line, by a shielding failure of a shielded line or due to back flashovers [15], [58], [59], [62]. Main distinguishing features of line arresters, which are in all cases MO arresters today, are

- gapped or gapless;
- porcelain-housed or polymer-housed;
- for distribution or for transmission line application;
- for lightning and/or for switching overvoltage protection.

Non gapped line arresters (NGLA) are tested according to IEC 60099-4, while the externally gapped line arresters (EGLA) are tested according IEC 60099-8.

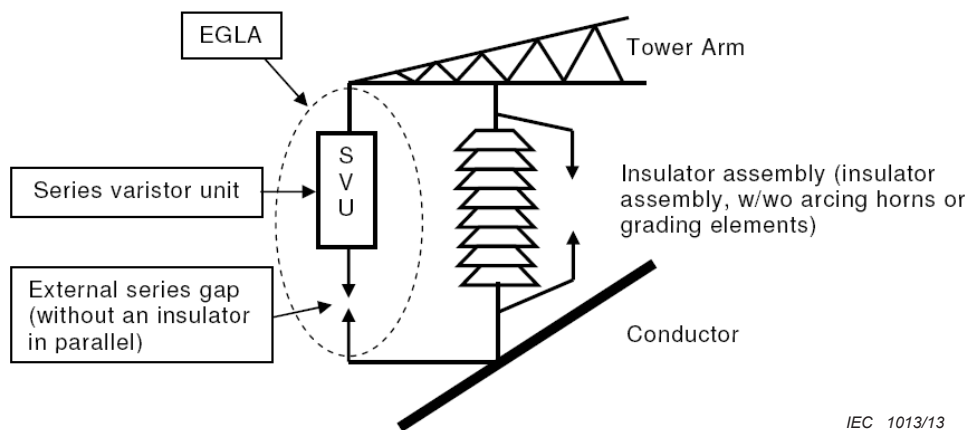


Figure 4 – Components of an EGLA acc. to IEC 60099-8

An EGLA consists of a series varistor unit (SVU) and an external series gap, as shown in Figure 4, where one electrode is installed on one end of the SVU and the other electrode is fixed to the line insulator. Another solution is to put the electrodes of the external gap across an insulator in series with the SVU, but this design is not covered by IEC 60099-8.

5.2.4.2 Electrical and mechanical characteristic data

5.2.4.2.1 General

EGLA protect only against the impact of lightning overvoltages, therefore, the following issues relevant to gapless station arresters or line arresters against the effects of switching overvoltages are not relevant for EGLA:

- residual voltage at switching impulse current;
- thermal stability;
- long duration current impulse withstand duty;

- power-frequency voltage vs. time characteristics;
- ageing duties by power-frequency voltage.

EGLA do not have operating duties for slow-front surges and power-frequency overvoltages. Therefore, they need not and cannot be classified by energy handling characteristics. The classification is exclusively based on the nominal discharge current and the high-current impulse withstand capability. As there is a long tradition in EGLA application in Japan, IEC 60099-8 includes two classification systems: Series "X" (ranging from "X1" to "X4") and Series "Y" (ranging from "Y1" to "Y4") arresters. The first should preferably be used for new applications, the latter takes the Japanese practice into consideration. As a particularity, for the "Y" series both the nominal discharge current and the high current impulse have a current shape 2/20, which is calculated as a typical shielding failure current in shielded transmission lines and has been agreed as a common practice in Japan.

The basic electrical characteristics of EGLA are the rated voltage, the class (X or Y, which includes the nominal discharge current and the high current impulse withstand), the lightning discharge capability, the coordination between the insulator withstand and the EGLA protective level, the follow current interruption capability under polluted conditions and the rated short-circuit current.

The mechanical characteristic data are subject to agreement between manufacturer and purchaser. As a minimum requirement, the EGLA must be able to withstand the vibration loads expected in service.

The following subclauses address the characteristics data of an EGLA.

5.2.4.2.2 Rated voltage, U_r

The rated voltage U_r is the maximum permissible r.m.s. value of power frequency voltage between the EGLA terminals, at which it is designed to operate correctly. It must therefore be higher than the maximum expected power-frequency temporary overvoltage expected in the intended installation. The rated voltage is also used as a reference parameter for the specification of operating and current interrupting characteristics.

5.2.4.2.3 EGLA class

EGLA are classified by a series name, which may be "X" or "Y". Within each series, there are subclasses "X1" to "X4" and "Y1" to "Y4", respectively. Each sub-class stands for a combination of the nominal discharge current and the high current impulse withstand. The classes are listed in Tables 1a and 1b of IEC 60099-8:2011.

5.2.4.2.4 Lightning discharge capability

The lightning discharge current was introduced especially to test line arresters and is also specified in Annex N of IEC 60099-4:2009. The current wave shape is approximately sinusoidal with a time duration of 200 to 230 μ s, which results in a current wave shape of about 90/200 μ s. Eighteen impulses have to be injected to each test sample (single MO resistor elements in still air) during the type test, making the test a durability test. The lightning discharge capability of the EGLA is specified by three different parameters:

- current peak value in kA,
- energy handling capability in kJ/kV of U_r ,
- charge transfer capability in C (this value has to appear on the EGLA nameplate).

5.2.4.2.5 Insulation withstand

An external series gap normally isolates SVU from the line and sparks over only when lightning overvoltages occur. Therefore the external series gap shall withstand temporary overvoltages and slow-front overvoltages (earth-fault overvoltages, energization and re-

energization overvoltages etc.) in the line and the SVU shall withstand its residual voltage when lightning current flows after sparkover of the external series gap. The gap length shall be designed on condition that the SVU has failed and is shorted and all of the overvoltages are applied to the external series gap.

5.2.4.2.6 Co-ordination between insulator withstand and EGLA protective level

The correct coordination between flashover characteristics of the insulator assembly, the sparkover voltage of the EGLA with front-of-wave and standard lightning impulses and the residual voltage of the EGLA at nominal discharge current has to be demonstrated either in a type test (with a "generic" gap assembly) or in an acceptance test (with the spark gap and insulator assembly specific for the intended application). Any sparkover operation for lightning impulse voltage must occur in the external series gap, without causing any flashover of the insulator assembly to be protected. Two different approaches for verification are allowed: the demonstration may be performed either as a type test, without the insulator assembly, or as an acceptance test including an insulator assembly of the shortest insulation distance of the intended application. In the first case, sparkover and residual voltages (including inductive voltage drops across the SVU, the gap and the connection leads) are determined and coordination with the insulator assembly is performed by statistical means. In the latter case, correct operation of the configuration (reliable sparkover of the gap, no flashover of the insulator assembly) comes out directly, and only safety margins are calculated by statistical means.

Switching impulse wet withstand tests and power frequency wet withstand tests must be performed with the SVU shortened to determine the minimum external gap length for which no sparkover will occur in the EGLA so that all switching overvoltage flashovers are across the line insulation.

5.2.4.2.7 Follow current interrupting performance under polluted conditions

The follow current interruption operation of the EGLA under wet and under polluted conditions is required to be demonstrated in a type test or acceptance test. In real service, no flash-over of the SVU surface is allowed, and the follow current in the external series gap must be reliably interrupted.

IEC 60099-8 specifies two different approaches for a "follow current interrupting test", named "Test method A" and "Test method B". If the pollution severity on site is "Very heavy" according to the definition in IEC/TS 60815, "Test method B" shall be applied. Otherwise, the choice of the test method is up to the manufacturer.

With "Test method A", the effect of pollution on the SVU external surface current is modelled by an additional linear resistor connected in parallel to the SVU, and the test is performed under clean and dry conditions. The parallel linear resistance is required to be selected such that the resulting follow current equals at least that through a solid pollution layer of conductivity according to the specified SDD level plus the expected current through the SVU in case the full line-to-earth voltage is applied to its terminals.

"Test method B" is a test under artificial pollution conditions.

For both methods, the test setup is energized at power-frequency voltage equal to the EGLA rated voltage, and then five sparkovers at each polarity are initiated by lightning impulse voltage application. The developing follow current is required to be interrupted within the first half cycle of the power-frequency during each of the ten operations, and no further sparkover shall occur in any subsequent half cycle.

5.2.4.2.8 Rated short-circuit current, I_s .

In the type test, basically the short-circuit test procedure of IEC 60099-4 applies. It is up to the manufacturer if the test samples are mounted standing upright or hanging (according to the intended installation). It is noted – but not required – that special mechanical requirements

after the test may apply, e.g. that the SVU remains mechanically intact and can be lifted and removed by its top end. A problem, also for other tests on EGLA, is that the spark gap and the SVU are independent devices, and that the gap may be of many different designs for each individual application. Therefore, the gap is not included in the short-circuit test, but has to be tested elsewhere.

Short-circuit tests according to IEC 60099-8 allow arresters to fall apart as long as the pieces fall within specific areas below. This allowance in the present standards should be noted as for many areas below a transmission or distribution line the public have access. It should also be noted that a failed SVU of an EGLA may be exposed to several short-circuit current events before it is exchanged as this will occur for every sparkover of the gap thereafter.

5.2.4.2.9 Mechanical performance

As for station arresters, specified long-term load (SLL) and a specified short-term load (SSL) shall be specified. Besides the mechanical tests as per IEC 60099-4, an additional vibration test has been introduced to IEC 60099-8. Basic requirement is a number of one million oscillations of $1 \times g$ at the arrester top terminal. It is also mentioned in a note that such a test should also be performed on the gap assembly.

5.3 Installation considerations for arresters

5.3.1 High-voltage station arresters

5.3.1.1 Installation considerations

An arrester, compared with other equipment in a substation, is essentially a simple device. In fact, there are not too many requirements to the user on transportation, storage and erection of an arrester. However, it should not be underestimated that an arrester with all its accessories such as grading and corona rings, flange covers or insulating base, contains semi-conducting, highly non-linear MO resistor elements, which are continuously connected to the line for the full arrester's lifetime. An arrester has been very carefully optimized by the manufacturer for a good compromise between stable operation under continuous operating voltage and environmental stresses on one hand and low protection levels and high energy handling capability on the other. This balance is easily disturbed if any accessories are omitted or assembled incorrectly. Therefore, it is essential to read and follow the manufacturer's installation and operation manuals.

The precautions specified by the manufacturer for transportation and storage should strictly be followed. Especially porcelain-housed arresters are usually very sensitive to transportation stress, which often represents the highest mechanical stress during an arrester's lifetime. In most cases transportation and storage in upright position are specified.

For polymer-housed arresters it is particularly important to ensure a controlled climate during storage. Biological growth, e.g. of moss and fungi, on the housing may be initiated or supported if the arresters are stored in the wrapping enclosure as used for transportation. The manufacturer usually gives clear instructions if the transportation enclosure shall be removed for storage or not.

Multi-unit arresters are usually delivered in individual units, which need to be assembled during erection on site. Again, it is important here to follow the manufacturer's mounting instructions. The units need to be assembled strictly in the correct order as they may have different voltage ratings and housing lengths. A wrong arrangement may cause e.g. external flashovers to the intermediate flanges or poor performance in polluted environment. If straps are used in order to lift the units care must be taken not to damage the insulating sheds in case of polymer-housed arresters.

Some types of surge arresters (usually porcelain-housed or polymer-housed arresters of "tube design") require mounting of metallic top cover plates and intermediate plates between the

individual units. If these plates are left out the short-circuit (pressure relief) performance of the complete arrester may be affected.

Beginning with a height of about 1,5 m to 2 m, MO surge arresters are equipped with grading rings. These rings serve for continuous operating voltage grading along the arrester axis. As a matter of course, these rings should not be omitted. It is also important that rings of exactly those dimensions as specified by the manufacturer are used. The number of rings, their diameter and the length of their supporting struts are carefully optimized with respect to voltage and temperature distribution within the arrester. Leaving out the grading rings or using such of wrong dimensions may lead to a complete failure of the arrester within short time.

Usually the highest stress due to uneven voltage distribution along the arrester, caused by earth capacitances, occurs when the arrester is erected directly on the ground. The delivered grading rings are dimensioned in order to handle this worst case situation. In addition, if the arrester is installed on top of a pedestal, which reduces the impact of earth capacitances, the grading rings must not be omitted or changed. For further details on this subject see IEC 60099-4:2009, Annex L.

In the case of an arrester with grading rings the manufacturer's declared minimum clearances to earthed or live parts count from the outer circumference of the largest ring must be adhered to. If the grading rings constitute a problem with clearances no change of the configuration is permitted. The manufacturer should then be contacted in order to decide – for the particular application – if another configuration can be adopted.

At 500 kV and above, arresters are delivered with additional corona rings, which shall be mounted on top of the arrester in order to electrically shield the high-voltage terminal. They serve to limit corona effects and the radio interference voltage (RIV) level. It is important during assembly not to mix up grading rings and corona rings, which may largely differ in dimensions. Figure 5 shows examples of HV arresters equipped with grading and corona rings.

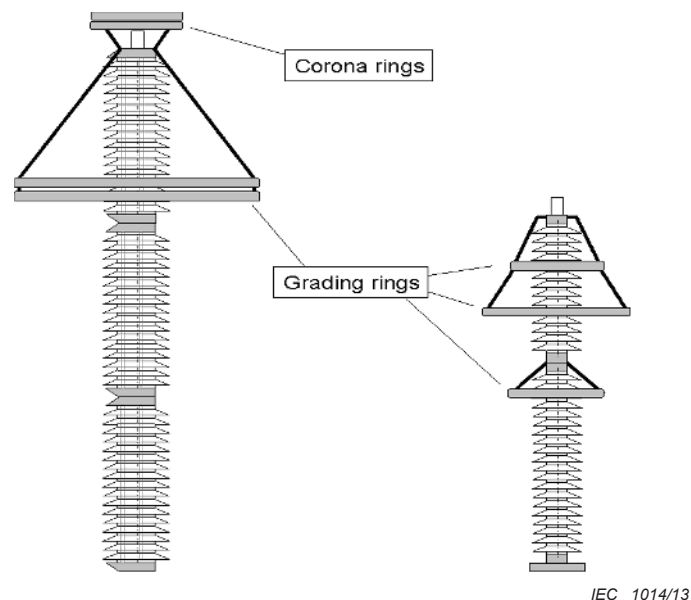
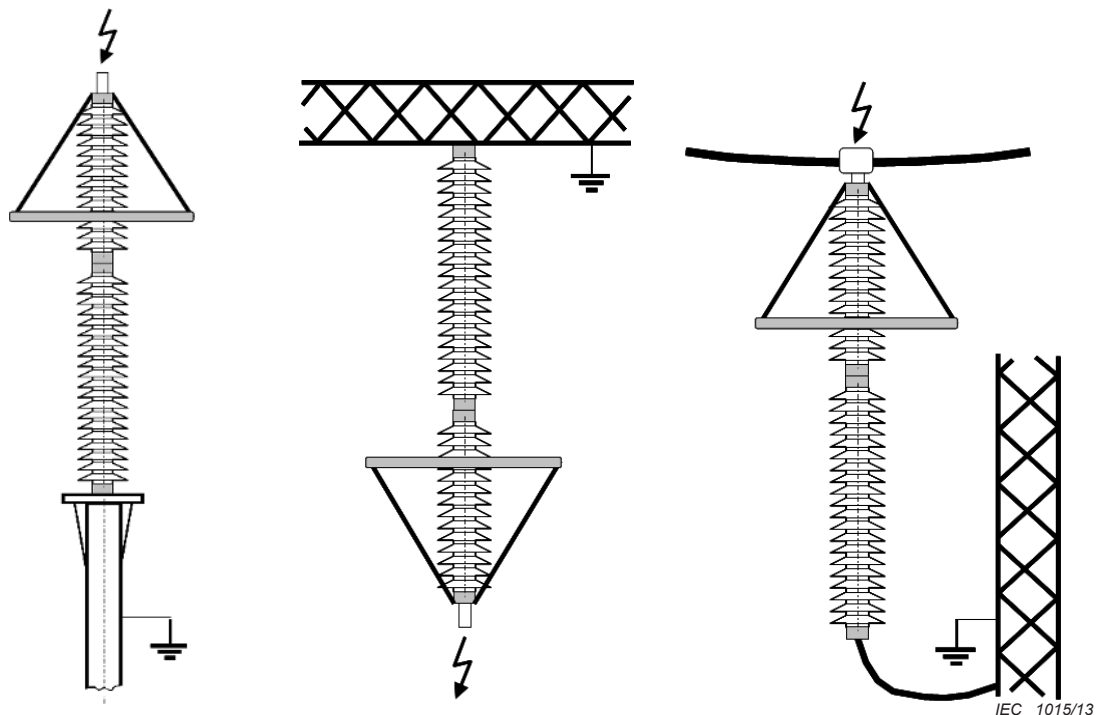


Figure 5 – Examples of UHV and HV arresters with grading and corona rings

The manufacturer also gives clear instructions on the possible mounting positions of the arrester (standing upright, suspended, inclined). In a suspended installation the orientation of the weather sheds shall not be changed, i.e. the upper surface of the sheds shall be directed

upwards. Similar considerations with regard to orientation of the weather sheds apply for mounting the arrester at a certain angle (if this is allowed by the manufacturer).

When mounted suspended from an earthed structure the functions of arrester top and base are exchanged: the top flange is earthed, and the base acts as high-voltage terminal. In this case the grading rings must be connected to the base (i.e. the high-voltage terminal). If, however, the arrester is suspended from a line conductor, the top terminal is the high-voltage terminal, and the arrester is installed as on a pedestal. Figure 6 gives examples for different kinds of installations. As aforementioned, the individual units of an arrester may have different voltage ratings and therefore have to be assembled in a predefined order from bottom to top, or, more precisely, from the earthed to the live end. In a suspended installation this order might thus be affected as the bottom flange represents the high-voltage terminal and the top flange is the earthed end. It should be carefully checked from the data sheet or the installation instruction if suspended installation is generally allowed or not, or whether it is allowed only if changes in the order of the individual units are applied. Usually, for that reason, intended installation other than standing upright should be specified at the time when the arrester is ordered. If there is any doubt during erection on site, the manufacturer should be contacted.



**Figure 6 – Same type of arrester mounted on a pedestal (left),
suspended from an earthed steel structure (middle)
or suspended from a line conductor (right)**

If the arrester is erected with an insulating base in order to allow connection of monitoring devices (such as counters or leakage current indicators) the insulating base must not be short-circuited in the new as well as in aged condition. This implies the need for occasional cleaning during service life. Although a short-circuited or bypassed insulating base will not affect the arrester's function this may lead to a malfunction of the connected monitoring devices.

If the arrester is equipped with pressure relief devices and vents (which usually is the case with porcelain-housed or polymer-housed arresters of the "tube design") the position of the vents should be carefully chosen. First of all, personnel have to be protected. A good compromise should be found to protect primarily people but also valuable equipment from the impact of a burning arc in case of pressure relief. It is important to mention that not only the direction of the venting outlet but moreover the direction of the acting electrodynamic (Lorentz) forces caused by the short-circuit current will decide on which way the burning arc is

travelling. In this sense also the arrester itself should be protected from direct contact with the arc in order to avoid possible thermal breaking (in case of porcelain) or burning (in case of polymer) of its housing and thus to minimize damage after failure.

5.3.1.2 Separation distance and protective zone

Due to their possible high rate-of-rise, travelling wave effects between arrester and equipment cannot be neglected for fast-front overvoltages (they do not play a role for slow-front overvoltages). Generally, fast-front overvoltages at the protected equipment are expected to be higher than the arrester residual voltage. The overvoltage at an open terminal with a high surge impedance will rise with two times the steepness of the original surge until, after two travelling times of the surge from the arrester to the apparatus terminal, the arrester will effectively reduce the voltage. A damped oscillation having an amplitude of up to two times the arrester's lightning impulse protective level U_{pl} and a cycle time of four times the travelling time from the arrester to the apparatus will be the result. The shorter the travelling distance is, the lower the amplitude of the resulting overvoltage. Therefore, it is always good practice to minimize separation distances between arrester and major equipment. Sometimes, it is possible to protect more than one apparatus with a single arrester installation provided that rates of rise can be limited as in the case where both the station and overhead lines are adequately shielded.

Insulation coordination and arrester selection are further discussed in Clause 6.

5.3.1.3 Connecting leads

The cross-sectional area of the connecting leads is determined more by mechanical than by electrical requirements. It mainly has to fit to the overhead line conductor or the bus bar with regard to corona performance. Due to the very short time of discharge current flow, power or energy consumption in the conductor plays less a role here even though the currents may be high. The inherent resistive and inductive impedance in the leads will increase the effective residual voltage seen by the equipment being protected. This issue is particularly sensitive for protection from fast-front overvoltages. Therefore it is important to keep these lead lengths short and free of inductive loops. As an example, a steepness of $5 \text{ kA}/\mu\text{s}$ of a lightning current impulse can be expected. Under these conditions the inductive voltage drop shown in the arrangement of Figure 7 is:

$$U_i = L \times \frac{di}{dt} = 10 \mu\text{H} \times 5 \text{ kA}/\mu\text{s} = 50 \text{ kV} \quad (1)$$

This does not necessarily appear simultaneously at the peak value of the arrester residual voltage. However, this value of 50 kV demonstrates the order of magnitude of possible inductive voltage drops which can superimpose the arrester residual voltage (which is typically 800 kV to 850 kV for this example).

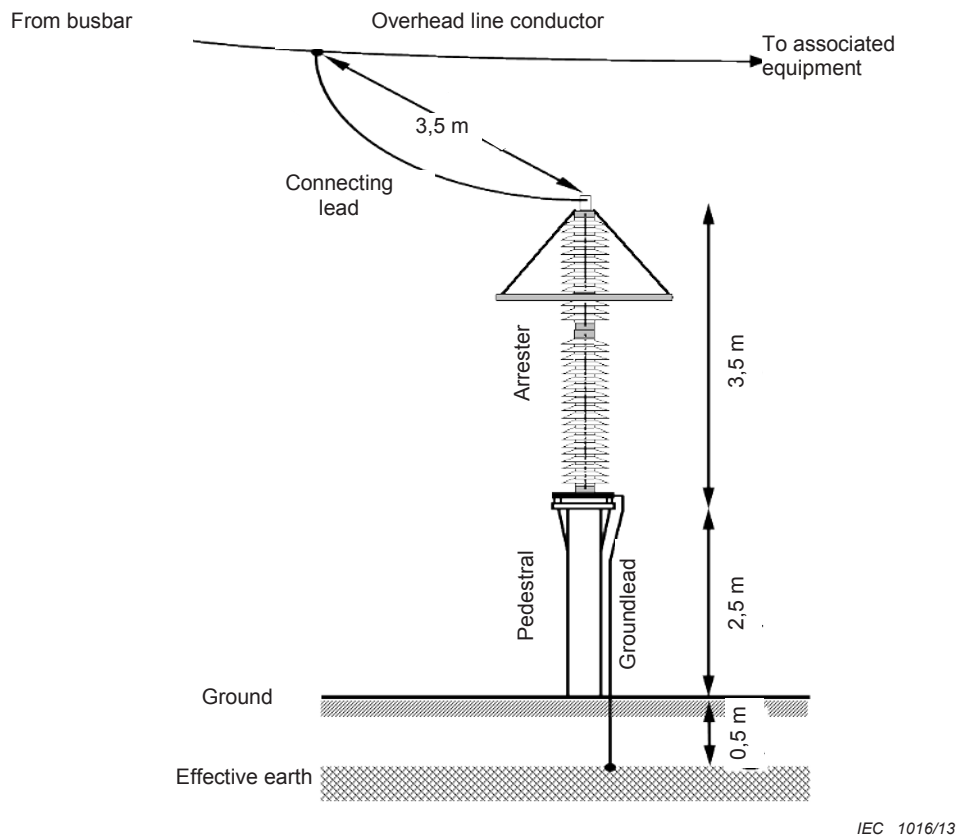


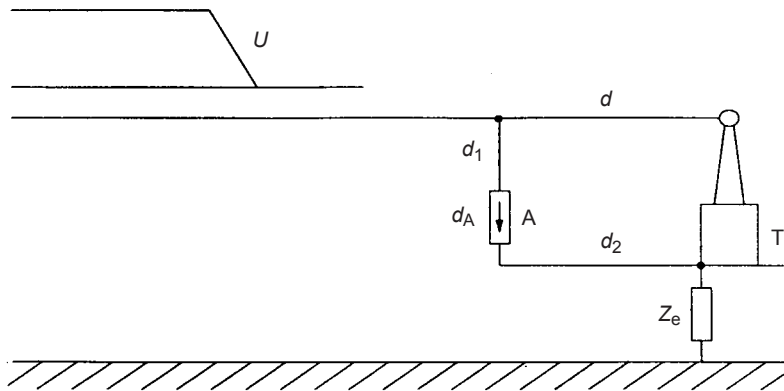
Figure 7 – Typical arrangement of a 420-kV arrester

The leads shall be rated for the arrester current during discharge operation and for short-circuit conditions (kA range; μ s to s time duration). The leads should see only a few mA of leakage current during steady state conditions. The connecting lead cable and termination shall be adequately rated for the impulse duty associated with the rated short circuit current. Any fixings shall also be capable of the mechanical duty necessary to meet the above, especially if used in an inverted or inclined from vertical applications.

5.3.1.4 Earthing of surge arresters

As a general rule, surge arresters should be located as close as possible to the equipment to be protected in order to ensure effective overvoltage protection. The length of HV and earth connection leads should be short and as straight as practical in order to minimise the loop inductance and ensure minimum voltage drop across the leads (see Figure 7). The HV and earth leads, together with the connection points, should be rated to withstand both the high-magnitude surge currents as well as short circuit current in the event of a flashover at the arrester or equipment location. A low earth impedance electrode is required to dissipate safely the high magnitude current into the earth.

The earth side of the arrester is connected to the substation earth. Figures 8 and 9 illustrate the difference between transmission and distribution models. The earth mat is the reference point for the effective protective voltage level. It is also the point at which the arrester will channel current into the mat quickly to provide overvoltage control.

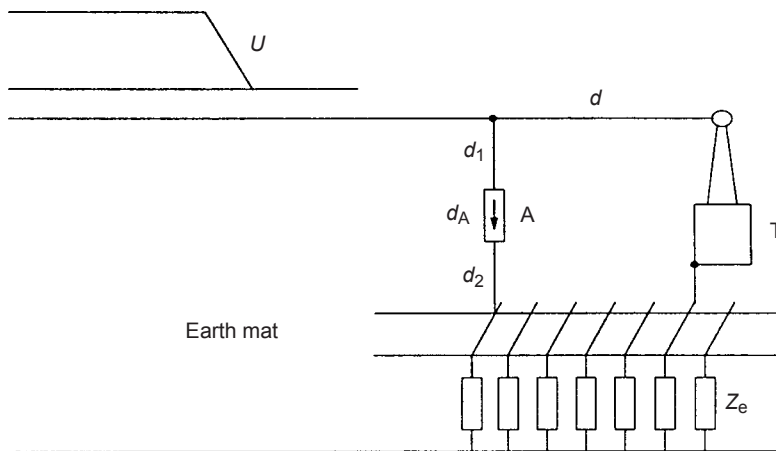


IEC 1017/13

Key

- | | | | |
|-------|----------------------------------------------------------------------------------------------|-------|--------------------------------|
| U | incoming surge voltage | d_A | height of arrester |
| d | length of conductor between transformer busing and point of connection of arrester line lead | d_2 | length of arrester ground lead |
| d_1 | length of arrester line lead | Z_e | grounding impedance |
| A | arrester | T | transformer |

Figure 8 – Installations without earth-mat (distribution systems)



IEC 1018/13

Key

- | | | | |
|-------|----------------------------------------------------------------------------------------------|-------|--------------------------------|
| U | incoming surge voltage | d_A | height of arrester |
| d | length of conductor between transformer busing and point of connection of arrester line lead | d_2 | length of arrester ground lead |
| d_1 | length of arrester line lead | Z_e | grounding impedance |
| A | arrester | T | transformer |

Figure 9 – Installations with earth-mat (high-voltage substations)

The connection between the arrester and the equipment necessitating protection should be kept as short as possible to minimise voltage drop due to conductor impedance to fast-front overvoltages. Furthermore, a loop in the earthing connection may cause flashovers of the arresters insulating base, which usually withstands only a few kilovolts. While direct connection to the equipment (e.g. transformer tank) is effective, due consideration needs to be given to the conduction path of high frequency current through the tank. This could cause potential rise problems elsewhere and introduce safety risks.

For inverted or under hung arresters the earth connection can be very long, with lengths over 20 m. This shall be taken into account when establishing the design protective margin.

The earthing effectiveness will affect the protection provided by the arrester. Therefore if the earth system is not solidly earthed, the margin offered for fast-front overvoltages needs to be considered through a study.

In high voltage systems, in particular, $U_s > 245$ kV, it is usually difficult to locate the arresters very close to the equipment. However, every effort shall be made to reduce the separation distance between the arrester and equipment. As a general rule, and for effective overvoltage protection, the separation distance should always be less than 10 m. Common practical separation distances are on average 3 to 5 m, which results in difficulties to establish a direct short connection between the arrester base and the earth terminal of the equipment to be protected. Under such circumstances the arrester is connected to the substation earth grid and effectively bonded to the equipment through the grid. However, without the provision of a low impedance earth connection at these locations, the overvoltage protection afforded by the arrester could be impaired, and high earth potentials could appear on the earthing connections close to the surge arrester itself and at the equipment following the passage of high magnitude, fast-front surge.

It is now well established that fast-front surges will rapidly attenuate in the earthing system, giving a sharp fall in surface earth potential, away from the point of injection. This may result in large voltage differences between close locations on the same earthing system. In order to minimise these potential differences, an earthing connection, as short and straight (free of bends) as possible, should be made between the earthing points of the plant and the arrester. To mitigate the rise of earth potential and help dissipate the surge current in an effective manner, the so-called high frequency rod is an alternative. These rods can be driven to depths of 5 m or deeper depending on the local soil resistivity. The rods allow contact with deeper, low resistivity soil layers, and hence, improve surge current dissipation and reduce the overall earth impedance. When rods are not practical, buried horizontal-conductor counterpoises can be used. If the separation distance is relatively long, the earthing connection should be routed directly underneath the high voltage connection between the arrester and the equipment, which reduces the loop inductance.

5.3.1.5 Mechanical considerations

Often there is only a vague idea as to the mechanical stress of an arrester in service, and accordingly no requirements are made, or, maybe even worse, required values are too high. If there is no information available about the actual requirements, the following values can serve as a guideline for the necessary static head loads: $F_{\text{stat}} = 400$ N up to and including $U_s = 420$ kV, $F_{\text{stat}} = 600$ N for $U_s = 550$ kV and $F_{\text{stat}} = 800$ N for $U_s = 800$ kV (F_{stat} corresponds to SLL according to IEC 60099-4). These values represent absolute minimum requirements assuming that the arrester is connected by strain relieving conductor loops and a wind velocity of 34 m/s (≈ 120 km/h) is not exceeded, which according to IEC 60099-4 belongs to the "normal service conditions". Regarding forces imposed by wind loads, IEC 60099-4:2009 gives guidance for calculation in its Annex M.5.

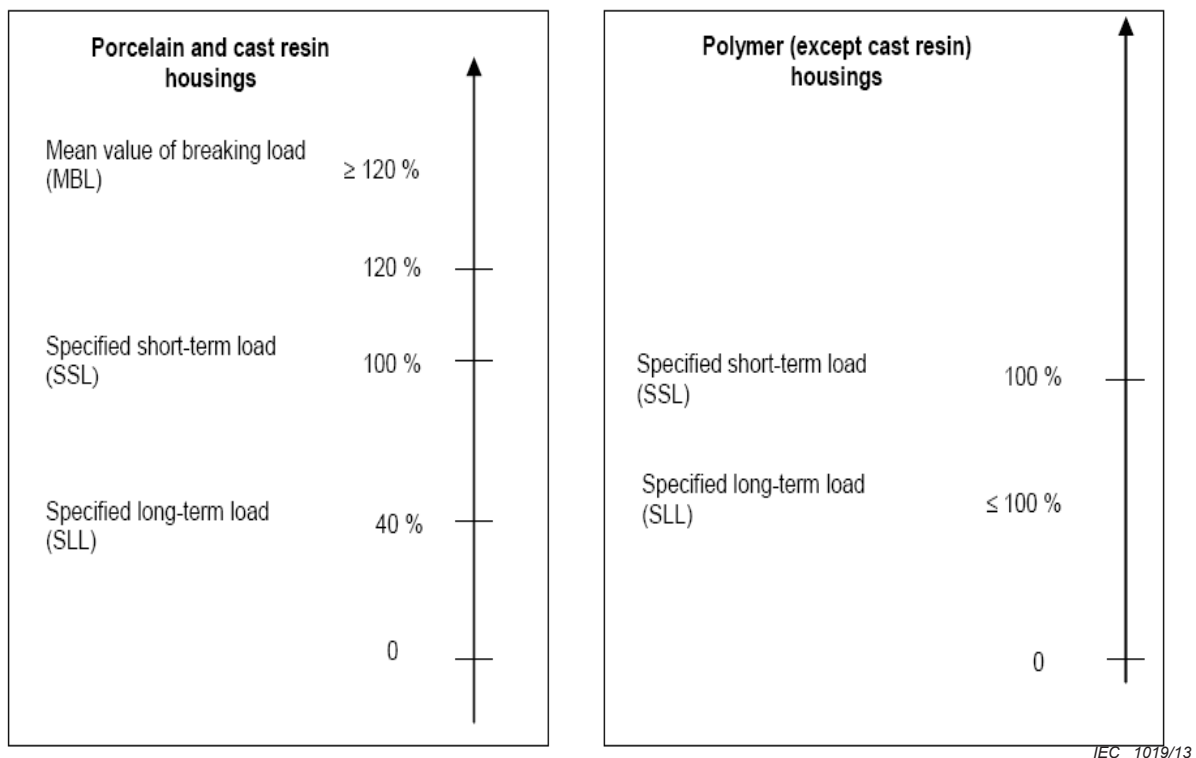
Besides the static cantilever loads, which normally cause the arrester few problems, dynamic requirements must also be considered. These can, for example, occur as a result of short-circuit currents on the line, or of gusting winds. In this case arresters with porcelain housing can, because of the brittle properties and statistical behaviour of the porcelain, be strained at only up to 40 % of its dynamic strength. The specified permissible dynamic head loads (SSL according to IEC 60099-4) should prove, on the other hand, to have at least a 20 % safety margin to the mean value of the actual breaking values (MBL according to IEC 60099-4), ascertained during tests. The cantilever load values mentioned above are accordingly expanded upon in Table 1.

Table 1 – Minimum mechanical requirements (for porcelain-housed arresters)

Highest system voltage U_s (kV)	$F_{\min, \text{static}}$ (N) ("SSL")	$F_{\min, \text{dynamic}}$ (N) ("SSL")	Minimum breaking value (mean value) ("MBL") (N)
≤ 420	400	1 000	1 200
550	600	1 500	1 800
800	800	2 000	2 400

Sometimes, mechanical strength is given in terms of cantilever strength. In a 420 kV-system, for instance, where the arrester height is about 3,5 m, the resulting required static cantilever strength is 1,4 kNm. In a 170-kV-system the arrester height is typically 1,7 m, and thus the minimum required static cantilever strength is 680 Nm.

A smaller distance might be adopted, since the polymer housing (with the exception of the cast resin housing, which has brittle characteristics similar to those of porcelain, and thus, is considered in exactly the same manner) diverges less in its mechanical characteristics. As no fix ratio between dynamic and static load is specified in the standard IEC 60099-4, special care should be taken when comparing catalogue values and technical data sheets. Figure 10 (from IEC 60099-4:2009) shows the different approaches for porcelain and cast resin housed as well as for polymer-housed arresters.

**Figure 10 – Definition of mechanical loads according to IEC 60099-4**

Polymer housings, in contrast to porcelain housings, are visibly deflected under the influence of mechanical forces. Generally, this is not a consideration, however, in those cases in which this sort of behaviour would cause problems, choosing a mechanically stiffer housing must be considered, which will be less strained under the loads occurring here, and thus be less deflected.

In particular for polymer-housed arresters, an installation different from the classical "standing upright" base mounted position may be an option, e.g. suspended mounting of the arrester requires only a minimum of mechanical strength of the arrester. However in such a case the

whole construction shall be prepared to carry the weight of the arrester, which is often not the case for existing installations. These mounting alternatives shall therefore be considered just in the planning phase.

5.3.2 Distribution arresters

5.3.2.1 General considerations

The manufacturer should give clear instructions about the assembly and installation, maintenance, transport, storage and disposal of MO arresters, found in the operating instructions (manual) provided by the manufacturer.

Distribution arresters are single unit arresters without grading rings often installed directly at the distribution transformers. However, they can be equipped with disconnectors, brackets (insulating or metallic), fault indicators, and/or wildlife protectors (bird caps).

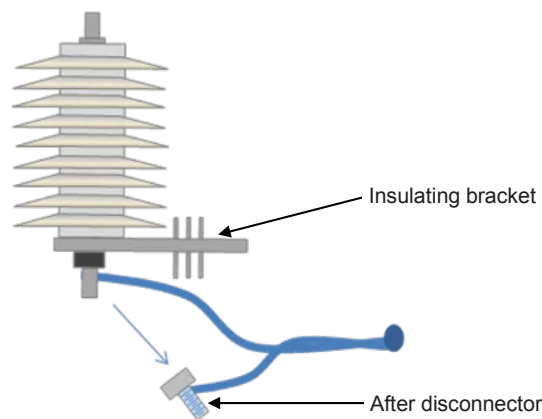
The disconnectors are used for automatically disconnecting a surge arrester that has been overstressed. They are generally placed on the earth side directly under the arrester. Disconnectors should both isolate the arresters from earth potential and at the same time indicate a faulty arrester that should be replaced. The earth connection shall be flexible and it is necessary to have sufficient insulation distance beneath the arrester, so that the disconnected earth connection can hang freely, and the applied operating voltage that occurs at the foot of the arrester does not lead to spark-over after disconnector operation.

The purpose of disconnectors is to prevent overstressed arresters from leading to a permanent short circuit resulting in an inoperable system. It is thus possible to provide continuous energy supply without prolonged interruptions. This is obviously an advantage in inaccessible areas or if the failed arrester cannot be quickly replaced. The disadvantage is that there is no overvoltage protection as long as the arrester is disconnected. That is why it is important to replace the arresters that are out of order and were disconnected from the system as quickly as possible.

Insulating bracket are used together with disconnectors to facilitate re-energization of the distribution transformer after arrester failure (Figure 11). Other kinds of brackets may be used for installation purposes only.

If high voltage fuses are installed in the same current path as the disconnectors, the response characteristics of both protection devices shall be coordinated with one another. The disconnector shall respond in time before the fuse or at the same time with it. This concept prevents the switching on of the current when a new fuse is installed as long as a short circuit still exists.

Fault indicators indicate with some bright colour material that the arrester has been overstressed and should be replaced. They do not separate the arrester from earth potential. These devices are installed either on the high voltage side or on the earth side directly at the arrester. If the arrester is overstressed, the short circuit is permanent and the system is switched off, but the damaged arrester can clearly be detected and in this way be quickly replaced.



IEC 1020/13

Figure 11 – Distribution arrester with disconnector and insulating bracket

To reduce the potential external flashover of distribution arresters wildlife protectors need to be considered. For short arresters where animals can bridge the high voltage terminal and other earthed points on or near the arrester the installation of barriers or large wildlife protectors can adequately affect this issue.

5.3.2.2 Connecting leads

The national specifications and the requirements of the system user are in principle to be observed for the connections. However, the diameter of the connections shall be chosen in such a way that at least the short circuit current for the respective arrester (for the given short circuit current duration) does not lead to the melting or the tearing off of the connections. This applies to both the high voltage connections as well as the connections to the earth.

The location of the distribution arrester relative to the protected equipment can be very important when considering the fast rising lightning surge [17]. When protecting from fast rising surges the lead length in series with the arrester and in parallel with the protected equipment can generate a significant voltage due to its inherent inductance. This lead voltage is in addition to the fast front characteristics of the arrester. The connections shall be installed as short and straight as possible. This is because inductive voltages appear at each conductor due to the self inductivity during the flowing of the impulse current. These inducted voltages are considerable during high rate of changes di/dt , such as when lightning currents occur. The MO material itself reacts almost instantaneously even with very steep voltage and current impulses [43] [44] [45] [46]. In view of the dimensions of the arrester itself and the connections, there are always inductive voltages and it is necessary to take them into account. If the residual voltages found in the datasheets does not contain an inductive voltage drop corresponding to 1 $\mu\text{H}/\text{m}$ of arrester length, then the arrester height must be considered.

The additional inductive voltage is consequently calculated as:

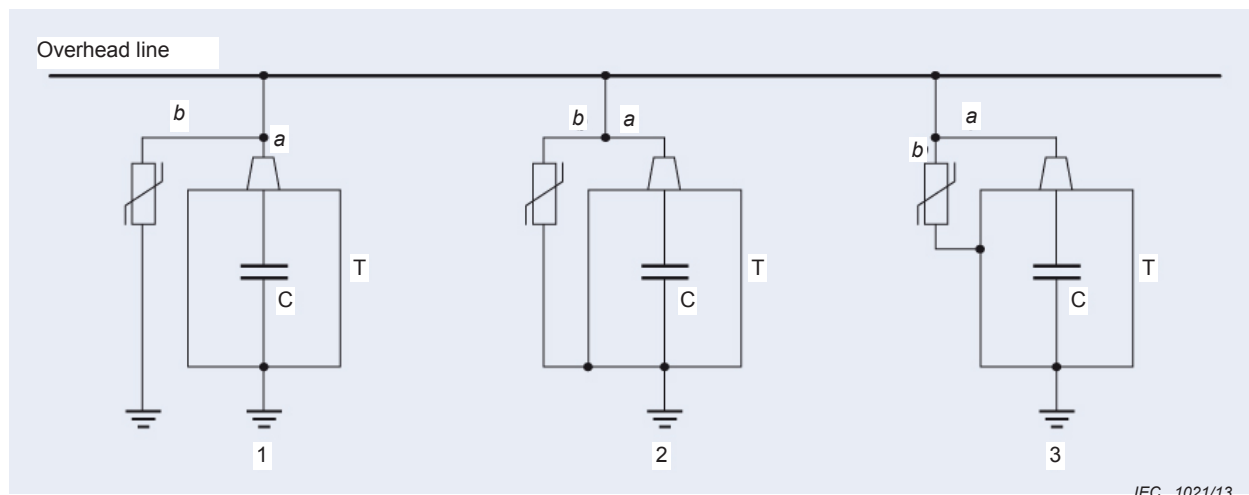
$$U_i = L \times \frac{di}{dt} \quad (2)$$

A voltage of $U_i = 10$ kV per meter of connection lead results from a steep current impulse with a rise time of $1\mu\text{s}$ and 10 kA peak value. This means that the connections and the entire loop shall be executed to the greatest degree possible without inductance. Both the arrester and the transformer shall of course be connected at the same earthing point.

When a 6 amp or lower fuse is in series and on the source side of an arrester as a result of reducing lead length, the fuse rating may need to be increased by a few per cent to avoid nuisance fuse blowing when the arrester conducts a surge.

5.3.2.3 Earthing of distribution arresters

At distribution voltage levels (U_s normally $\leq 36\text{kV}$), often arresters can be located very close to the equipment to be protected, e.g. transformers. In this case, and where possible, the earth terminal of the arrester and equipment should be bonded with a very short straight conductor (see Figure 12).



IEC 1021/13

Key:

- 1 Poor. The arrester and the transformer do not have the same earthing point. The incoming overvoltage reaches first the transformer bushing. The connection *b* is too long.
 - 2 Good. The arrester and the transformer have the same earthing point. The connections *a* and *b* are about the same length.
 - 3 Very good. The arrester is earthed directly at the transformer tank. The connection *b* is almost zero. In this way, the incoming overvoltage reaches first the arrester, which limits the overvoltage without delay.
- a* conductor between transformer busing and point of connection of arrester line lead
b arrester line lead
C internal capacitance of transformer
T transformer

Figure 12 – Examples of good and poor earthing principles for distribution arresters

Low earth resistances is essential and should be as small as possible in order to limit the earth potential rise at the earth terminal, and hence mitigate safety hazards and flashover on the voltage side of the transformer. A value of earth resistance $\leq 10 \Omega$ is considered to be sufficient. This is why specially designed earthing installations are used in order to discharge the current impulse. Earth resistances are measured mainly with direct current or 50/60 Hz alternating current; however, in case of high frequency (or current impulse with high frequency content) the value will in general be different. For pole mounted transformers, careful consideration needs to be given to the design of the earth electrode in order to achieve a low earth resistance using rods and horizontal counterpoises. The applicable earthing standards should be consulted.

5.3.2.4 Mechanical considerations

Static cantilever loads are small on distribution arrester due to their shortness. The maximum allowed torque during installation may be more important together with the forces due to wind gusts as distribution arresters are often installed up in poles connected to the overhead lines.

5.3.2.5 Oil immersed arresters

There are distribution transformers with built-in distribution MO resistor elements, which give optimized protection for the transformer. The drawback is that if the arrester has failed due to lightning or any other reason the whole transformer has to be replaced. Hence, these are only used when single-phase transformers are used.

5.3.3 Line surge arresters (LSA)

5.3.3.1 Installation considerations

LSA are directly installed in the overhead line. In the majority, LSA are polymer-housed arresters and serve for protection against lightning overvoltages only. Polymer, compared with porcelain-housed arresters, offer lower weight and easier handling, and they often have a better overload performance. It is important to note that safety issues (mechanical strength, short-circuit performance) play a very significant role for line arrester applications, as LSA are installed in areas of general public access. Therefore, a reasonable compromise between economical and safety aspects should be found for each particular application.

Usually, installation of non-gapped line arresters (NGLA) is easier than that of EGLA. In the simplest case, an LSA in a distribution system is just a standard distribution arrester, with no additional requirements on mechanical or electrical characteristics. While distribution LSA are mainly gapless, many of the installed transmission LSA are of the EGLA type. An external series gap allows for lower rated voltage of the series varistor unit (SVU). Energy handling requirements of an EGLA on one hand may be lower, as the arrester is not involved in switching overvoltage events; on the other hand it may be higher as the charge transfer (and thus energy dissipation) is not necessarily shared with other parallel connected arresters. Requirements on polymer housing material may be lower for the EGLA, as the SVU is not continuously energized. On the other hand, adjusting of the sparkover voltage is sometimes difficult – it must not exceed the insulators' lightning impulse withstand voltage when the SVU is intact, and it must withstand switching overvoltages on the line when the SVU has failed.

NGLA for transmission lines, sometimes named TLA, are in most cases directly suspended from the line conductor close to an insulator. The earth connection is connected to the tower steel structure. For NGLA utilization of appropriate disconnectors is essential. The electrical characteristics of the disconnector are in general different from those of disconnectors for distribution arresters, because the operating duties, where disconnection shall not occur, are harder. It should be ensured that after disconnection no part (swinging in the wind) will be able to produce a flashover to earth.

There are different possible ways of mounting an EGLA. Suspended installation from the cross arm of a tower is quite common. But there are also designs where the EGLA is directly connected to the line insulator. In this case the SVU may be installed in a horizontal position.

The grading rings should not be omitted under any circumstances.

5.3.3.2 Connecting leads and earthing

The length of the earth lead shall on one hand be large enough to allow for movements of the arrester due to wind forces. On the other hand it should be as short as possible in order to minimize the current loop and the related inductive voltage drop under fast-front overvoltages. NGLA usually have a disconnector in the earth lead.

5.3.3.3 Mechanical considerations

It has become apparent that the long term performance of the mounting hardware is in many cases much more critical than that of the arrester itself. Special care should therefore be taken when specifying the hardware. A design should be chosen that imposes least mechanical stress to the components, and the quality should take the extreme mechanical and environmental operating conditions into account.

In case the arrester is installed directly on the tower (e.g. standing upright vertically or inclined on a cross arm, or horizontally at the tower's main structure) it should be ensured that the arrester has sufficient mechanical strength. It should not be underestimated that vibration, wind and ice loads are much more of an issue in this application than in standard substation applications. If the arrester hangs down from the cross arm, the correct orientation of the weather sheds shall be regarded (see Figure 6).

EGLA installations need overall assemblies that allow movements of the SVU and the line conductor, respectively, without affecting the sparkover voltage of the gap. In all cases it has to be considered that EGLA (as well as all LSA in general) are exposed to wind and possibly ice loads much more than arresters in substation applications. Therefore, mechanical requirements may be higher and different from substation applications.

It should be noted that short-circuit testing according to IEC 60099-4, IEC 6009-6 or IEC 60099-8 does not automatically mean that the LSA is mechanically intact after a successful test. The whole LSA may actually fall down. This allowance in the present standards should be noted as the public have access to many areas below a distribution or transmission line.

5.3.3.4 Fault clearing

The risk of electrical overloading of LSA and subsequent failure due to excessive energies from lightning strikes may be higher for LSA applications than for arresters applied in substations due to the absence of the substation shielding which prevent direct strikes of high current amplitudes. As overhead line insulation is generally self-restoring, a failed LSA needs to facilitate fast reclosing. This can be done by isolating the line arresters from the line in the event of overloading by the use of a disconnecter for NGLA as they may fail short. In the case of EGLA, the sparkover voltage of its gap shall be coordinated with maximum switching impulse withstand voltage (SIWV) of the line insulation so that the line can be energized again without causing a sparkover of the EGLA gap.

6 Insulation coordination and surge arrester applications

6.1 General

Insulation coordination determines the dielectric withstand and the characteristic response of power systems to electromagnetic stresses. This requires selection of the dielectric strength of equipment in relation to the voltages that can appear on the system for which the equipment is intended, while taking into account the service environment and the characteristics of the available protection and control devices.

The first part of this section outlines the basic principles and insulation coordination practice, which specifically affect or determine surge arrester characteristics. This includes the procedure for establishing equipment protection margins, the different types of overvoltages and application of surge arresters to both equipment and the network.

The remaining parts of this section provide recommendations for the selection and application of surge arresters to be used in three-phase systems with nominal voltages above 1 kV. It applies to gapless metal-oxide surge arresters as defined in IEC 60099-4, to surge arresters containing series gapped structure – rated 52 kV and less as defined in IEC 60099-6 and EGLA for overhead transmission and distribution lines as defined in IEC 60099-8.

6.2 Insulation coordination overview

6.2.1 General

The process of insulation coordination is defined in IEC 60071-1, *Insulation coordination: Part 1 – Definitions, principles and rules*. This is supported in greater detail by IEC 60071-2, *Insulation coordination: Part 2 – Application guide*, which expands on the principles defined in Part 1. The standard deals with the selection of insulation and the determination of rated withstand voltage for equipment in range I (up to 245 kV) and range II (above 245 kV).

Insulation coordination practices in power systems can be divided into two basic categories; line and station. Line insulation coordination deals primarily with prevention of line faults from lightning and line switching operations, while station coordination deals predominantly with protection of station equipment from incoming lightning surges on lines and impact on local and remote equipment during station switching operations. In modern insulation coordination practices, application of surge arresters is considered a fundamental and economical method of achieving the desired equipment protection and/or system performance [1] [2] [3] [4] [5] [6] [7] [8] [9] [10] [11] [12] [13] [14].

6.2.2 IEC insulation coordination procedure

A typical insulation coordination procedure adopts the following format to determine:

- 1) System analysis: Representative voltages and overvoltages in service.
 - Selection of arrester protective characteristics and location
- 2) Determination of coordination withstand voltage (U_{cw})
 - Selection of arrester protective characteristics and location (for fast-front overvoltages, step 1 is left out)
- 3) Determination of required withstand voltages (U_{rw})
- 4) Selection of the rated insulation level

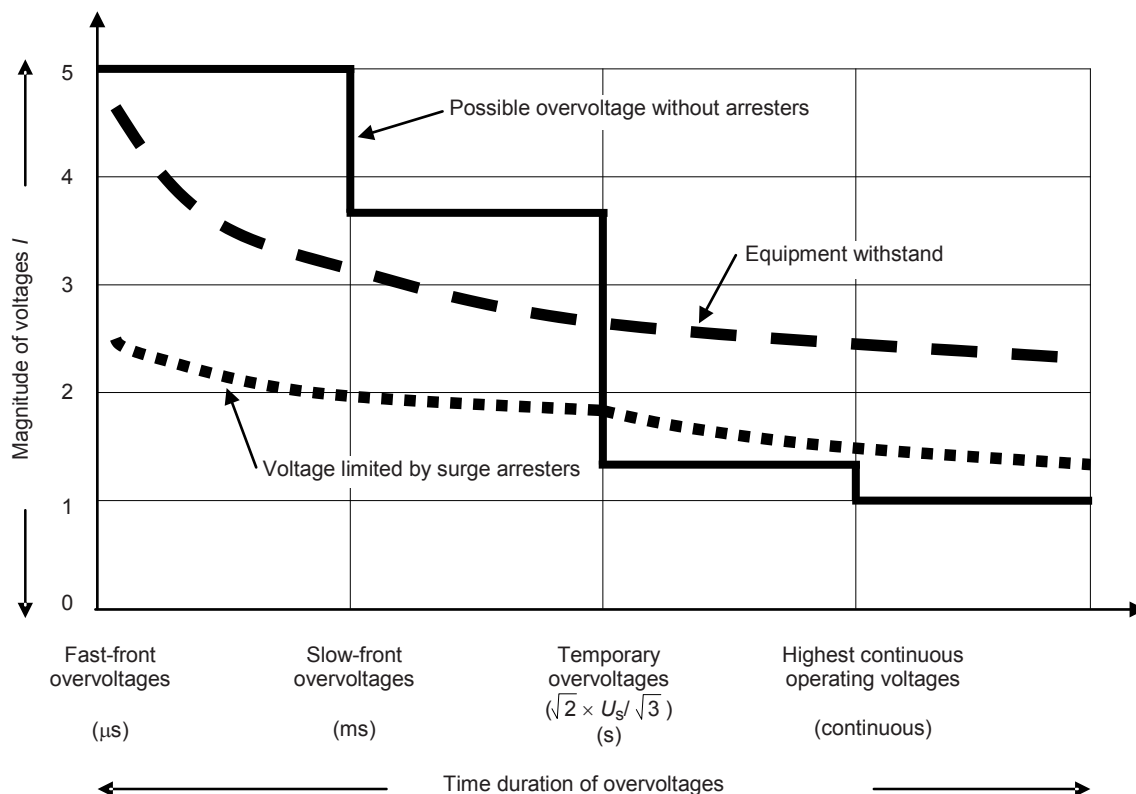
Stages 1 to 4 are covered in IEC 60071-1 and IEC 60071-2. These selection and application recommendations will address the issues when considering the selection of arrester protective characteristics and location in the analysis, and will determine the coordination withstand voltage for fast-front and slow-front overvoltages.

6.2.3 Overvoltages

6.2.3.1 General

Overvoltages occur in power systems as a result of system disturbances such as faults, lightning strikes or switching activity. These can stress equipment beyond their design capability and detrimentally affect system performance. The type of overvoltage is important when specifying a surge arrester, as this will define the required TOV capability, protective margin, and energy handling capability.

Relationships between typical overvoltage stress with and without surge arrester protection and insulation strength encountered in power system is illustrated in Figure 13. Some examples of overvoltages typically encountered in power system which are available from numerous publications on related overvoltage phenomena are summarized in Figure 14 [7] [24] [25] [58] [59] [60] [61] [62] [63] [64] [65] [66] [67] [68] [69] [70] [71] [72] [73] [74]. The standard power equipment is expected to have sufficient natural insulation strength in the power frequency and temporary overvoltage range. Although insulation strength usually increases steadily as surge fronts gets faster, critical overvoltages can still be expected from lightning surges and uncontrolled switching operations such that arrester protection is usually required [27].



IEC 1022/13

NOTE 1 p.u. = $\sqrt{2} \times U_s/\sqrt{3}$

Figure 13 – Typical voltages and duration example for an efficiently earthed system

Recommended overvoltages on power equipment with non-self-restoring insulation are usually limited below 85 % of insulation strength. On the other hand, for self-restoring insulation where some flashovers are tolerated, overvoltages may be limited by arresters to achieve desirable equipment and/or system performances.

Normalized voltage-current characteristic of typical metal-oxide surge arrester is shown in Figure 15. Arresters are applied primarily for lightning and switching overvoltage protection duties since most system equipment do not require overvoltage protection during normal and temporary overvoltage conditions. Defining arrester duties therefore includes determining arrester cumulative energy absorption capabilities and related current magnitudes. When arrester protection is desired during extreme temporary overvoltage conditions, special attention must be given to energy accumulation with overvoltage duration and current sharing amongst parallel arresters [19] [20] [43].

6.2.3.2 Very-fast-front overvoltages

Very-fast-front overvoltages with rise times below 0,1 μ s are typically produced by disconnector operation or faults within gas insulated substations (GIS) due to the rapid breakdown of the SF₆ gas gap and the nearly undamped surge propagation within the GIS. Their amplitudes are rapidly damped on leaving the GIS, e.g. at a bushing and their front times usually are decreased into the range of those of fast-front overvoltages.

Generally, arresters are not very effective against very-fast-front overvoltages for two main reasons. Firstly, voltage magnitudes are typically below the arrester protective level and secondly, the necessary comparatively very fast protective response times are adversely affected by both separation distances from equipment and arrester dimension.

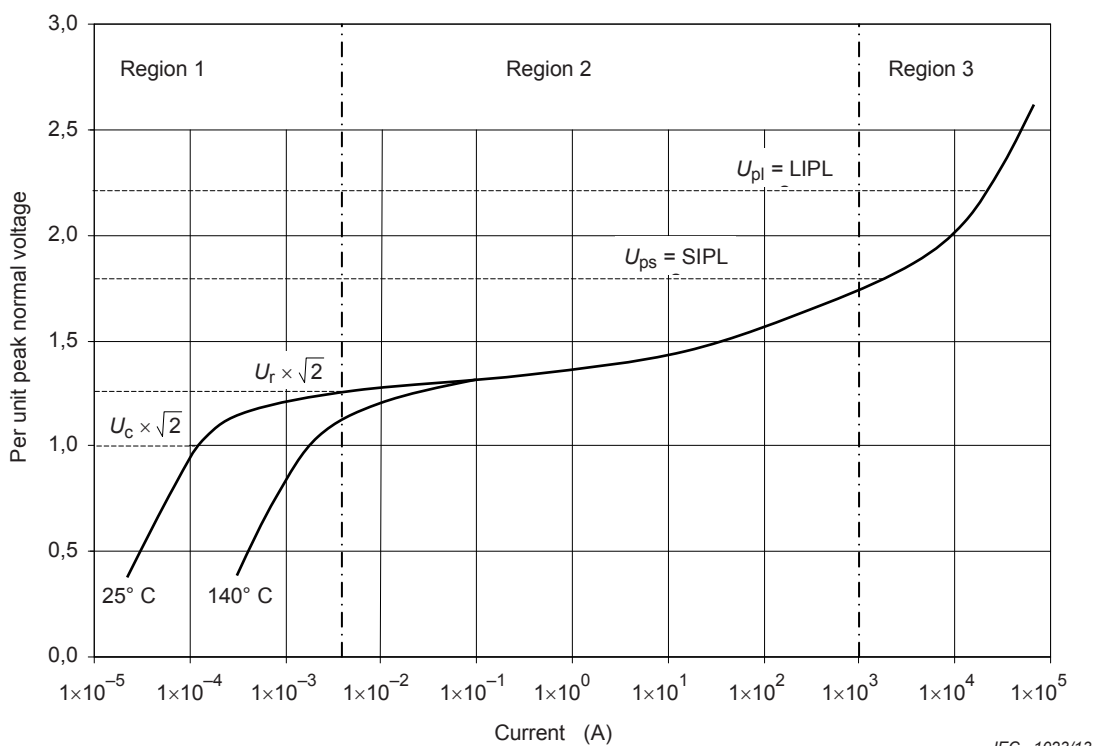
<u>Sources</u>	<u>Typical p.u. Range</u> (1 p.u.= $\sqrt{2 \times U_s / \sqrt{3}}$)	<u>Breaker RRRV</u> kV/ μ s
<u>Temporary Overvoltages:</u>		
Single-Line-To-Earth Faults: Effectively Earthed System Unearthed System	1,3 to 1,4 $\geq 1,7$	
Load Rejection	1,2 to 1,5	
Ferranti Effect: 200 km line 300 km line	1,02 1,10	
Closing of Transformer Terminated Line	1,2 to 1,8	
<u>Slow-front Overvoltages:</u>		
<u>Line Energization</u>		
Discharged Line	1,5 to 2,9	
Three-phase reclosing without Preinsertion Resistors	3,0 to 3,7	
Three-phase reclosing with Preinsertion Resistors	1,6 to 2,2	
Three-phase reclosing with arresters (3 sets at 1,5 p.u. U_{ps})	1,8 to 2,5	
Three-phase reclosing with Breaker Control Closing at zero voltages	1,5 to 1,7	
Single-phase reclosing	1,5 to 2,0	
Fault Initiation: Unfaulted Phase	2,1	
Coupled Circuit	1,5	
Fault Clearing	1,7 to 1,9	
<u>Shunt Capacitor Switching:</u>		
Earthed; breaker condition without restrike	1,7	
Unearthed; breaker with restrikes, no surge arrester	> 3,0	
breaker with restrikes, with surge arrester	~ 2 to 3 ^a	
<small>(^aNOTE specific overvoltages are dependent on arrester ratings and installation.)</small>		
<u>Circuit Breaker Transient Recovery Voltages (TRV) & Rate-of-Rise-of-Recovery Voltages (RRRV; kV/μs):</u>		
Normal Circuits TRV crests	1,7	
RRRV		< 2,0
Inductive circuits TRV crests	~ 3,0	
RRRV; no TRV capacitors		> 4,0
RRRV; with TRV capacitors		< 3,0
<u>Fast-front Line surges Entering Stations:</u>		
Unshielded Line	> 4,0	
Shielded lines	< 4,0	

Figure 14 – Typical phase-to-earth overvoltages encountered in power systems

6.2.3.3 Fast-front overvoltages

Fast-front over-voltages are often generated by lightning strikes to lines and sometimes by switching operations near equipment. These overvoltages have rise times typically in the range of 0,1 μ s to 20 μ s and tails as long as 300 μ s.

Lightning current impulses (up to 200 kA) generate voltages on circuits, as a product of the surge impedance associated with the propagation of an electromagnetic wave. These travelling waves reflect at surge impedance boundaries (interfaces between equipment) and where this change is significant, can cause flashovers when the dielectric strength is exceeded.



IEC 1023/13

Legend:

- Region 1: pre-breakdown region is the low current region associated with steady state operation
- Region 2: breakdown region is the highly non-linear region normally associated with TOV and slow-front (switching) surges
- Region 3: high current region is the region associated with currents > 1 kA, normally Fast-front (lightning) surges

NOTE 1 U_c : Arrester continuous operating voltage normally equal to highest voltage of the system, U_s , divided by $\sqrt{3}$.

NOTE 2 U_r : Arrester rated voltage.

NOTE 3 $LIPL=U_{pl}$: Arrester lightning impulse protective level i.e. the maximum residual voltage at the nominal discharge current, I_n .

NOTE 4 $SIPL=U_{ps}$: Arrester switching protective level i.e. the maximum residual level at the specified switching impulse currents.

NOTE 5 The currents at $U_c \cdot \sqrt{2}$, $U_r \cdot \sqrt{2}$, LIPL and SIPL are only given as examples.

Figure 15 – Arrester Voltage-Current Characteristics

Lightning is very difficult to predict and quantify, but statistical data suggest most lightning currents are greater than 10 kA. The frequency and occurrence will vary dramatically between regions and countries, but can be determined by the local ground flash density [47].

Generally, three types of lightning incidents are concerns for overhead lines. The first is a direct strike to a line due to shielding failure or lack of shielding. The second case is caused by nearby strikes to ground which generate inducing voltage surges on the circuits. The third case, called a back-flashover, can occur following strikes to shield wires or the tower due to earth/ground voltage build-up causing flashback across the insulator to the phase conductor(s).

The impact of lightning on a sub-station, except direct strikes which are usually prevented by shielding of the station, more frequently will be determined by the strike distance on a line from the station, since only a small percentage of surges generated by lightning strikes arrive

at the station with sufficient magnitudes and fast-fronts to cause problems. Other factors such as the station configuration will affect the travelling waves associated with lightning impulses; typically these will divide between parallel circuits connected to a bus bar, reducing the impulse seen by critical station equipment [7].

Fast-front overvoltages may also occur during reactive equipment switching with short connections to the switchgear. Disconnecter switching of unloaded transformer and shunt reactor switching are likely sources, which generate a high number of very rapid pre-strike and restrike overvoltages [71]. The duration and propagation is short lived but may occur several times. In general, arresters applied between the equipment and switchgear are effective in reducing these fast-front switching overvoltages and simultaneously assist in reducing the frequency of switchgear restrikes.

6.2.3.4 Slow-front overvoltages

Slow-front overvoltages occur whenever the initial voltage at the time of switching is not equal in magnitude and polarity to the final voltage. During the transition from the initial state to the final state, the voltage overshoots by as much as 200 % if there are no losses. In power systems, the losses are generally such that only the first two or three cycles of the transient oscillation have significant amplitude.

The wave shape for the slow-front surges may vary over a wide range depending on the circuit involved. Typically, the front times range from 20 μ s up to 5 ms.

Switching overvoltages originating from line energization and fast reclosing can generate currents up to approximately 2 kA through the arresters. In this current range, the knowledge of the exact current amplitude is not so important due to the extreme non-linearity of the metal-oxide material. The influence on the current front times can be ignored for slow-front overvoltages, but the duration of over-voltage is very important as the arrester can only absorb a limited amount of energy.

In addition to line switching events slow front overvoltages may also result from reactive switching of shunt capacitors and reactors, bypassing of series capacitor banks or remote distance lightning strikes.

Circuit operations that involve fast circuit reclose, or equipment, which is prone to restrike, or re-ignition is particularly onerous and may challenge the energy handling capability of the arrester. Cable circuits can have significant trapped charge particularly at EHV; this can result in large energy discharges under restrike conditions.

6.2.3.5 Temporary overvoltages

A temporary overvoltage (TOV) is an oscillatory phase-to-earth or phase-to-phase condition that is of relatively long duration and is undamped or only weakly damped. TOV magnitudes are determinable and the effect on insulation is considered in steady-state terms. The following causes of temporary overvoltages are typically considered:

Earth fault overvoltages occur over a large part of the system. Guidance for the determination of temporary overvoltage amplitudes is given in Annex A. The duration of the overvoltage corresponds to the period of the fault (until fault clearing). Within earthed neutral systems it is generally less than 1 s. For resonant earthed neutral systems, with fault clearing, it is generally less than 10 s and systems without earth fault clearing the duration may be several hours.

Load rejection, following disconnection of a load, the voltage can rise at the source side of the operating circuit breaker. The amplitude of the overvoltage depends on the disconnected load and the short-circuit power of the feeding substation. The temporary overvoltages have particularly high amplitudes after full load rejection at generator transformers depending on magnetizing and over-speed conditions. The amplitude of load rejection overvoltages is

usually not constant during its duration. Accurate calculations have to consider many parameters, the following typical values of such overvoltages may be considered

- In moderately extended systems, a full load rejection can give rise to phase-to-earth overvoltages with amplitude usually below 1,2 p.u. The overvoltage duration depends on the operation of voltage-control equipment and may be up to several minutes.
- In extended systems, after a full load rejection, the phase-to-earth overvoltages may reach 1,6 p.u. or even higher when Ferranti or resonance effects occur. Their duration may be in the order of some seconds.
- For load rejection of generator transformers, the temporary overvoltages may reach amplitudes up to 1,4 p.u. for turbo generators and up to 1,5 p.u. for hydro generators. The duration is approximately 3 s.

The following causes of temporary overvoltages may also require consideration depending on the nature of the network:

- resonance effects, e.g. when charging long unloaded lines or resonance between systems;
- voltage rise along long lines (Ferranti effect);
- harmonic overvoltages, e.g. when switching transformers;
- backfeed through interconnected transformer windings, e.g. dual transformer station with common secondary bus during fault clearing or single-phase switched three-phase transformer with an unbalanced secondary load.

Temporary overvoltages due to Ferro resonance should not form the basis for the surge arrester selection. The use of a surge arrester as an extra burden to damp out the Ferro resonance is not effective and unproven. The same argument is applicable to linear resonance. There are different modes of Ferro resonance. The sub-harmonic mode Ferro resonance will not generate an overvoltage. However, for the fundamental frequency mode Ferro resonance, a high temporary overvoltage is possible.

The sequence of causes for temporary overvoltages, e.g. load rejection caused by an earth fault, needs consideration, since both overvoltages have comparable severity. In such cases, however, the amount of rejected load dependent on the fault location and the arrester location shall be carefully examined.

A combination of causes such as earth faults and load rejection may result in higher temporary overvoltage values than those from the single events. When such combinations are considered sufficiently probable, the overvoltages for each cause shall be compounded taking into account the actual system configuration and carefully examining the amount of rejected load dependent on the fault and arrester locations [25].

6.2.4 Line insulation coordination: Arrester Application Practices

6.2.4.1 General

Faults and line trips can significantly affect circuit availability and jeopardize end customers equipment and power quality of industrial processes, so means of reducing these risks are of increasing importance. In order to improve the overall outage rate of an overhead line, surge arresters can be installed to prevent flashover of the line insulation at all or just selected poles/tower structures along the line. These arresters are named line surge arresters, LSA, and can be used both for distribution and transmission lines.

The protective characteristics of the LSA are coordinated with the LIWV and SIWV of the line insulation, but considerations to separation distances are not always necessary as the arresters are installed directly in parallel to the line insulators. Only for LSA installations with very long slacks for connecting the arrester to phase and earth this may be necessary.

LSA may also be used on one of the circuits in multi-circuit towers to prevent simultaneous tripping of double-circuits. Installation of LSA on one circuit will also reduce the risk of line tripping of the unprotected circuit.

LSA application on single or multi-circuit lines when combined with single-pole or high speed 3-phase reclose features can improve the switching surge control and the system availability [14].

Other applications of LSA include upgrading of existing lines, new compact lines, extended protection of substations, and reducing the risk of having dangerous touch and step potential in urban areas.

6.2.4.2 Line fast-front overvoltage performances

6.2.4.2.1 General

Fast-front overvoltages are created by lightning strikes directly to or in the vicinity of overhead lines. In many areas more than 50 % of line outages are due to lightning overvoltages causing flashover of the line insulators. The majority of LSA presently used are for improving the lightning performance of overhead lines and reducing the line-to-earth outage rate.

Overhead line insulation is generally self-restoring. Therefore, it is not appropriate to use a fixed coordination current to calculate protective margins. Instead, the probability distribution of lightning strike currents is applied to the line, and the probability of flashover is calculated. Typically the U_{50} % value together with a typical σ of 3 % is used to calculate the probability of flashover. The line insulation strength is also a function of the wave front and tail. Combined with local ground flash density, this will produce a lightning flashover rate per unit length per year. This flashover rate is the lightning performance metric for the line. A typical target of the flashover rate for overhead transmission lines of 72,5 kV and higher, might be 1 flashover to 2,5 flashovers per 100 km per year. For distribution lines and areas with very high ground flash density, GFD , a reasonable target may be somewhat higher. The relation between ground flash density, GFD , and T_D is expressed as in Formula (3). Also in countries with short line lengths higher rates may be tolerated. The expected performance rate of the line after installation of LSA should be calculated also considering failures rates of the arresters.

$$GFD = 0,04 \times T_D^{1,25} \quad (3)$$

The effect of a flashover depends on protective relaying practices and in the case of wooden poles also on the possibility of arc quenching. Line performance evaluation can be done accounting for the benefits of line arrester installations. Factors to consider when evaluating lightning performance include soil resistivity, tower footing earthing impedance, ground flash density, tower dimensions, span length, shield wire locations if used, insulation levels, etc. Part of the line performance evaluation should include what lightning flashover rate is aimed for but also expected arrester energy overloading risks since this will typically result in a line tripping.

6.2.4.2.2 Direct strikes to a phase conductor

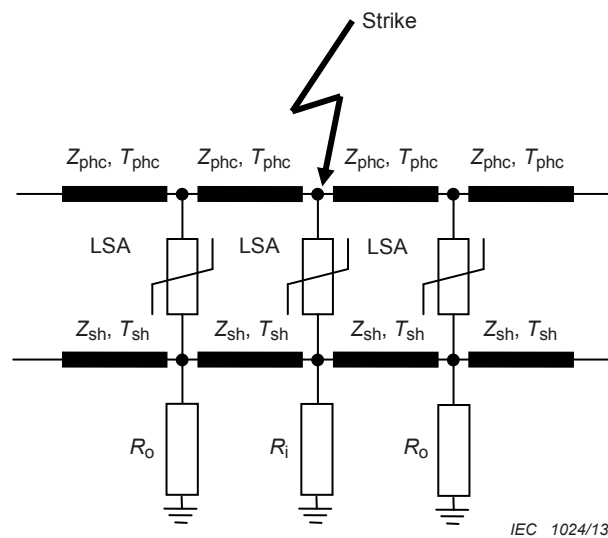
Direct strikes can either occur on unshielded lines or as shielding failures on shielded lines. The flashover occurs from the phase conductor to the tower/pole structure. For unshielded overhead lines, direct strikes to the phase conductors will be much more frequent than for shielded lines and will involve the full spectrum of lightning strike currents. Typically, systems studies will have to be performed in order to determine suitable arrester energy discharge requirements in this case, as this application is harsher than for shielded line applications. Depending what outage rate and failure risks are expected for the LSA, the LSA energy requirement is then selected.

Shielding failure flashovers typically occur in the lower end of the current magnitude range, typically below 20 kA, but the wave shape has a longer tail than for back-flashovers. For properly shielded lines, shielding failure flashover rates chosen for the tower design are very small (typical design values are 0,05/100 km-years) compared to back-flashovers. [7]

For a direct strike terminating on the phase conductor (Figure 16), most of the current will discharge to earth through the nearest LSA as there is no other current path to earth. Adjacent arresters will discharge some of the energy, limited by the span inductance. If the struck pole or tower earth resistance is reduced due to soil ionization, the energy sharing is less effective. There is no energy sharing to account for on the tail of the surge, due to the very high non-linearity of the U-I characteristics of the arresters for lower current amplitudes. The lower the tower footing resistance, R_i , is for this tower, the higher discharge current passes through that LSA.

Since a surge from a lightning strike terminating somewhere along a span travel in two directions, LSA must be at both structures to prevent flashover. For this reason, it may be considered to install LSA at consecutive structures to be effective at addressing direct strike or shielding failure flashovers.

LSA may also be used instead of shielding wires especially when earthing conditions are poor or on lines with triangular phase conductor arrangements. Instead of an overhead shield wire, the LSA are used to “protect” the topmost phase from flashover and effectively acting similar to a shield wire where the topmost phase intercepts most lightning strikes. In order to eliminate direct-strike flashovers on distribution lines, the LSA should be installed on every pole/tower.



Key:

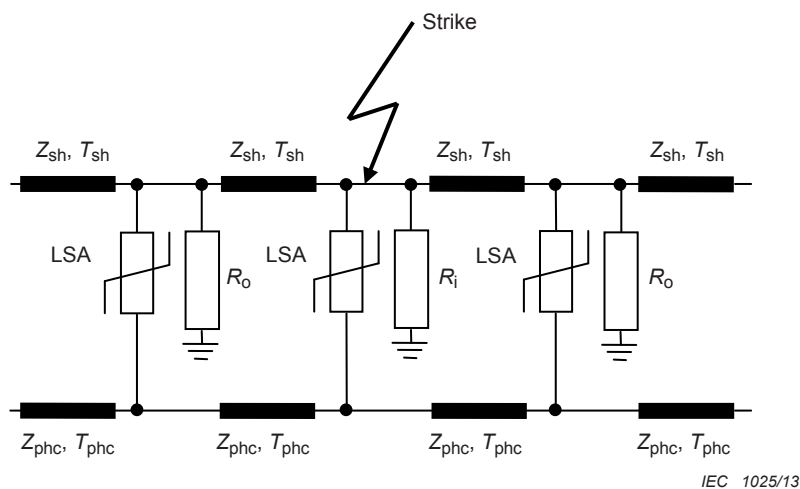
- Z_{sh} : Surge impedance of shield wires
- T_{sh} : Surge travel time of shield wires
- Z_{phc} : Surge impedance of phase conductors
- T_{phc} : Surge travel time of phase conductors
- LSA: Line surge arrester
- R_i : Tower footing resistance at closest tower
- R_o : Tower footing resistance at adjacent towers

Figure 16 – Direct strike to a phase conductor with LSA

6.2.4.2.3 Strikes to shield wires or tower structures, back-flashovers

These events result from a lightning strike terminating on the shield wire or tower causing a potential increase across the line insulators, which causes a flashover from the tower to the phase conductor to occur. Therefore they are named back-flashovers and they are an important reason for lightning-triggered line outages on shielded lines. Local earthing conditions (soil resistivity and footing design) have a major impact on back flashover performance.

An overhead shield wire is designed to intercept most lightning strikes that would otherwise hit the phase conductors. Most of the current will discharge through the tower and pole earths, with relatively low current flowing through the LSA (Figure 17). Back-flashover reduces the energy duty on the LSA, but their energy stress increases with higher tower footing resistance.



Key:

- Z_{sh} : Surge impedance of shield wires
- T_{sh} : Surge travel time of shield wires
- Z_{phc} : Surge impedance of phase conductors
- T_{phc} : Surge travel time of phase conductors
- LSA: Line surge arrester
- R_i : Tower footing resistance at closest tower
- R_o : Tower footing resistance at adjacent towers

Figure 17 – Strike to a shield wire or tower with LSA

Outages due to back-flashovers can be reduced by placing LSA in all phases or only on the phase(s) with the lowest coupling factor to the shield wires. For conductors on the tower, lowest coupling factor is normally associated with the bottom conductor(s). In many cases, the lowest phase will experience the lowest coupled voltage and the highest insulator voltage stress. LSA may be applied on just the most stressed phases. These LSA will operate during a prospective back-flashover event, effectively creating another earthed conductor and improving the coupling to the remaining phases. This increased coupling reduces the probability of a back-flashover on the phases that have no LSA installed. In towers with vertical conductor configuration, insulator voltage stress on each phase will depend on the specific parameters of the line such as footing resistance or surge impedance of OHGW (overhead ground wire) and tower structure. Therefore the phase(s) to apply LSA may be determined by an analytical approach.

System studies may be useful in deciding location, number of LSA, and which phase(s) to protect. For applications in high footing resistance areas, it is important to apply the arresters not only on structures in those areas, but as well also one or two structures away from the

high footing resistance areas. Otherwise the insulation stress will be transferred to the adjacent pole/tower that is without LSA.

For distribution systems the existing distribution transformer arresters will provide some line protection. These should be included in the line performance evaluation. If adding LSA to improve the line flashover rate, they should be applied first on poles with an earthed neutral that do not already have an arrester and poles with lower than normal insulation strength, such as dead-end and guyed poles.

A special case is flashovers of an under-built distribution line that shares a tower with a shielded transmission circuit. The under-built distribution conductors are not likely to be struck directly. However, the distribution line is most vulnerable to back flashovers, because the coupling between distribution conductors and shield wires is the weakest. The insulation strength on the distribution line is also weaker. Once a distribution conductor flashes over, coupling to the transmission conductors will increase and make a back flashover less likely on the transmission circuit. The transmission circuit's lightning performance may improve at the expense of the distribution circuit's lightning performance. The situation can be remedied with LSA on the distribution circuit. Usually LSA are needed at every tower, in at least one phase.

6.2.4.2.4 Strikes to earth in the vicinity of the line

Flashovers can result from nearby lightning strikes inducing voltages on phase conductors of an overhead line. The induced overvoltages rarely exceed 300 kV. This is a concern mainly for distribution lines as the LIWV is typically above 300 kV for line insulators of transmission lines. The flashover occurs from the phase conductor to the tower/pole earth and current flow is according to Figure 16.

For lines susceptible to induced voltage flashovers, LSA are usually required on all phases every 200 meters to 400 meters to minimize the effects of these induced overvoltages.

6.2.4.3 Line slow-front overvoltage performances

6.2.4.3.1 General

High speed reclosing on transmission lines generates travelling waves on the phase conductors which may cause flashover to the tower along the line if not controlled. Today, virtually all EHV lines are designed using the probabilistic method [7]. The method is used at 362 kV and higher but less often at 245 kV. Their performance assessment methods are based on expected slow front line overvoltage profile and specified line insulation levels. For lines below 245 kV, line insulation requirement for lightning performance provides sufficient switching strength for smaller switching transients generated at the lower level.

6.2.4.3.2 Risk of flashover: Statistical coordination factor charts

The IEC 60071-2 method assumes that distributions of overvoltage and electric strength can be defined by a point on each of those curves. The overvoltage distribution is identified by the statistical overvoltage, which is the overvoltage having a 2 % probability of being exceeded. The insulation strength distribution is identified by the statistical withstand voltage, which is the voltage at which the insulation exhibits a 90 % probability of withstand.

The statistical coordination factor is the ratio of the statistical withstand voltage to the statistical overvoltage and the risk-of-flashover is obtained from the Risk vs. Coordination Factor charts (IEC 60071-2). The correlation between the statistical coordination factor and the risk of flashover appears to be only slightly affected by changes in the shape of overvoltages due to the fact that 2 % value chosen falls in the overvoltage region which provides the major contribution to the flashover rate.

6.2.4.3.3 Switching surge flashover rate (SSFOR)

Statistical switching studies can be combined with computer numerical processing to estimate the switching surge flashover rate (SSFOR). Both case peak or phase peak method might be employed to obtain the overvoltage distribution and the line overvoltage profile appropriate for the type of switching control used, particularly the influence of LSA when present. It is also customary to monitor the LSA currents and energies associated with these switching overvoltages.

The SSFOR is determined by numerical integration of the stress-strength relationship. The stress or switching overvoltage (SOV) distribution can be approximated by one of the three probability density functions; Gaussian, Extreme Value: Positive Skew or Extreme Value: Negative Skew while strength is defined by an equivalent strength distribution for large number of parallel insulation [7].

6.2.4.3.4 Arresters for line slow-front overvoltage protection

There are various methods of controlling switching overvoltages, such as closing resistors, controlled switching, and/or LSA arresters. Unlike lightning related applications where arresters may be installed at consecutive structures, arresters to control switching surges are only needed at both ends of the line and possibly one or two other locations along the line depending on the SIWV of the line insulation and the length of the line. Typically, LSAs are applied around the midpoint or approximately one third and two thirds of the line length for one or two point installations, respectively. Also, based on the knowledge that highest switching overvoltages occur over short portion of the line between LSA locations towards the receiving end of the line, higher insulation strength might be considered for those towers to achieve superior line switching performance. Arresters at the line ends can be either LSA installed on the last towers or normally mounted substation arresters at the line terminal. For switching overvoltage control, LSA should be installed on all phases [15], [16].

LSA for this application are typically used for system voltages 245 kV and above. The advantages of using arresters for this application as compared to using circuit-breaker closing resistors are that they are passive devices requiring no maintenance, can provide better control of the voltage profile along the line, and are not influenced by harmonics in the voltage. For very long lines and/or lines with low SIWV, non-gapped line arresters combined with controlled switching may be one of the most advantageous solutions.

6.2.5 Substation insulation coordination: Arrester application practices

6.2.5.1 General

Substation performance can be affected by both station and line operating requirements during various system conditions. Generally, substations often contain several expensive equipment with non-recoverable insulation such as transformers, circuit-breakers and gas insulated bus where the desired overvoltage protection employing surge arresters is more deterministic than statistical in nature.

6.2.5.2 Protection from fast-front overvoltages, FFOV

6.2.5.2.1 General

FFOV are typically generated by lightning. The protection of a substation from lightning involves two fundamental tasks:

- Preventing lightning strikes from directly terminating on the station equipment and the bus work. This is achieved by providing station shielding. As an additional safety in case of shielding failure, surge arresters applied near important station equipment will provide additional protection.
- Protection of station equipment from incoming surges caused within the network. This is based on the line design, station configuration and strategic application of surge arresters.

The severity of an incoming surge is estimated by a lightning surge originating at a minimum design distance from station which is attenuated by corona according to the line electrical characteristics.

A major factor in locating arresters within a substation is the effectiveness of line and station shielding. It is usually feasible to provide shielding for the substation even though the associated lines are unshielded. Station shielding reduces the probability of high voltages and steep wave fronts within the station resulting from high-current lightning strikes. However, it should be recognized that the majority of strikes will be to the lines, which will create surges that travel along the line and into the station. If the lines are shielded, the surges entering the station are usually less severe than those from unshielded lines. Consequently, the magnitude of the arrester current is lower, resulting in lower arrester residual voltage and better protection of the equipment [23].

6.2.5.2.2 Station shielding

The basis of design for air insulated switchgear (AIS) substation shielding is somewhat different from that for lines. While the same concept of designing to a specific shielding failure flashover rate (SFFOR) is valid for buses in the station, the design based on a SFFOR for specific pieces of equipment is difficult. For this reason and for simplicity, the design is approached on a basis of establishing a design current for the substation [3], [4], [5].

Another difference in station shielding is that either or both shield wires and masts may be used, the decision being that of the designer. Shield wires are generally used for large-area stations, whereas masts are in normal use for low voltage, small-area stations. Shield wires usually provide better protection.

6.2.5.2.3 Air insulated substations (AIS); Incoming surges from lightning strikes on lines

Since stations are usually shielded from direct strikes to station equipment, station lightning performance depends primarily on the incoming surges from the lines [7]. The overall procedure can be outlined as shown in 1) to 6):

- 1) Evaluate the need for and type of opened circuit breaker protection. The need for opened circuit breaker protection is evaluated first, since if arresters are needed, they should be included in the initial study of the station.
- 2) Select the Incoming Surges: The methodology based on reliability criterion of a mean time between failures (MTBF) should be used.
- 3) Select potential LIWVs: Potential LIWVs are normally limited between one to three values based on system voltage or U_m , highest voltage for equipment.
- 4) Evaluate Normal and Contingency Conditions: For station with several lines, a typical contingency may include loss of circuits. However, conditions with less than all lines have low probability and, according to IEC 60071-2, the number of lines is maximised to two connected lines in order to determine the representative overvoltage.
- 5) Select Arrester Type, Rating and Preliminary Location of Arresters: Typically, arresters are employed at the transformer terminal and possibly at the station entrance of lines.
- 6) Follow IEC 60071-1.

Incoming surges from shielded lines are usually lower in amplitude and steepness than from unshielded lines. In many cases, this will permit some separation between the arresters and the insulation to be protected. With a single shielded incoming overhead line, one set of arresters may be located at a point that provides protection to all equipment but preference should be given to the transformer since this is the key item at risk.

The method to estimate the magnitude and shape (steepness) and tail time constant of the surge that arrives at the entrance of the station is based on:

- the distance between the station and the strike-terminating point,

- the magnitude of the strike current
- the initiating event – shielding failure or backflash.

In turn, the number of surges that arrive at the station is a function of this distance and the backflashover rate (BFOR) and shielding failure rate (SFR). Since the strike current and the BFOR/SFR are statistical quantities, the magnitude and shape of the surge is a random event and must be considered in probabilistic terms. Thus the incoming surge is statistical, which leads to the concept that the magnitude and shape of the incoming surge may be based on a design rate of the number of surges per year that equal or exceed a specific steepness and magnitude.

The reciprocal of the number of surges is the return period or mean time between surges in units of years/surge. That is, a surge may be selected so that the probability that its severity is exceeded is, for example once in 400 years. If this 400 year surge produces the voltages within the station that just exceed the insulation strength, the mean time between failures of the equipment (MTBF) is 400 years.

For multi-line station, the situation is more complex, since each line may bring a different number of surges into the station. For station transformers and all equipment on the transformer bus, the total number of surges encountered is the sum of all lines. For equipment on other buses, however, it is based on the single line since it produces the most severe voltage on the bus.

6.2.5.2.4 Subsequent strikes (open breaker conditions)

Subsequent strikes are concerns for line circuit breakers and terminal equipment, especially for unshielded lines. Following fault clearing, breakers may be open longer than 500 ms and line terminal equipment can be exposed to surges from subsequent strikes which occur typically between 30 to 300 ms after the initial strike.

Breakers on lower voltage systems are prone to this event and should be protected if there are problems, while those on higher voltage systems may not require protection, since they are designed to withstand high fast-front overvoltages. Typically, protection comprises installation of arresters on the line side of the breaker [6].

6.2.5.2.5 Cable connections

When short sections of cables are used to connect equipment into AIS substations, complications can arise regarding the provision of adequate protective margins by surge arresters.

Only a fraction of the lightning surges generated on the overhead line are initially transmitted into the cable due to the low impedance ratio between the cable and line. For cables longer than 1 km, the travelling wave established within the cable is expected to be damped by natural resistance losses as the transmitted surge travels back and forth within the cable. For cables shorter than 1 km, however, there are possibilities for a voltage build-up at the cable terminals due to multiple reflections and insufficient damping. Consequently, for short cable lengths, surge arrester protection may be required at one or both terminals. This is more of an issue for lower voltage systems.

On the whole, cable-connected substations are for the same dimensions better protected than open-air stations.

For shorter cable lengths, surge arresters should be considered at the overhead line-cable terminal to protect the cable entrance, but for longer cable lengths, surge arresters may not be needed at the entrance. The separation distance effects can be conservatively estimated as with open-air substations. When more than one line remains connected to the substation through cables during lightning, the arresters are sufficient to protect the substation. If it is likely that cables connected to the substation are in open-end conditions during lightning, and

if the cable length exceeds a value of approximately five times the value calculated with Formula (17), additional arresters are recommended at the open end. This also applies to the open end of cables which are connected to the overhead line through a substation.

6.2.5.2.6 Arrester protection of gas insulated switchgear (GIS) substations

6.2.5.2.6.1 General

GIS substations are, in general, better protected than AIS substations because surge impedances are much lower than that of overhead lines. Because of the complexity of a GIS substation in which steep front surges can be created for various switching condition it is recommended that the substation is studied using an electromagnetic transient program. Flashovers are not accepted in GIS due to that the possibility of permanent damage is much higher.

Unlike AIS, a breakdown in the GIS of SF₆ cannot be simply regarded as self-restoring and subsequently inspected, therefore the threat from flashovers needs to be eliminated where possible. As a general rule, surge arresters should be installed at the line entrance to the GIS. The voltage should be controlled before it enters the GIS.

6.2.5.2.6.2 Protection from fast-front overvoltages

SF₆ will initiate faster dielectric breakdown than that of air, leading to fast-front and very fast-front transients.

The use of the general formula for the open-air substation results in conservative estimates. Computer models are really necessary to establish the stresses seen in the GIS coordination lightning impulse withstand voltage or of the protective range, however as a rough guide a reduction of the constant A to half the value shown in Table 3 can be considered.

Additional surge arresters at the transformers may be necessary, either when the separation distances to the line entrance arresters are too long, or when high overvoltages at the transformer are expected during conditions when the line entrance arresters are disconnected. Arresters installed at suitable locations inside the GIS may also be necessary for extended GIS.

Where it is impossible to use AIS arresters to provide adequate line entry protection, better fast-front overvoltage protection may be achieved by installation of the line entrance arrester inside the GIS. This eliminates the effects of the outdoor arrester leads. Although this arrester would be more expensive than an outdoor arrester, additional arresters may be superfluous and this may be the more economic solution.

When the protective ranges indicate that additional arresters should be installed within the GIS, the approximation formula should not be used, but travelling wave calculations should be performed.

6.2.5.2.6.3 Protection from very fast-front overvoltages

Surge arrester protection from very-fast-front overvoltages generated within GIS, for example by switching of disconnectors, is usually not possible due to the very high frequencies and low amplitudes involved. Improvements in GIS station arrangement and equipment design are possible means to reduce such risks.

6.2.5.3 Protection from slow-front overvoltages (Switching)

6.2.5.3.1 Basic substation switching

Slow-front overvoltages are typically generated by switching operations. A substation overvoltage insulation coordination method is described in IEC 60071-2. While the application

of insulation coordination method is similar to that for lines, there are significant differences [7]:

- station insulation and line insulation must be coordinated
- number of insulators in parallel are small compared to overhead lines
- voltage profile $E_s/E_r=1,0$ (E_s : sending end, E_r : receiving end)
- substation equipment with different dielectric strengths
- station insulation strengths are described by LIWV for apparatus(transformers) or CFO for air clearances (bus)
- design value of the SSFOR for the station may be a decade lower than that of the line. IEC specifies the SIWV and LIWV for each system voltage.

The ratio of phase-earth and phase-phase clearances recommended by IEC increases with voltage class.

6.2.5.3.2 Practical substation equipment switching

There is no difference between AIS and GIS protection. However, coordination between the AIS equipment and the GIS equipment is needed.

Besides line switching, many other types of equipment such as capacitors, reactors and transformers are switched under load and fault conditions. Normally, disconnect switches (DS) are limited to isolation of bus sections and possibly unloaded transformers, circuit switchers and breakers are used for load, while only circuit breakers can safely interrupt most faults. For effective equipment protection from switching overvoltages, arresters must be located on the equipment side of the switching device.

Switching load and fault currents can generate severe transient recovery voltages (TRV) across the switch. If the TRV is too fast or too large, relative to the switch thermal or dielectric recovery rate, switches can re-ignite or restrike, resulting in switch failure and/or damages to unprotected equipment caused by single or multiple restrike transients. If equipment is protected by arresters, arrester failure from excessive energy absorption during restrike is possible.

6.2.6 Insulation coordination studies

6.2.6.1 General

Insulation coordination studies can be complex depending on the depth of analysis undertaken to achieve the desired accuracy. Furthermore, the analysis associated with system disturbance and/or transients can be very subjective dependent on the type of power system phenomena being investigated.

6.2.6.2 Computation guide and modelling techniques

Some cases are easier to examine than others, such that equations and rules of thumb methods derived from statistical methods such as those described in IEC 60071-2 can be used for preliminary estimations. For more complex and/or practical applications, results provided by these simplified formulas are considered to be too conservative. When more accurate results are desired and/or complex network and equipment solutions which include travelling waves and important effects such as surge arrester non-linear characteristics and statistical distributions of switch operations, computer simulations using electromagnetic transient analysis tools should be employed.

Basic computer models tend to provide conservative results, primarily because some effects such as attenuation are difficult to accurately predict or model. A technical report on guidance for insulation coordination studies, IEC 60071-4 provides details and examples of the subtleties associated with the representation of networks and equipment for various types of

analysis; lightning or switching transients and temporary overvoltages. Also both deterministic and statistical methods of insulation coordination are described in IEC 60071-2.

Accurate arrester models for fast-front simulations should include the inductive effects of the connecting leads as well as the arrester itself. Some arrester modelling techniques recommended for fast-front and slow-front simulations are described in Annex C.

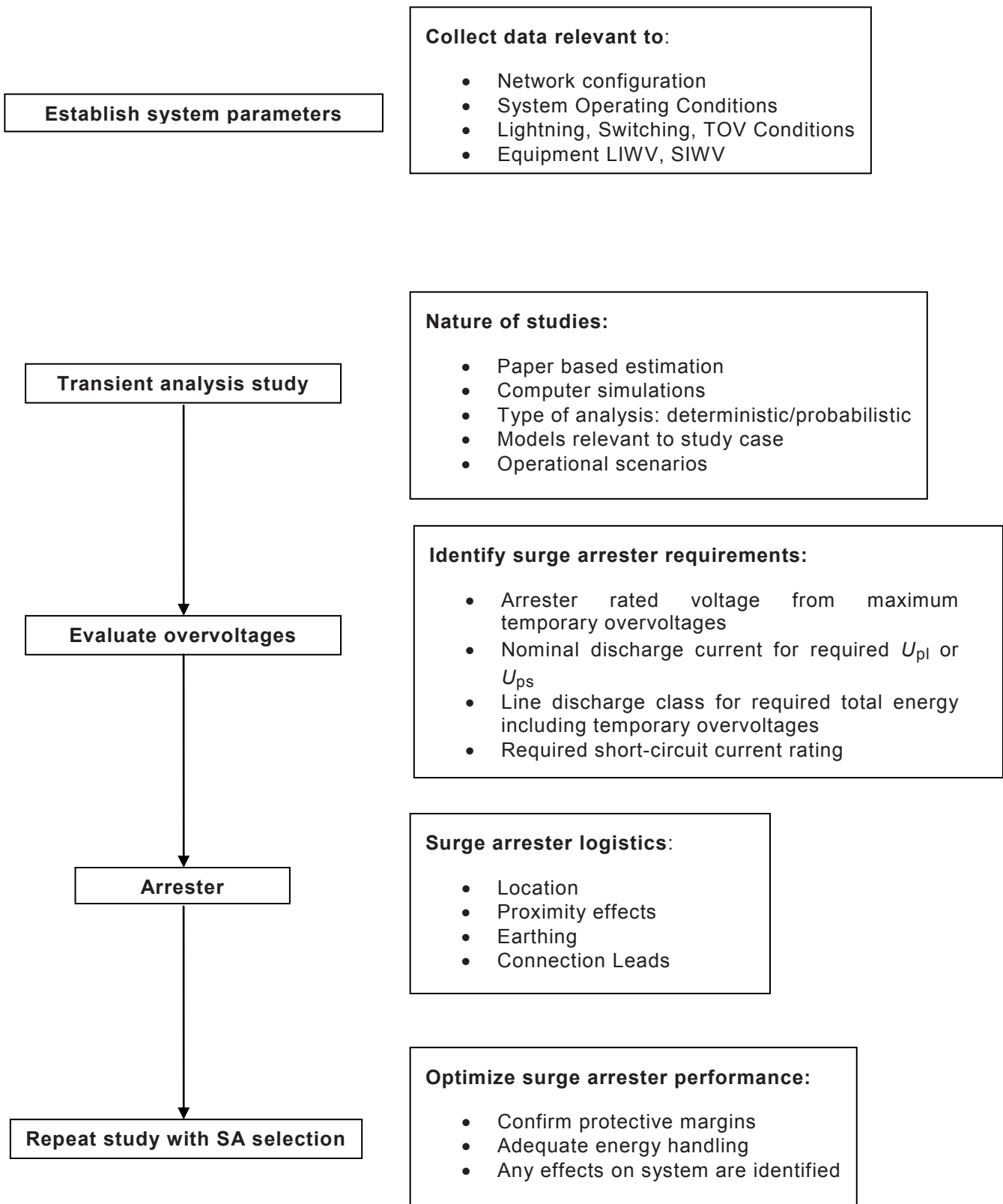
6.2.6.3 Study procedure

Figure 18 describes an insulation coordination study procedure to follow when reviewing the suitability of a surge arrester application. In general, the required arrester application type and their location(s) depend on the desired equipment protective margins considering the nature of the phenomena and the complexity and/or variations of the system operating conditions being examined. The dimensioning of surge arresters can be generally (but not always) evaluated on the worse case conditions associated with the lightning or switching protection levels and the surge arrester energy handling capability [28].

6.3 Selection of arresters

6.3.1 General

Surge arresters are considered essential protective device in modern insulation coordination applications for lines and substations. The most common application of surge arresters is to protect high-voltage substation and distribution equipment against fast and slow-front overvoltages. To ensure reliability and system security, the surge arrester's protective level and its energy handling capabilities shall be reviewed for the entire spectrum of overvoltage conditions. Secondly, the proper surge arrester shall be chosen for the appropriate service conditions.



IEC 1026/13

Figure 18 – Typical procedure for a surge arrester insulation coordination study

6.3.2 General procedure for the selection of surge arresters

6.3.2.1 General

The complete selection procedure of an arrester comprises the selection of a suitable arrester which matches electrical as well as mechanical requirements. It is recommended to first make a selection with respect to electrical performance and thereafter complete the selection with the mechanical requirements.

The following iterative procedure, shown in the flow diagram of Figures 19a and b, is recommended for the standard selection of surge arresters for protection of high-voltage substation equipment [21], [24], [26]:

- 1) determine the continuous operating voltage of the arrester with respect to the highest system operating voltage;
- 2) determine the rated voltage of the arrester with respect to the temporary overvoltages;
- 3) estimate the magnitudes and probability of the expected lightning discharge currents through the arrester, determine the transmission line discharge requirements and select the nominal discharge current, the high current impulse value and the line discharge class of the arrester;
- 4) select a surge arrester that fulfils the above requirements;
- 5) determine the lightning and switching impulse protection characteristics of the arrester;
- 6) locate the arrester as close as possible to the apparatus to be protected;
- 7) determine the coordination switching impulse withstand voltage of the protected equipment taking into account the representative slow-front overvoltages and system layout;
- 8) determine the coordination lightning impulse withstand voltage considering:
 - a) the representative impinging lightning overvoltage surge as determined by the lightning performance of the overhead line connected to the arrester and the acceptable failure rate of the protected equipment;
 - b) the substation layout;
 - c) the distance between surge arrester and protected equipment;
- 9) determine the rated insulation level of the equipment from IEC 60071;
- 10) if a lower rated insulation level of the equipment is desired, then a lower rated voltage, a higher nominal discharge current, a higher line discharge class, a different arrester design or a reduced distance between arrester and protected object should be investigated. Regarding selection of a lower rated voltage it should be noted that a too low rated voltage may affect the service reliability of the arrester.
- 11) selection of electrical data finished – start with mechanical selection!
- 12) consider the pollution level and required withstand voltages of the arrester;
- 13) make a selection of a creepage distance and preliminary length of arrester and flashover distance;
- 14) select the short-circuit rating with respect to the expected fault current;
- 15) consider different mechanical loads e.g. due to wind, terminal connections, earthquakes, short-circuits etc.;
- 16) consider dynamic/static combinations of loads;
- 17) check housing capability against the loads;
- 18) if necessary reconsider the preliminary selection;
- 19) make a final choice of arrester housing.

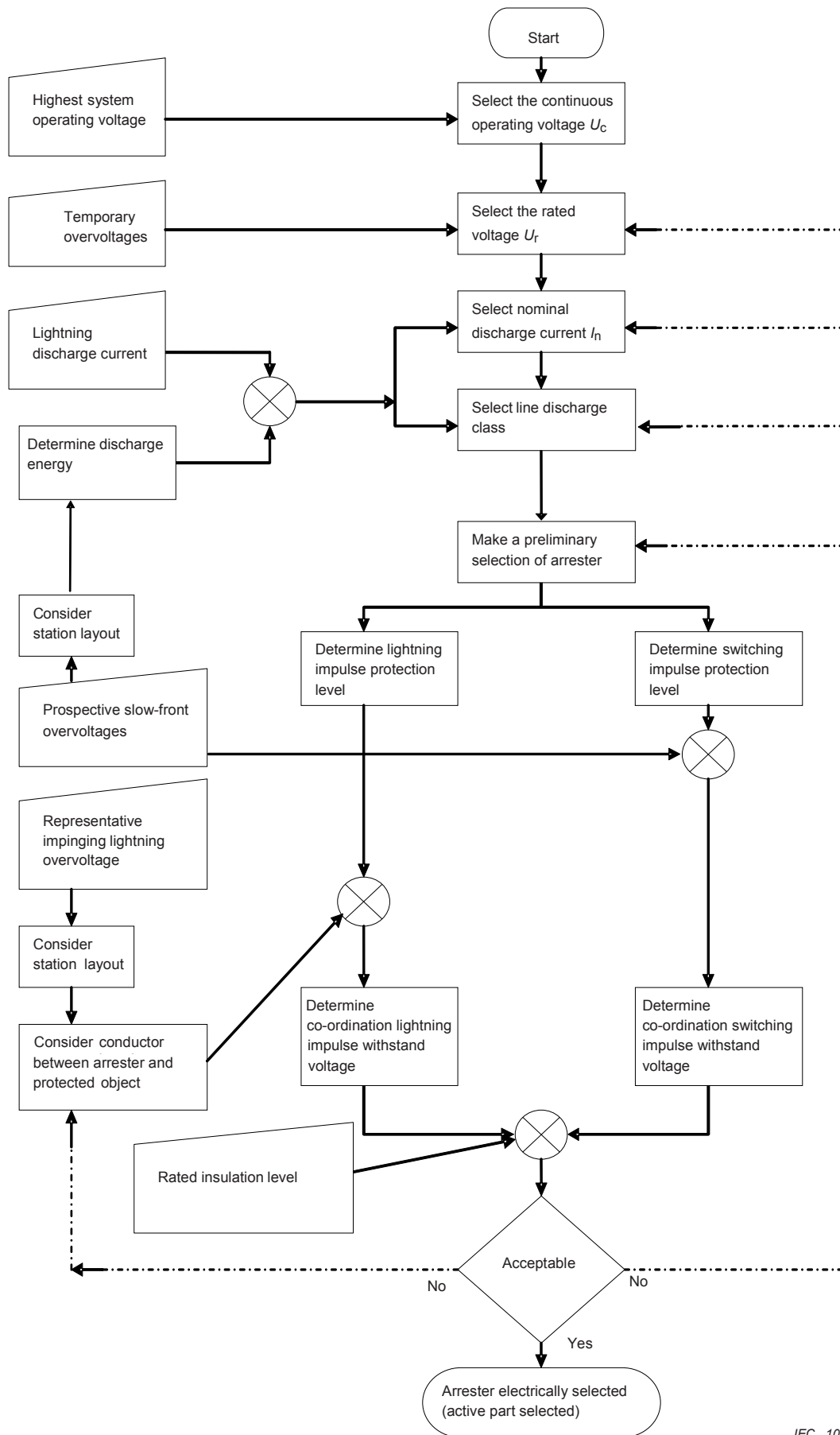
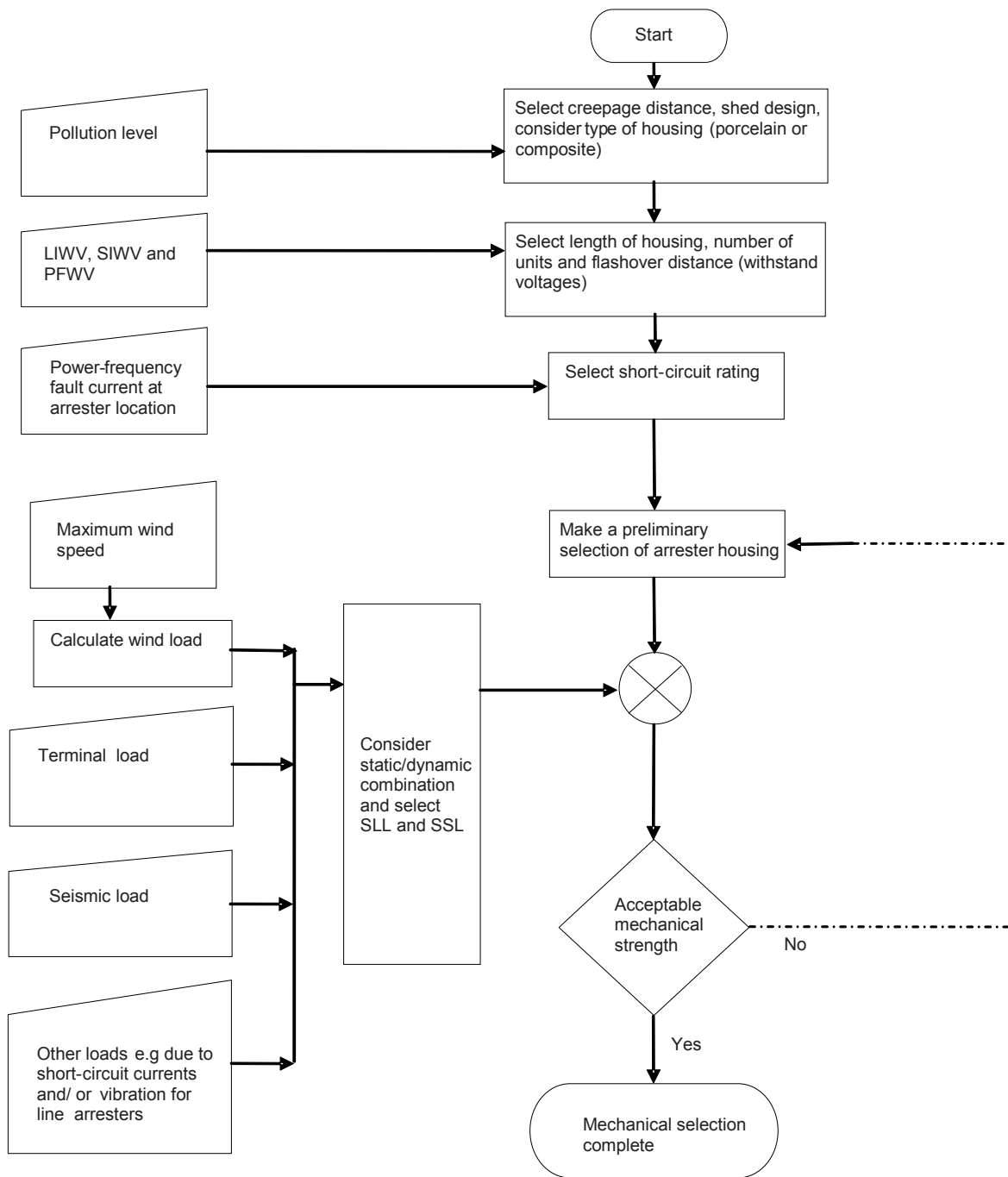


Figure 19a – Selection with respect to electrical data



IEC 1028/13

Figure 19b – Selection with respect to mechanical data

Figure 19 – Flow diagrams for standard selection of surge arrester

Annex E shows typical data which the user needs from arrester manufacturers for the selection of arresters.

6.3.2.2 Selection of the continuous operating voltage U_c and the rated voltage U_r

The continuous operating voltage of the arrester, U_c , is selected higher than or equal to the highest actual continuous operating voltage across the arrester. This is normally, for phase-earth arresters, equal to $Um/\sqrt{3}$.

To fulfil the requirements on TOV capability a suitable rated voltage thereafter is selected.

The rated voltage as defined in the standard is the 10 s power-frequency voltage used in the operating duty test after application of high-current or long duration current impulses. Rated voltage is thus a minimum TOV capability for 10 s as per the standard. For other combinations of magnitude and duration of TOV the manufacturers give the TOV capability either in factors of the rated voltage, U_r , or in factors of the U_c .

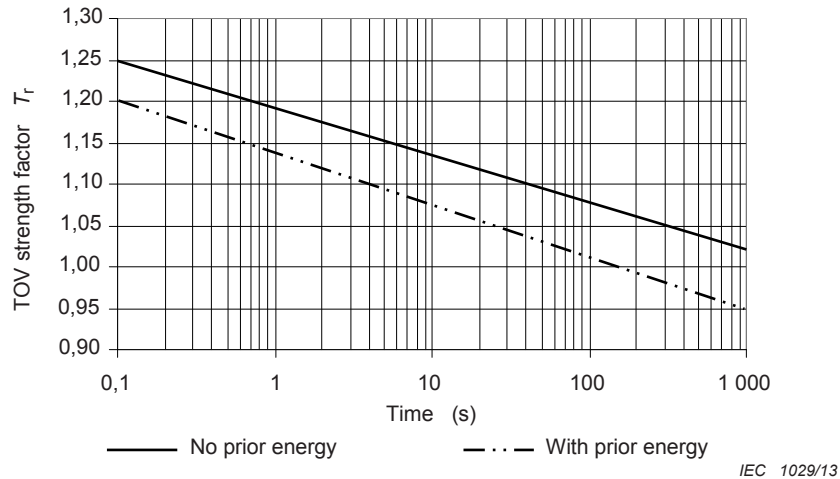


Figure 20a – Given as a factor of rated voltage, $T_r = U/U_r$

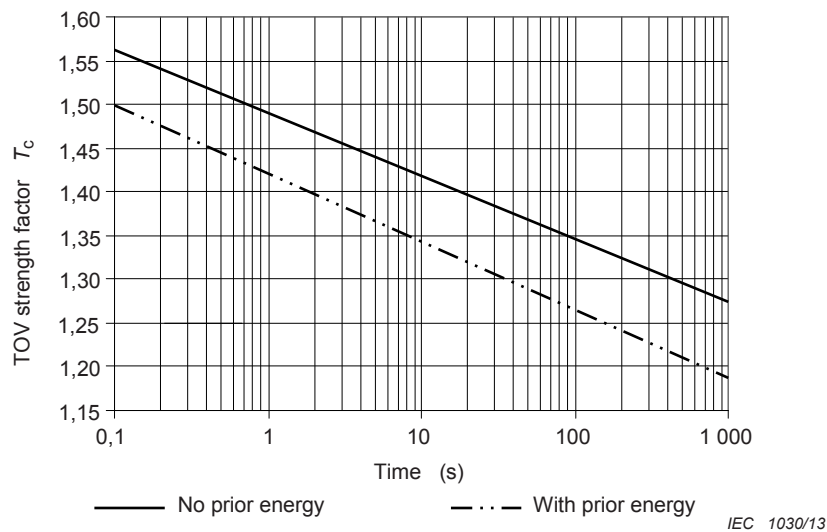


Figure 20b – Given as a factor of continuous operating voltage, $T_c = U/U_c$

NOTE 1 Each arrester has unique curves given by the manufacturer.

NOTE 2 Figures 20a and 20b are for the same arrester with a $U_c = 0,8 \times U_r$.

Figure 20 – Examples of arrester TOV capability

Factors affecting TOV capability are ambient temperature and energy absorbed (i.e. the initial temperature of the resistor elements prior to the application of TOV) and the applied voltage following the TOV. Manufacturers, therefore, also normally give several curves for the TOV capability with and without prior energy.

The two ways of expressing the TOV factor, either in a factor, $T_r = U/U_r$, or in a factor, $T_c = U/U_c$, are illustrated as examples in Figures 20a and 20b respectively. Note that the examples in this case are for the same arrester with a U_c equal to $0,8 \times U_r$.

For arresters with the TOV capability expressed as factor of the rated voltage $T_r \times U_r$ shall be higher than or equal to the expected temporary overvoltage at the arrester terminals for the considered time duration.

For arresters with the TOV capability expressed as a factor of the continuous operating voltage $T_c \times U_c$ shall be higher than or equal to the expected temporary overvoltage at the arrester terminals for the considered time duration.

6.3.2.3 Selection of nominal discharge current and line discharge class

The nominal discharge current, I_n which provides the lightning impulse protection level, LIPL of a surge arrester is used as one of the metal oxide arrester classification. However the value of the nominal discharge current alone does not give enough information about the performance of the arrester. Additional information about the line discharge class or generally the required energy withstand capability is needed. Usually the IEC LD class is chosen first and then the user will automatically get a nominal discharge current (see Table 2). Particularly between IEC LD classes 3 and 4 it should be noted that I_n changes from 10 to 20 kA so that the LIPL for the LD class 4 arrester may look higher but is in reality lower for the same coordinating current. The co-ordinating current for the LIPL shall be selected to correspond to the actual risk of substation flashover due to lightning strikes on the connected OH lines. However, the user may still use another coordinated current than the nominal discharge current for determining of the LIPL of the arrester, such as 0,5 or 2 times I_n . In addition the nominal discharge current is combined with a specific high current impulse (see Table 2).

For surge arresters protecting high-voltage substation equipment line discharge classes 2 to 5 are used. In medium voltage systems mainly 5 kA and 10 kA arresters with line discharge class 1 are used. For specific applications as protection of cables, rotating machines or capacitor banks higher line discharge classes may also be selected for medium voltage systems.

Table 2 – Arrester classification for surge arresters

LD class	-/-	1	2	3	4	5
I_n in kA	5	10	10	10	20	20
I_{hc} in kA	65	100	100	100	100	100
I_{sw} in A	-/-	125 and 500	125 and 500	250 and 1000	500 and 2000	500 and 2000

6.3.2.4 Surge arrester energy dissipation during lightning current discharges

The energy from lightning strikes can be estimated from Formula (4) [3], [4]:

$$W = \left[2 \times U_f - N \times U_{pl} \left(1 + \ln \left(2 \times \frac{U_f}{U_{pl}} \right) \right) \right] \frac{U_{pl} \times T_l}{Z} \quad (4)$$

where

W is the energy. If the distances between stations in distribution systems are small, the energy can be divided because of current sharing.

\ln is the natural logarithm;

U_{pl} is the lightning impulse protection level of the arrester;

U_f is the negative flashover voltage of the line insulation;

Z is the line surge impedance;

N is the number of lines connected to the arrester;

T_1 is the equivalent duration of the current of a lightning flash including first and subsequent strikes. Typical value 3×10^{-4} s.

NOTE The formula is derived from an integration of an exponentially decreasing overvoltage.

Computer analysis according to IEC 60071-4 on lightning energy dissipation into surge arresters can give more accurate values.

6.3.2.5 Surge arrester energy dissipation during line switching

The arrester switching energy is dependent on surge magnitude, wave shape, system impedance and configuration, arrester protective characteristics and frequency of switching operations within a short time period. Ultimately, the selected surge arrester shall have energy capacity greater than the accumulated energies over the severest operating duty. The required surge arrester energy duty is obtained during the insulation coordination step determining the representative overvoltages. In most practical cases, since nature of switching is statistical and generated waveforms are typically complex especially with highly non-linear characteristics of an arrester, it is desirable to perform computer simulation studies. When such studies are unavailable for line switching, a conservative estimate can be obtained from an equation similar to that used for defining arrester line discharge class (IEC 60099-4:2009, Table 5). The simplified arrester energy Formula (5) is derived based on the assumption that the entire line is charged to a prospective switching surge voltage and is discharged through the arrester at its protective level during twice the travel time of the line [7].

$$W = U_{ps} \times \frac{U_{rp} - U_{ps}}{Z_s} \times 2 \times \frac{L}{c} \quad \text{per switching} \quad (5)$$

where

W is the energy

L is the line length;

c is the speed of light;

Z_s is the line surge impedance;

U_{ps} is the arrester residual voltage at the lower of the two switching impulse currents;

U_{rp} is the representative maximum switching voltage.

6.3.2.6 Protection from slow-front overvoltages

Metal-oxide surge arresters are suitable for limiting slow-front overvoltages from line energization and switching of inductive and capacitive currents, but not in general overvoltages caused by earth faults and fault clearing, as the expected amplitudes of the latter are too low.

The influence on the current front times can be ignored for slow-front overvoltages. Furthermore, separation effects within substations can be neglected.

Surge arresters are usually installed phase-to-earth and, if metal-oxide arresters are used to limit slow-front overvoltages to a low level, the phase-to-phase overvoltages will reach about twice the protection level of the arrester phase-to-earth, irrespective of the transformer neutral treatment. The phase-to-phase overvoltage will consist of two phase-to-earth components with the most frequent subdivision 1:1. If lower phase-to-phase protective levels are required, additional arresters phase-to-phase is needed.

The problem with switching overvoltages is the capability of surge arrester to withstand the thermal stress associated with heating. This can only be controlled through adequate

identification of likely sources of overvoltages and appropriate specification of a surge arrester with a suitable energy absorption capability.

The impact of switching related overvoltages becomes more critical at higher system voltages; therefore typically transmission networks are more susceptible to equipment damage from these overvoltages than compared to range I networks. In practice, the effect of switching overvoltages become important for system nominal with voltages greater than 245 kV (range II).

In range I, the standard insulation level of the equipment is usually so high that protection from slow-front overvoltages is not generally necessary (exceptions are rotating machines). However, the common use of reactive compensation equipment on range I voltages increase the use of surge arresters and the awareness of slow-front overvoltages protection.

The representative overvoltage at the equipment protected by arresters is equal to the switching impulse protection level, because, with the exception of transmission lines, travelling wave effects can be neglected and the voltage at the equipment is equal to that at the arrester. For the phase-to-phase overvoltages, it can be up to twice this value without phase-to-phase arresters.

In the case of surge arrester protection against switching overvoltages, a severe skewing in the statistical distribution of overvoltages takes place. This skew is more pronounced the lower the protection level, as compared to the amplitudes of the prospective slow-front overvoltages. In these situations, small variations of the insulation withstand have a large impact on the risk-of-failure. To cover this effect, it is proposed to make the deterministic coordination factor dependent on the relation of the surge arrester protective level to the 2 % value of the prospective overvoltages, Formulas (6), (7), (8) and (9) [68]:

$$\frac{U_{ps}}{U_{e2}} \leq 0,7; K_{cd} = 1,1 \quad (6)$$

$$0,7 < \frac{U_{ps}}{U_{e2}} \leq 1,2; K_{cd} = 1,24 - 0,2 \frac{U_{ps}}{U_{e2}} \quad (7)$$

$$1,2 < \frac{U_{ps}}{U_{e2}}; K_{cd} = 1,0 \quad (8)$$

and the coordination switching impulse withstand voltage as

$$U_{cw} = K_{cd} \times U_{ps} \quad (9)$$

where

U_{ps} is the switching impulse protective level of the arrester;

U_{e2} is the 2 % value of the prospective slow-front overvoltage amplitude to earth;

U_{cw} is the coordination switching impulse withstand voltage of the equipment;

K_{cd} is the deterministic coordination factor.

NOTE 1 The factor 1,0 to 1,1 takes into account the high frequency of overvoltages with amplitudes equal to the protection level due to the truncation of the overvoltage distribution by the arrester. The lower the protective level the more frequent will be the overvoltages. Due to the uncertainties in the equipment withstand, the margin between the withstand voltage and the protective level should increase with increasing overvoltage frequency to maintain a given risk level.

NOTE 2 If U_{e2} is less than $U_{ps}/1,2 U_{cw}$ may be calculated without considering the protection by arresters.

6.3.2.7 Protection from fast-front overvoltages

6.3.2.7.1 General

For high voltage arresters in the substations size significantly affects the protection margin where fast-front transients are concerned. Surge arresters cannot adequately protect equipment with large separation distances between line entries and transformer bushings, so typically arresters must be dedicated to critical plant items and additional arresters installed to control the number of overvoltages entering the substation. The coordination lightning impulse withstand voltage can be determined from the following “modified” empirical formula (15) which considers the fundamental characteristics of lightning overvoltage behaviour in stations (see IEC 60071-2).

This modification considers the existence of sizable surge capacitance, C_s , at the line terminal or station entrance which could reduce the steepness of the incoming surge based on line corona distortion factor and accepted failure rate alone as explained in Annex G. The voltage response with capacitance at the line terminal due to the incoming surge with crest, V_s , can be estimated using the formula for the capacitance terminated line where the capacitance, C_s , is charged through the line surge impedance, Z .

Capacitance Terminated Line Voltage:

$$V_c(t) = 2 \times V_s \times \left[1 - e^{-\left(\frac{t}{Z \times C}\right)} \right] \quad (10)$$

Slope of $V_c(t)$:

$$S = \frac{d}{dt} V_c(t) = \frac{2 \times V_s \times e^{-\left(\frac{t}{Z \times C}\right)}}{Z \times C} \quad (11)$$

When $(t/(Z \times C))$ is kept constant, the ratio of slopes (steepness factor, f_s), with two different value of capacitances, C_0 (equivalent capacitance derived from line corona factor) and C_s (additional capacitance), becomes;

$$f_s = \frac{S_s}{S_0} = \frac{C_0}{(C_0 + C_s)} = \frac{1}{(1 + C_s/C_0)} \quad (12)$$

where

S_0 is steepness due to corona alone;

S_s is steepness with added capacitance.

The estimated reduction in the incoming voltage surge steepness is dependent on the ratio of the initial equivalent capacitance, C_0 , and presence of sizable capacitance, C_s , relative to C_0 (Annex H). For the incoming voltage steepness estimation, it is convenient to evaluate the slope when constant 0,5 is selected for the exponent $[t/(Z \times C)]$ at 0,5 at which time the capacitor voltage $V_c(t) = 0,5 \times Z \times C$ becomes $0,8 \times V_s$. Then, the equivalent capacitance value, C_0 , can be obtained by equating the time, $t_0 = 0,5 \times Z \times C_0$, to the same time derived from the same capacitor terminal voltage value ($0,8 \times V_{crest}$) divided by the steepness of the incoming line voltage, S_0 , where S_0 is estimated using line corona and light speed parameters ($A \times c/2$) divided by the accepted failure rated distance from station, $(L_{sp} + L_f)$.

$$t_0 = 0,5 \times Z \times C_0 = 0,8 \times V_s / S_0 \quad (13)$$

where corona steepness

$$S_0 = (A \times c/2)/(L_{s0} + L_f)$$

Thus, equivalent capacitance due to corona

$$C_0 = (1,6 \times V_s)/(Z \times S_0) \quad (14)$$

where

$$V_s \approx 1,2 \times \text{CFO of line}$$

NOTE Factor f_s is introduced to take into account the current reducing effects of capacitances at the line entrance.

$$U_{cw} = U_{pl} + \frac{A \times f_s}{N} \times \frac{L_t}{L_{sp} + L_f} \quad (15)$$

where

U_{cw} is the coordination lightning impulse withstand voltage;

U_{pl} is the lightning impulse protection level of the surge arrester;

A is the voltage according to Table 3 describing the lightning performance of the overhead line connected to the station;

$f_s = 1 / [1 + C_s/C_0]$ steepness reduction factor with surge capacitance at line terminal

where

C_s is the effective surge capacitance at line terminal, μF

C_0 is the equivalent surge capacitance of incoming surge related to corona, μF

$C_0 \approx (0,8 \times 1,2 \times \text{CFO})/(Z \times S)$ μF

CFO is the line insulation criteria (50 %) flashover voltage, kV

Z is the line surge impedance ($\sim 300\text{-}400$ ohms)

$S = (A \times c/2)/(L_{sp} + L_f)$ kV/us

N is the number of lines connected to the substation ($N = 1$ or $N = 2$);

L_t is the total length $d + d_1 + d_2 + d_A$, (see Figures 8 and 9);

L_{sp} is the span length;

$L_f = R_a/r$ is the length of the overhead line in front of the station, which gives a rate of lightning events equal to the acceptable failure rate. The right fraction multiplied by A/N is proportional to the steepness of the representative impinging surge. Note that in formulas (15), (16) and (17) consistent units must be used;

R_a is the acceptable failure rate (number of failures per unit time) for the protected equipment;

r is the overhead line outage rate (number of outages per unit time and unit length) per year for a design corresponding to the first kilometre in front of the station. If $N = 2$, the rates have to be added.

For distribution lines the outage rates are usually large compared to the acceptable failure rates, i.e. the overhead line length L_f in Formula (15) is small and can be neglected. Formula (15) is then simplified to:

$$U_{cw} = U_{pl} + \frac{A \times f_s}{N} \times \frac{L_t}{L_{sp}} \quad (16)$$

Induced lightning overvoltages need to be considered in distribution systems, where the equipment is not protected against direct lightning strikes to the conductors or against back-flashovers.

Table 3 – Definition of factor A in formulas (15) to (17) for various overhead lines

Overhead Line configuration	A (kV)
Distribution lines (phase-to-phase flashovers)	
– with earthed cross-arms (flashover to earth at low voltage)	900
– wood-pole lines (flashover to earth at high voltage)	2 700
Transmission lines (single-phase flashover to earth)	
– single conductor	4 500
– double conductor bundle	7 000
– four conductor bundle	11 000
– six and eight conductor bundle	17 000

NOTE The voltages A for distribution lines are lower than that for the single conductor transmission line, because in distribution lines phase-to-phase flashovers or multiple phase-to-earth flashovers occur, thus leading to current sharing, and in case of earthed cross-arms, to a limitation of the incoming surge amplitude.

The protective zones for fast-front overvoltages of surge arresters installed may also be determined by the acceptable failure rate chosen for a study. IEC 60071-2 suggests values between 0,1 % per year and 0,4 % per year. A typical value of 0,25 % per year is used in the examples of Table 4.

Table 4 – Examples for protective zones calculated by formula (17) for open-air substations

System voltage	Protection level	Withstand voltage		Span	Axfs	Protective zone L_p					
		rated	Coordination			$r = 0,1^a$	$r = 0,5^a$		$r = 2^a$		$r = 6^a$
kV	kV	kV	kV	m	kV	$N = 2$ m	$N = 1$ m	$N = 2$ m	$N = 2$ m	$N = 2$ m	$N = 2$ m
24	80	125	109	100	2 700	–	–	–	2,4	4,8	<u>3,0</u>
				200	900	–	–	–	10,4	20,8	<u>15,5</u>
123	350	550	478	300	$f_s=1,0,$ 4 500	<u>160</u>	<u>23</u>	46	12,0	<u>24</u>	–
					$f_s=0,5,$ 2 250	<u>320</u>	<u>46</u>	92	24,0	<u>48</u>	–
420	900	1 425	1 239	400	$f_s=1,$ 11 000	<u>180</u>	<u>28</u>	56	16	<u>32</u>	–
					$f_s=0,5,$ 5 500	<u>360</u>	<u>56</u>	112	32	<u>64</u>	–

^a Dimensions in 1 per 100 km and year.
 f_s surge capacitance factor e.g. no surge capacitance: $f_s = 1,0$, ($C_s = 0$, C_o estimated from incoming surge),
 $f_s = 0,5$, (when $C_s = C_o$ added)

Formula (15) describes the per unit voltage drop depending on the lightning performance of the overhead line connected to the equipment, on the substation layout and on the adopted acceptable failure rate of the equipment. Using the existing knowledge of the lightning

performance of overhead lines and of corona damping effects, the constant A has been determined to obtain agreement between the withstand voltages calculated with Formula (15) and the service experience obtained with protective zones used for a long time (see Table 4). The formula may not be used to determine overvoltage amplitudes for a specific lightning event on the overhead line.

When the rated lightning impulse withstand voltage of the equipment is selected, the protective zone of the arrester can be estimated from Formula (17):

$$L_p = \frac{N}{(A \times f_s)} \left[\left(\frac{U_{rw}}{1,15} \right) - U_{pl} \right] (L_{sp} + L_f) \quad (17)$$

where

L_p is the protective zone;

U_{rw} is the required lightning impulse withstand voltage.

Formula (17) indicates that for a given substation, the protective zone increases with:

- increasing difference between rated withstand voltage and protective level;
- decreasing outage rate of the overhead line in front of the station, thus demonstrating the effect of improved shielding by earth wires and reduced tower footing impedance;
- increasing acceptable failure rates, this means that the equipment outside the protective range still may be protected, however with a higher failure rate.

6.3.3 Selection of line surge arresters, LSA

6.3.3.1 General

There are two different designs of LSA: non gapped line arresters, NGLA, or externally gapped line arresters, EGLA, which have somewhat different features making them more or less suitable for certain applications. The NGLA are tested according to IEC 60099-4, while the EGLA are tested according IEC 60099-8. Today's LSA are typically polymer housed which give them significant advantages over porcelain designs for this application. For more information see CIGRÉ 440 [56].

6.3.3.2 Selection of NGLA, non gapped line arresters

6.3.3.2.1 General

Non gapped line arresters are suitable for all system voltages and for protection against both lightning and/or switching related phenomena.

The selection of NGLA for line protection differs only slightly from typical arrester selections. The most significant difference is the use of disconnectors for NGLA also for system voltages above distribution systems. The following iterative procedure, shown in the flow diagram of Figure 21, is recommended for the selection of NGLA:

- determine the continuous operating voltage of the arrester with respect to the highest system operating voltage;
- determine the rated voltage of the arrester with respect to the temporary overvoltages;
- estimate the magnitudes, charge (or related arrester energy) and probability of the expected lightning discharge currents through the arrester, determine the transmission line discharge requirements and select the nominal discharge current, the high current impulse value, the line discharge class and the lightning impulse discharge capability of the arrester considering an acceptable arrester failure rate;

NOTE Lightning discharge currents and related discharge energy may be significantly higher than for station applications in particular in the case of unshielded lines. Switching impulse currents may be lower.

- select the short-circuit rating with respect to the expected fault current;
- select a surge arrester that fulfils the above requirements;
- determine the lightning and switching impulse protection characteristics of the arrester;
- locate the arrester as close as possible to the insulators to be protected with consideration to sufficient clearances in the event of arrester overloading and disconnector operation;
- determine the coordination switching impulse withstand voltage of the protected equipment taking into account the representative slow-front overvoltages and system layout;
- determine the coordination lightning impulse withstand voltage considering:
 - the representative lightning current surge as determined by the lightning performance of the overhead line to which the arrester is connected (ground flash density, strike incidence to the line, tower footing resistance etc.) and the acceptable flashover rate of the protected insulation;
 - the line layout;
 - the length of connection leads between surge arrester and protected insulation;
- determine the rated insulation level of the equipment from IEC 60071;
- if a lower rated insulation level of the equipment is desired, then a lower rated voltage, a higher nominal discharge current, a higher line discharge class, a higher lightning impulse discharge capability, a different arrester design or a reduced length of connection leads between arrester and protected insulation should be investigated;

NOTE 1 A lower rated voltage may affect the service reliability of the arresters, due to the higher specific voltage stress under COV.

NOTE 2 Insulation levels for lines may differ from the levels given in IEC 60071.

NOTE 3 The normal case may be that the arresters are to be installed on an existing line. The coordination switching and lightning impulse withstand voltages are then compared with the existing insulation levels of the line.

- the risk of arrester overloading due to lightning discharges should be considered and taken into account in the calculated flashover and outage rate of the line.

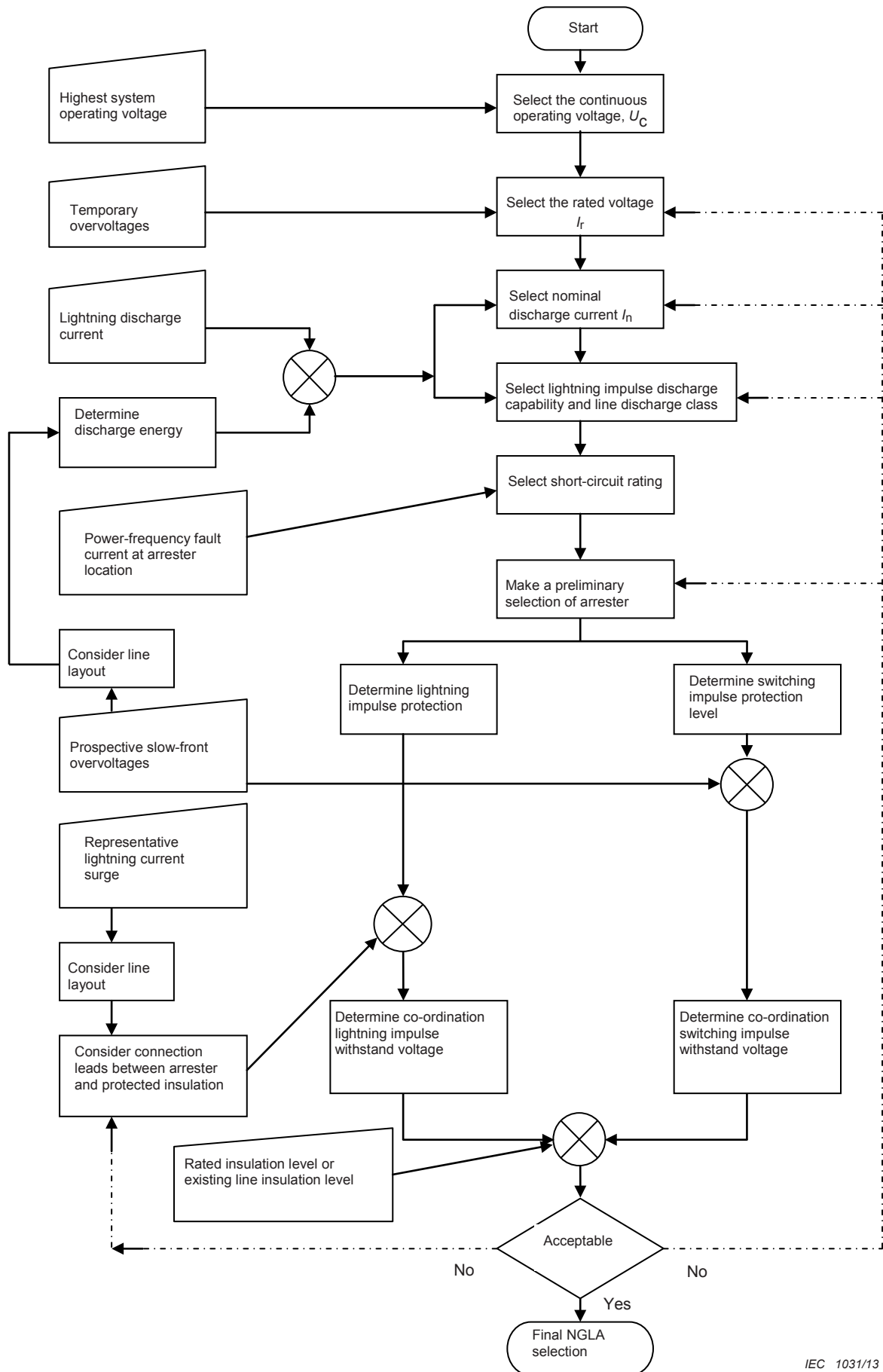


Figure 21 – Flow diagram for the selection of NGLA

6.3.3.2.2 Rated voltage

The rated voltage shall be selected so that the lightning and switching surge protective levels are coordinated below the LIWV, and SIWV of the line insulation respectively. Selection of rated voltage is not especially crucial, as there usually is an ample margin between LIWV of line insulation and protective levels, and there is no benefit of extra protective margins. Thus it is not recommended to choose the lowest possible characteristics, as this will increase the risk that these arresters may be stressed by unnecessary high power frequency overvoltages. This is typically done by selecting a higher rated voltage and/or a lower IEC line discharge class of the NGLA than for the substation arresters. Such a selection also ensures that the arresters are not unnecessarily stressed by high switching energies or capacitor discharges, which should be handled by the substation arresters.

6.3.3.2.3 Arrester class and energy requirements

NGLA are selected both with respect to their arrester classification and for NGLA with a rated voltage higher than 52 kV also from their lightning impulse discharge capability in Annex N of IEC 60099-4:2009. NGLA on shielded lines typically has a nominal discharge current of 5 kA or 10 kA according to IEC with line discharge classes 1 to 3, depending on their application.

For NGLA installed for lightning protection on unshielded lines a nominal discharge current of 10 kA or 20 kA according to IEC with line discharge classes 2 to 4 may be used depending on the isokeraunic levels (thunder days/year, T_D) and expected outage rate. There are special software available on the market which will give guidance for the dissipated charge/energy from lightning strokes.

NGLA for protection of switching overvoltages are selected to have the same or in many cases one IEC line discharge class lower than what the substation arresters have, due to that for longer lines the NGLA are installed around the midpoint reducing the line length for the involved NGLA. Typically a nominal discharge current of 10 kA or 20 kA according to IEC with line discharge classes 3 to 5 may be used.

6.3.3.2.4 Fault clearing and disconnectors

Disconnectors are used to facilitate fast reclosing as NGLA are connected directly across the line insulators which are self-restoring. Disconnectors are usually not permitted to disconnect high voltage substation arresters automatically in the event of an arrester failure since the insulation of the substation equipment is generally not self-restoring and should not be re-switched in without protection.

These disconnectors in series with the NGLA also serve as indicators making it simple to find overloaded NGLA with visual inspection.

These disconnectors will have somewhat different requirements from the ones used for distribution arresters in that they must match the energy handling capabilities of the NGLA. Therefore these disconnectors must be capable of withstanding both higher impulse currents as well as longer duration impulses compared to disconnectors for distribution arresters; in fact the disconnectors must pass all the type tests that the NGLA is capable of. The crucial requirements of the disconnector are to verify that it does not operate unless the NGLA is overloaded and that it operates quickly enough. For unearthed systems without shield wires, having a very low short-circuit current out on the lines, such as only a few tens of Amps, this leads to conflicting requirements of the disconnectors.

The disconnector device is often mechanically weaker than the rest of the installation. Hence, the conductor connecting the NGLA to earth or the phase conductor must be sufficiently long to ensure that the movements of the arresters and/or the transmission line will not risk that the disconnector device may break off by mechanical fatigue.

The tower with an overloaded gapless line arrester shall after the disconnecter operation preferably have LIWV and SIWV as prior to the line arrester installation, as it may take some time before failed NGLA can be replaced.

6.3.3.2.5 Applications of NGLA

NGLA are suitable for all mentioned applications mentioned in 6.2.4, as they can be selected to protect against both lightning and switching overvoltages.

However, in areas with high ground flash density, one should make sure that disconnectors with proper operation characteristics are selected for the application of NGLA for unshielded overhead lines on compensated/non directly earthed high voltage systems with earth fault currents below 100 A.

With NGLA installed on every tower it is today possible to design compact transmission lines with significantly smaller clearances than what is traditionally used, if pollution is not the limiting factor of line insulation. NGLA can also be used to upgrade existing system voltages using existing towers and lines, especially for old not commonly used system voltages. For this application NGLA can be used either on the top phase(s) as a substitute for shield wires in areas with moderate ground flash density or on all three phases together with shield wires. NGLA are recommended as both fast-front and slow-front overvoltages may be critical.

By locating NGLA on all phases of the towers closest to a substation the incidence of back-flashovers near the substation can be more or less eliminated. This results in a reduction of steepness and amplitude of incoming surges. This improves the protection performance of the station arresters for air-insulated substations, and may eliminate the need for metal-enclosed arresters even for large GIS. For this application NGLA shall be used, as the incoming overvoltage should have both reduced magnitudes and as slow rise time as possible when entering the substation. This will increase the minimum protection distance inside the GIS. Even parallel columns may then be the most economical solution. These parallel columns of the same rated voltage do not have to be matched with respect to current sharing as they are only for reducing the protection levels.

6.3.3.3 Selection of EGLA, externally gapped line arresters

6.3.3.3.1 General

One difference from NGLA is that the series varistor unit (SVU) of the EGLA is not continuously exposed to the system voltage. Hence the selection of the rated voltage of EGLA will differ from NGLA. Another important feature is the coordination of its gap characteristics with the LIWV and SIWV of the protected line insulation.

The following iterative procedure, shown in the flow diagram of Figure 22, is recommended for the selection of EGLA:

- determine the rated voltage of the arrester with respect to the highest system operating voltage and temporary overvoltage during spark over operations;
- estimate the magnitudes, charge (or related arrester energy) and probability of the expected lightning discharge currents through the arrester, select the nominal discharge current, the high current impulse value and the lightning impulse discharge capability of the arrester considering an acceptable arrester failure rate;
- select the short-circuit rating with respect to the expected fault current;
- select a surge arrester that fulfils the above requirements;
- determine the insulation withstand of EGLA (with shorted SVU) with respect to maximum slow-front overvoltages on the system;
- determine the lightning impulse protection characteristics of the arrester comprising the spark over voltage for fast-front, and standard lightning impulse and residual voltages for the nominal discharge and high current;

- determine the coordination lightning impulse withstand voltage considering:
 - the representative lightning current surge as determined by the lightning performance of the overhead line to which the arrester is connected (ground flash density, strike incidence to the line, tower footing resistance etc.) and the acceptable flashover rate of the protected insulation;
 - the line layout;

NOTE 1 A lower rated voltage may reduce the service reliability of the arresters.

NOTE 2 Insulation levels for lines may differ from the levels given in IEC 60071.

NOTE 3 The normal case may be that the arresters are to be installed on an existing line. The coordination lightning impulse withstand voltage is then compared with the existing insulation level of the line.

- the risk of arrester overloading due to lightning discharges should be considered and taken into account in the calculated flashover and outage rate of the line;
- EGLA is considered to be installed directly in parallel with the insulator assembly. The effect of connection leads shall be considered in the residual voltages given for the arrester as per IEC 60099-8.

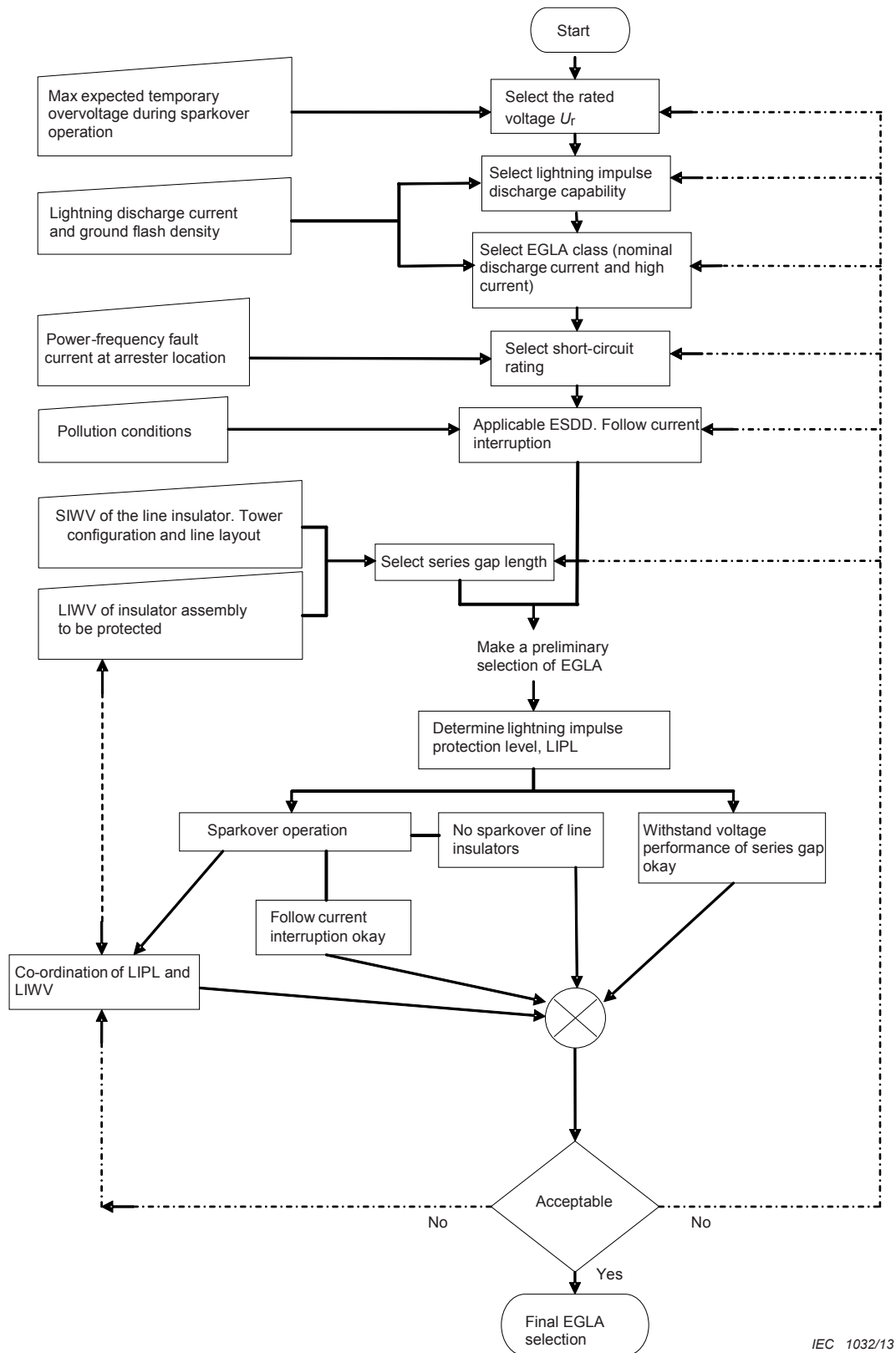


Figure 22 – Flow diagram for the selection of EGLA

6.3.3.3.2 Rated voltage

The rated voltage of the SVU is determined by the maximum line-to-earth voltage during arrester operation so that the SVU can handle this power frequency voltage for the duration of a half cycle. This duration comes from the fact that the gap must always be able to reseal within the first half cycle at a maximum. In addition the rated voltage of the SVU is selected so that the protective characteristics of the EGLA, which consider both the residual voltage of the SVU plus the spark over voltage of the external gap, are coordinated to be below the LIWV of the line insulation. There are no requirements of U_c . Hence the rated voltage for the SVU is selected

lower than for any other arrester application in the system. Thus the SVU can be made more compact and lighter compared to NGLA, which also facilitates installation of EGLA in crowded multi-circuit towers.

6.3.3.3.3 Arrester class and energy requirements

6.3.3.3.3.1 General

EGLA are selected both with respect to their arrester classification and from their lightning impulse discharge capability in Annex N of IEC 60099-4:2009. EGLA on shielded lines does typically have a nominal discharge current of 5, 10, 15, or 20 kA for classes Y1-Y4 (wave shape 2/20 μ s), or 5, 10, or 20 kA for classes X1-X4 (wave shape 8/20 μ s) according to Table 1 in IEC 60099-8:2011. The selection of the EGLA class strongly depends on the application conditions, such as EGLA locations (all towers on three phases of one circuit in double-circuit line, limited towers on all phases of two circuit in double-circuit line, etc.), line configurations (shielded line, unshielded line, conductor and shielding wire positions, tower span, tower height, etc.), tower footing resistance, ground flash density, lightning current distribution, lightning strike wave shape, etc. Therefore the detailed simulation is recommended to obtain the lightning current duty of EGLA, i.e. maximum lightning current through EGLA, energy or charge absorbed by EGLA.

An example of the condition for calculating lightning current duty of EGLA in 77 kV transmission lines in Japan is shown in Table 5, where a shielding wire is used, EGLA are installed at all towers on three phases of one circuit in double-circuit line, and the lightning strike wave shape is 2/70 μ s. In this case, the high current impulse of 25 kA (2/20 μ s) in class Y2 corresponds nearly to the direct lightning strike of 30 kA (2/70 μ s) to the conductor adjacent to EGLA or the strike of over 400 kA to the shielding wire [76].

Table 5 – Example of the condition for calculating lightning current duty of EGLA in 77 kV transmission lines

Item		Condition	
Shielding of the line		Shielded	
EGLA location		All towers on 3 phases of one circuit in double-circuit line	
Lightning strike	Waveform		
	Strike point	Shielding wire	– Top of tower
		Conductor (Shielding failure)	– Conductor adjacent to EGLA – Conductor at 1/4 span from tower – Conductor at 1/2 span from tower
Height of conductors (from the ground)	Shielding wire		37,3 m
	Upper phase		34,2 m
	Middle phase		30,4 m
	Bottom phase		27,0 m
Tower	Span		300 m
	Footing resistance		10 Ω
	Surge impedance		133 Ω
	Velocity of surge propagation		210 m/μs

6.3.3.3.2 Insulation withstand

EGLA shall have the voltage withstand capability against temporary overvoltages and slow-front overvoltages if, as the worst case scenario, the SVU is shorted by a failure. The withstand voltage of EGLA should be determined taking the overvoltage values and the frequencies of their occurrence and are recommended not to be lower than the practical insulation levels of the line (as for power frequency withstand voltage, 1,2 times the rated voltage is specified in IEC 60099-8). EGLA shall withstand these voltages under wet conditions on condition that the SVU is failed and is shorted, where the failed SVU is simulated by shorting it with a metal wire.

SVU shall withstand its residual voltage when lightning current flows after sparkover of the external series gap. In IEC 60099-8, the housing of SVU is required to withstand a lightning impulse voltage of 1,13 times the residual voltage at high current impulse for "Series Y" and 1,4 times the residual voltage at the nominal discharge current for "Series X", where the factor of 1,4 covers variations in atmospheric conditions and discharge currents up to three times the nominal discharge current.

With regard to the insulation withstand of external series gap, a larger clearance is preferable, but the insulation coordination between the sparkover voltage of the external series gap and the withstand voltage of the insulator assembly shall be taken into consideration; a shorter clearance is preferable for insulation coordination.

6.3.3.3.4 Insulation coordination of the gap

The EGLA is intended only for protection of the insulator assembly installed in parallel to the EGLA against lightning overvoltages. An EGLA shall not spark over for any slow-front overvoltages and power frequency overvoltages occurring on the system even under polluted and/or wet conditions. If the SVU is overloaded it will be short-circuited and the gap shall not spark over when reclosing occurs or for any slow-front or temporary overvoltages of the system. To obtain an acceptable insulation coordination between the LIWV strength of the insulator assembly, in parallel to the EGLA, and the protection performance of EGLA the following criterion is recommended:

$$U_{50\text{EGLA}} + X \times \sigma < U_{50\text{LI}} - X \times \sigma \quad (18)$$

where

$U_{50\text{LI}}$ is the 50 % probability flashover voltage for the insulator at the standard lightning impulse

$U_{50\text{EGLA}}$ is the 50 % probability spark over voltage for EGLA at the standard lightning impulse. Furthermore $U_{50\text{EGLA}}$ shall be the maximum voltage with or without the SVU short-circuited

σ is the standard deviation and for lightning impulses set to 3 % of U_{50}

X recommended value is 2,5

A higher value of X in (18) provides a lower probability of insulator flashover. Assuming that lightning overvoltages are always high for EGLA enough to sparkover, the distribution of sparkover voltage can be regarded as the distribution of voltage stress to the insulator. When

$$U_{50\text{EGLA}} + X \times \sigma = U_{50\text{LI}} - X \times \sigma \quad (\sigma = 3 \%) \quad (19)$$

the probability of insulator flashover can be obtained by the joint probability of the sparkover voltage (voltage stress to the insulator) and the insulator flashover voltage as shown in Table 6. From this table, the value X of 2,5 provides enough low probability of insulator flashover.

Table 6 – Probability of insulator flashover in Formula (19)

Value X	Probability
2	0,0 024
2,5	0,00 021
3	0,000 012

6.3.3.3.5 Application of EGLA

EGLA can only be used for protection against flashovers due to shielding failures and are typically used for shielded lines to protect against back flashover or shielding failures.

In case of arrester overloading it should be noticed that it may be difficult to visually detect a failed SVU. Therefore a fault indicator may be used. Fault indicators should give a clear visual indication of a failed EGLA.

It shall be noted that the tower with a failed EGLA will always have a lower LIWV than originally due to the required spark over characteristics. Hence a quick replacement is recommended.

6.3.4 Selection of arresters for cable protection

6.3.4.1 Overvoltage protection of cables

The essential difference between the electrical parameters of overhead lines and cables is the surge impedance and the velocity of the travelling wave. Values for overhead single conductor lines are in the range of 300 to 450 Ω and for cables in the range of 20 to 60 Ω . First of all, this difference causes a remarkable reduction of an incoming overvoltage as soon as the travelling wave enters the cable. The reduced voltage wave travels through the cable and it is reflected at the cable end, so that the voltage is there nearly doubled. Subsequently the wave returns to the cable entrance and is there once more reflected, etc. In this way the overvoltage in the cable is built up to a theoretical maximum of two times the overvoltage on the overhead line. This maximum overvoltage peak is depending on the cable length, so for a

short cable of just tens of meters the maximum overvoltage may reach close to the theoretical value and the longer the cable is the lower the maximum overvoltage will be.

The flashover of a bus bar or an overhead line in air towards earth causes a short outage at the most. Subsequent damage is however extremely rare. In cables, flashover at the cable bushings or breakdown of the insulation is completely different and leads to the damage of the cable and requires extensive repair. Cables must therefore be treated as station equipment and protected against overvoltages by MO surge arresters.

In general for cables, the use of shield wires on the overhead line close to the cable (about three spans) and low footing impedances for the towers at the cable terminals are recommended.

The arresters are to be placed directly next to the cable ends. The connecting leads should be as short as possible. The earth connection of the arrester has to be connected in the shortest way straight to the cable sheath.

Longer cables require arrester protection at both ends. For short cable sections one-sided protection is, in some cases, sufficient. This is because an arrester at one end can still offer sufficient protection on the other end. Cables connected between two overhead lines should be protected by surge arresters at both terminals, if the cable length exceeds five times the value determined according to Formula (17).

As cables can store a relatively high energy it is advisable to choose arresters with a higher energy capability than used for the protection of distribution stations. This offers, besides the higher energy handling capability, at the same time a better protection due to the normally lower residual voltage of the arrester at the same U_c .

6.3.4.2 Protection of the cable sheath

Due to thermal reasons (power losses in the cable sheath) cable sheaths of power cables in high voltage systems are earthed at one end only. The open cable sheath has to be protected against overvoltages. This is standard practice for high voltage cables.

In distribution systems it depends on the general system management and on the length of the cable sections whether a cable sheath is earthed at both ends or at one end only.

In case both ends of the cable sheath are earthed any dielectric stress on the sheath insulation is avoided. Due to increasing load currents the thermal stress on power cables in distribution systems may increase as well to a critical value. A general disadvantage of earthing both ends of the cable sheath is an increase of the total power losses. For typical medium voltage polymeric insulated cables the additional losses in the cable sheath are around 2 % up to 10 % of the total power losses of a cable connection. However, the additional power losses can be avoided if only one side of the cable sheath is earthed, and a surge arrester is installed at the unearthed side of the cable sheath.

The voltages and currents of the cable sheath are influenced by:

- the short circuit current with a time duration of $t = 3$ s (maximum value in distribution systems)
- the load current
- the laying of the cables (triangular or single plane)

The induced voltage in the cable sheath due to the load current can be neglected, while the induced voltage due to the short circuit current is dimensioning for the continuous operating voltage of surge arresters for the cable sheath protection.

With an approximation the U_c for cable sheath arresters can be calculated from Formula (20).

$$U_c \geq \frac{U_i \times I_k \times L_k}{T} \quad (20)$$

where

U_c is the continuous operating voltage of the surge arrester in kV

I_k is the max. short circuit current of the cable (single phase) in kA

L_k is the length of the unearthed cable section in km

U_i is the voltage induced in the per unit length of cable sheath in kV/(kA × km)

T is the TOV factor of the MO-surge arrester (e.g. for $t = 3s$ in distribution systems

$$T_r = U_{TOV} / U_c$$

NOTE 1 U_i reaches in maximum 0.3 kV per kA of fault current and km of cable length.

NOTE 2 For transmission cables details calculations may have to be performed.

NOTE 3 The TOV capability can either be given as T_r or T_c but should in this case be recalculated to T_c for the actual cable sheath arrester. The ratio between T_r and T_c is the same ratio as between U_r and U_c for the actual arrester.

The continuous operating voltage of these arresters should be higher than the induced sheath-to-earth voltage at maximum fault current. The nominal charge rating should be the same as that of the phase-to-earth arresters at the cable terminals. The protection level should be as low as possible, because the withstand strength of the sheath during its service life is not well defined and is not assured by any standardized test.

NOTE 4 Surge arresters for cable sheath protection are sometimes called sheath voltage limiters (SVL).

6.3.5 Selection of arresters for distribution systems – special attention

6.3.5.1 General

These systems are seldom shielded from lightning and therefore are subject to direct lightning strikes. The transient overvoltages developed by lightning are of the highest concern for this type of arrester. Slow front overvoltages occurring on distribution systems are much less than fast-front overvoltages are therefore not considered.

The same procedure, as shown in Figures 19a and 19b for high-voltage arresters, is also used for distribution voltage arresters protecting distribution equipment but in that case only items 1 to 7 for lightning impulse protection characteristics are appropriate.

6.3.5.2 Energy handling capability

The most significant energy event distribution arresters must handle is associated with a lightning discharge. During this event (charge transfer) heat is generated in the arrester as a function of the arresters residual voltage. The higher the residual voltage, the more energy is dissipated. All distribution arresters are designed to handle the charge that is contained in two high current impulses 4/10 μs of 65 kA or 100 kA amplitude. These are the impulse currents which are applied in the operating duty test. These test currents must not be confused with real lightning currents of the same amplitude. As a rule, there is no joule rating of distribution arresters, only charge transfer capability that in combination with the arresters residual voltage under the applied current is an indirect means of assessing energy handling capability.

6.3.5.3 TOV considerations

Because the overvoltage levels on distribution systems are not well monitored and in many cases not well known they are assumed as worst case during a system earth fault. Since earth faults are the most common cause of temporary overvoltages on a distribution system and the magnitude of the voltage rise on the unfaulted phase is seldom known, it is assumed

for arrester sizing purposes to be the worst case. The worst case voltage rise depends on the system neutral configuration.

Common neutral configurations are shown in Figures 23a, 23b, 23c and 23d.:

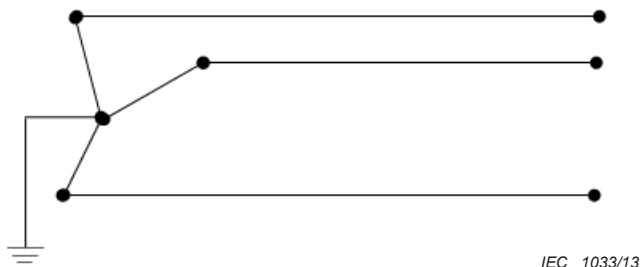


Figure 23a – Three-wire single earthed systems (earthed at source only)

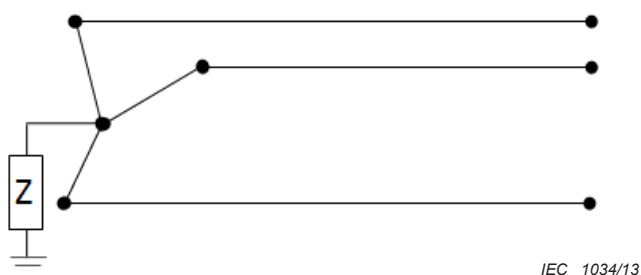


Figure 23b – Three-wire impedance earthed systems. Earth Fault Factor 1,73

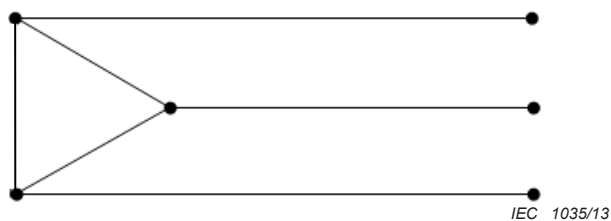


Figure 23c – Delta systems. Earth Fault factor 1,73 (up to 2,3)

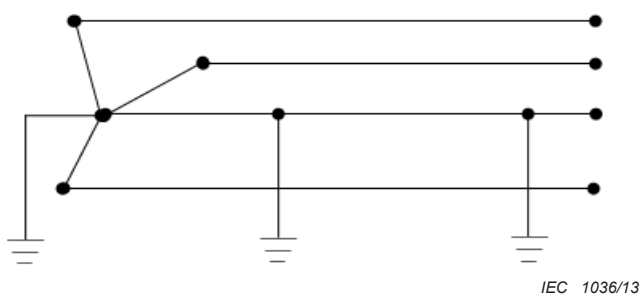


Figure 23d – Four-wire multi-earthed -wye systems. Earth Fault Factor 1,25

Figure 23 – Common neutral configurations

For each of the above systems an earth fault factor is used to determine the temporary overvoltage rise on the system on the unfaulted phases. The voltage rise is the line to earth voltage times the fault factor. U_c and/or U_r are then selected with help of manufacturers' TOV-data (see Figures 20a and 20b).

6.3.5.4 Failure modes

Distribution arresters manufactured in polymer housings are tested per IEC 60099-4 to withstand fault currents in the 10 kA to 20 kA range without significant scattering away from

the arrester. It is notable that according to IEC 60099-4, short-circuit tests are only mandatory if the manufacturer claims a short-circuit rating, which means that arresters still fulfilling IEC 60099-4 can have a totally unknown failure mode and even shatter violently, which is a safety issue.

NOTE Future revision of 60099-4 will make this test mandatory.

6.3.6 Selection of UHV arresters

6.3.6.1 General

Basically the same selection procedure is applicable for UHV arresters as for all other arresters. However, the existing IEC 60099-4 does not fully consider the arrester designs needed on UHV systems. In particular the standard needs revision in the following areas:

- energy requirements. (Arrester energies for UHV arresters may significantly exceed the existing test energies.)
- external insulation. (The existing requirements for switching impulse withstand voltage lead to higher insulation requirements on arresters than for other equipment which of course is not correct.)
- operating duty tests (The importance of very low protective levels leads to that highest possible voltage ratio i.e. U_c/U_r needed to be applied. However, even if arrester designs allow for a higher ratio the existing standard requires tests with $1,2 \times U_c$ which does not allow for the use of higher ratios. In addition the preheating temperature in operating duty tests is set to 60 °C which may be too low for multicolumn designs even at ambient temperature of 40 °C)

6.3.6.2 Insulation coordination

Insulation coordination throughout transmission lines and substations is a key factor for realizing a reliable and economical UHV system. Optimal insulation coordination can be achieved based on surge arresters, as demonstrated in UHV projects of the 1990s and later in Japan, Italy and China. Sophisticated design of insulation coordination by means of accurate computer-aided calculations and simulations is common practise for such projects, while withstand voltage can be roughly estimated by the IEC's simplified method.

Low protective levels of UHV-arresters are decisive factors for the system insulation of UHV systems. As lightning overvoltages dominate the non-self-restoring internal insulation design of equipment such as GIS and transformers, here it is important to rationalize LIWV by means of proper surge arrester arrangements. The classifying current for UHV arresters is typically 20 kA for LIPL which makes it rather easy to achieve proper LIPL by using multi-column LDC 4 or 5 arresters. To effectively suppress lightning overvoltages, single or multi-column surge arresters must be installed at an adequate number of locations, such as at line entrances, bus bars and transformers. Typically parallel columns are also needed for energy requirements.

Suppressing switching overvoltages as much as possible is a prerequisite for air clearance to insulation in order to reduce the height of transmission towers and the dimensions of open-air parts in substations. For economical reasons a SIWV to around 1,6 to 1,7 p.u. is desirable. There are different possible solutions:

- multi-column surge arresters with low SIPL at line entrances;
- Non-gapped line arresters at strategic towers along the transmission lines;
- multi-column GIS arresters which can have a higher voltage stress in the SF₆ and hence a higher U_c/U_r ratio [11];
- controlled switching algorithms;
- circuit breakers with opening or closing/opening resistors;
- single phase reclosure;
- any combination(s) of the above.

These possibilities can greatly contribute to optimize the economical design and size of UHV equipments and power transmission lines.

6.3.6.3 Mechanical design

Due to the size of UHV arresters, and AIS arresters in particular, mechanical requirements will be demanding. Many of the UHV systems are also located in seismic active areas and/or polluted sites. Polymeric designs with silicone rubber will be advantageous as you keep both the height down as shorter creepage distances are needed for silicone housed arresters as well as the weight will be lower. Solutions with polymer-housed arresters for suspended mounting or high strength base mounted designs may have additional advantages and will easily cope with also severe seismic stresses. Porcelain-housed arresters usually require dampers. Separation distances have to be considered for UHV protection as the UHV arresters themselves will have a significant height. Therefore also solutions with GIS arresters which have a high voltage stress can be built to reduce the separation distances.

Considering the huge size of UHV arresters and possible severe consequences of an arrester failure/explosion due to overloading the performance under short-circuit should be an important issue. Furthermore, AIS arresters most probably are located very close to other equipments in order to achieve the desirable protection zone which of course makes it even more important that a possible arrester failure occurs in a “controlled” way. Also this gives clear advantages for polymer housed designs which can be made explosion proof. Short-circuit tests according to IEC 60099-4 allow arresters to fall apart as long as the pieces fall within specific areas below. This allowance in the present standards should be noted as the height of air insulated surge arresters is significant and there may be consequences of a mechanical failure.

6.4 Normal and abnormal service conditions

6.4.1 Normal service condition

Normal service conditions for the arresters are specified in IEC 60099-4:2009, 5.4.1.

6.4.2 Abnormal service conditions

6.4.2.1 General

A list of possible abnormal service conditions is given in Annex A of IEC 60099-4:2009. A short guidance on the topics is given as follows:

6.4.2.2 Temperature in excess of +40 °C or below –40 °C

Higher ambient temperature may result in the preheating to 60 °C in the operating duty tests as per IEC 60099-4 no longer covering actual service temperature due to self-heating. A higher preheating may be required. This depends on actual applied continuous operating voltage, power losses and thermal performance of the arrester housing.

Low temperature may give problems with the sealing for arresters with enclosed gas volume. Polymer-housed arresters may be sensitive to very low temperatures close to and below –50 °C cracking of the polymer material may occur. The manufacturer must be consulted before use at lower temperatures than given by IEC and verification tests requested.

6.4.2.3 Application at altitudes higher than 1 000 m

The external insulation strength decreases with altitudes. In particular this requires that the design and positioning of grading rings must be considered regarding the decreased insulation strength. Also the creepage should be compensated for altitude. Guidance is found in IEC 60071-2.

6.4.2.4 Fumes or vapours that may cause deterioration of insulating surface or mounting hardware

For particular fumes or vapours, consult the manufacturer.

6.4.2.5 Excessive contamination by smoke, dirt, salt spray or other conducting materials

The pollution withstand capability of the arrester concerns three aspects [42]:

- a) The arrester housing has to withstand the pollution stresses without flashover. This can be verified according to IEC 60507 or is assured by a design according to IEC 60815. The pollution performance could be improved by increasing the creepage distance considering the recommendations in IEC 60815 and/or selecting a polymer-housed arrester.
- b) The arrester has to withstand the possible temperature increase due to the changes in voltage distribution caused by the pollution activity on the surface of the housing. Consideration should be given to the pollution level and the frequency and amplitude of overvoltages caused by faults and reclosing operations during polluted conditions. A suitable test method for porcelain-housed surge arresters is given in Annex F of IEC 60099-4:2009. In this case the pollution performance could be improved by following measures:
 - Selecting a higher TOV capability i.e. higher rated voltage for the same arrester type
 - Selecting an arrester with higher energy handling capability
 - Selecting an arrester with better heat transfer mechanism
 - Selecting an arrester with lower power losses at U_c
 - Selecting an arrester housing that is hydrophobic under these conditions.
- c) The arrester has to withstand internal partial discharges, caused by disturbed voltage grading on the housing due to pollution, without damage to the resistor elements or to the internal mounting elements.

6.4.2.6 Excessive exposure to moisture, humidity, dripping water, or steam

The manufacturer shall be consulted. However, most polymer arresters should be able to withstand if their performance has been verified in moisture and weather ageing tests as per IEC 60099-4.

6.4.2.7 Live washing of arrester

Washing of polymer-housed arresters are in general not recommended. High pressurized water may give damage to the polymer insulators.

Porcelain-housed arresters may need to be washed. If the washing is to be carried out live care should be taken to obtain as uniform wetting as possible of the arrester housing. Special attention should be paid if the arrester is equipped with big grading rings. The manufacturer shall be consulted.

6.4.2.8 Explosive mixtures of dust, gases or fumes. Installations in sensitive explosive areas such as mines/underground

In general it should not be a problem to install gapless metal-oxide surge arresters in sensitive areas but the manufacturer shall be consulted. Special attention shall be taken to the arrester connections to avoid sparks and partial discharges. The effect of a possible arrester failure shall be considered since this, most probably, will result in an open current arc. Over design with respect to energy capability and TOV capability may be recommendable to reduce the risk of failure.

6.4.2.9 Unusual transportation or storage

The manufacturer shall be consulted and in particular cases tests shall be performed to verify an acceptable performance of the arrester.

6.4.2.10 Nominal frequencies below 48 Hz and above 62 Hz

In general the power losses of a gapless metal-oxide surge arrester increase significantly with frequency. The arrester U_c therefore may have to be derated for higher frequencies to avoid thermal instability. In particular this is the case for application in filters with the arresters connected across a reactor in the filter. If the U_c has to be derated, the relative protected level will also usually be higher than for normal arrester applications which has to be considered in the insulation coordination process.

At lower frequencies than 48 Hz the problem may first arise at DC. Resistor elements stable at AC may not necessarily be stable against DC. The manufacturer shall be consulted.

A frequency of $16\frac{2}{3}$ Hz used for railway supply should normally be no problem for gapless metal-oxide arresters. (For the old type of gapped SiC-arresters the increased duration of follow current at lower frequencies gave a much more severe duty for the arrester)

Commissioning tests on e.g. GIS with higher frequencies than 62 Hz and with arresters installed shall not be done without the permission of the arrester manufacturer. Not only do the power losses increase with increase in frequency, but since the arrester at U_c also acts mainly as a capacitor the capacitive current increases as well, however linearly with the increase in frequency.

6.4.2.11 Heat sources near the arrester

This may reduce the temperature thermal stability limit of the arrester. The arrester therefore may have to be derated with respect to U_c and/or energy capability and TOV capability.

6.4.2.12 Non-vertical erection and suspended erection

Non-vertical erections introduce a bending moment therefore this erection shall be checked with and accepted by the manufacturer. Suspended erection may also result in a bending moment if the connection is not made moment-free.

6.4.2.13 Abnormal mechanical conditions (earthquakes, vibrations, high wind velocities, high ice loads, high cantilever stresses)

6.4.2.13.1 Wind speed > 34 m/s

The additional mechanical stress on the arrester shall be considered. The manufacturer shall be consulted.

6.4.2.13.2 Earthquake

The stress on the arrester approximately can be estimated from standard seismic data and arrester data on resonance frequency and damping and compared with mechanical withstand standards for the arrester. The installation methods are important as pedestals may magnify the stresses while e.g. flexible hanging will lower the stresses.

For more accurate information different seismic tests could be applied. (See IEC 62271-300, IEEE 693 or national standards such as from Japan, China or Chile).

6.4.2.13.3 Torsional loading of the arrester

The manufacturer shall be consulted.

6.4.2.13.4 Tensile loading of the arrester

Some arresters may withstand tensile loadings much better than bending loading. The manufacturer shall be consulted.

6.4.2.13.5 Use of the arrester as mechanical support

This may be possible depending on the design of the arrester and the required mechanical loads. However, in case of arrester overloading the possible mechanical effect on the arrester shall be considered as well as the fact that the arrester after overloading may constitute a high-ohmic or low-ohmic short circuit.

6.4.2.13.6 Vibrations

In some applications the arresters may be exposed to severe mechanical vibrations. In particular line surge arresters (LSA) can be subjected to vibration stresses. In particular cases for NGLA the manufacturer shall be consulted or tests performed to verify an acceptable performance of the NGLA.

7 Surge arresters for special applications

7.1 Surge arresters for transformer neutrals

7.1.1 General

One of the most widely used special applications of arresters is for the protection of transformer neutrals. Each unearthed neutral brought out through a bushing should be protected against lightning and switching overvoltages by an arrester. Without protection, the neutral insulation may be overstressed by switching overvoltages due to asymmetrical faults or switching operations in the power systems.

Furthermore, in case of resonant earthed neutral systems, high switching overvoltages may arise at the transformer neutral and across the winding when a double phase-to-earth fault is interrupted, and the circuit left connected to the transformer line side has a small capacitance to earth.

The energy absorption capability of neutral arresters should be at least the same as required for the phase-to-earth arresters or higher.

The residual voltage at a discharge current of 1 kA can be used for the determination of the protection level of the arrester, since high current values do not occur. For neutral arresters, the protection ratio may be considerably smaller due to the small rate of voltage rise.

7.1.2 Surge arresters for fully insulated transformer neutrals

Protection of fully insulated transformer neutrals can be achieved by using arresters having a protection level equal to or lower than that of the phase-to-earth arresters. Because of the lower power frequency voltage between neutral and earth, the rated voltage of the neutral arrester can be lower. A rated voltage of at least 60 % of that necessary for the phase-to-earth arresters is recommended.

Two kinds of arresters are used:

- either the same design as for the arresters phase-to-earth, but with reduced rated voltage;
or
- special arresters with reduced protection levels.

During abnormal system conditions, or during intermittent earth faults, overvoltages of long duration and amplitude high enough to cause successive arrester operation may occur, with

consequent damage of the phase arresters. In such cases, it is beneficial to coordinate the arresters so that the neutral arrester operates prior to operation of the phase-to-earth arresters. A high energy neutral arrester may withstand the stresses and prevent damage of the phase-to-earth arresters. It is recommended that the switching impulse protection level of the neutral arrester be about 45 % of the switching impulse protection level required for the phase-to-earth arresters.

7.1.3 Surge arresters for neutrals of transformers with non-uniform insulation

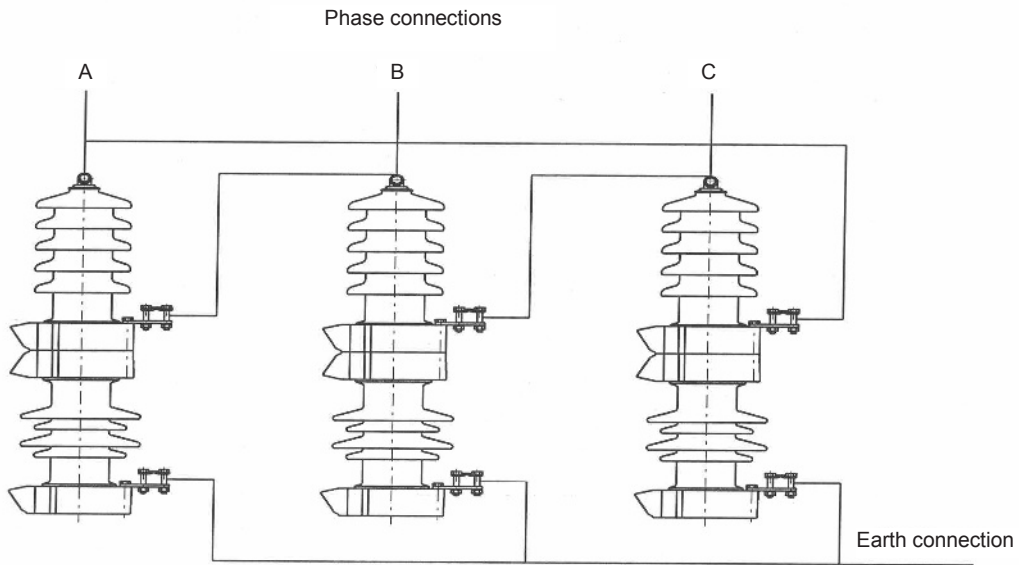
Transformers with the dielectric strength graded from the phase terminal to the neutral are commonly applied in earthed neutral systems. If the transformer neutral is not directly earthed to limit the short-circuit currents in the system, it should be protected by an arrester with characteristics selected according to the system conditions and the withstand voltage of the neutral using the same selection methods used for the phase-to-earth arresters.

7.2 Surge arresters between phases

Considerable overvoltages between the phase terminals of transformers or reactors may occur when a reactor or a reactive loaded transformer is switched off. The withstand voltage of the reactor or the transformer between phases may be exceeded without operation of the phase-to-earth arresters. If such switching operations are expected, surge arresters should be applied between phases in addition to those applied phase-to-earth. The phase-to-phase arresters should have a continuous operating voltage equal to or higher than 1,05 times the highest system voltage. For metal-oxide surge arresters this covers temporary overvoltages up to 1,25 times the highest system voltage. For higher temporary overvoltages, arresters with higher rated voltage should be used. Typical configurations are shown in Figures 24a and 24b.

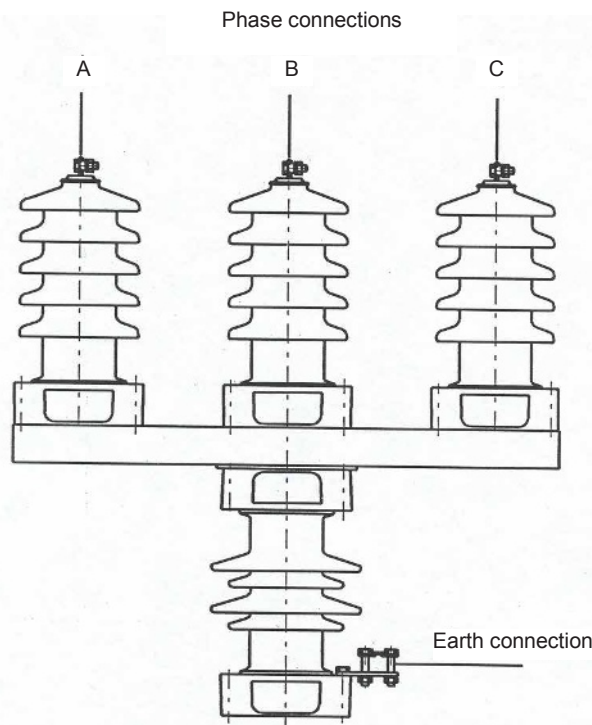
For transformers with a delta-connected low-voltage winding, arresters between phases may be necessary on the low-voltage side to limit inductively transferred overvoltages. These arresters can also protect the high-voltage side of the transformer by absorbing the magnetic energy when switching off transformers.

Furnace transformers may require arresters between phases in addition to those connected phase-to-earth. A detailed specification for each case may be necessary.



IEC 1037/13

Figure 24a – Six arrester connection



IEC 1038/13

Figure 24b – Four arrester (Neptune) connection

Figure 24 – Typical configurations for arresters connected phase-to-phase and phase-to-ground

7.3 Surge arresters for rotating machines

A recommendation for insulation coordination for rotating machines has not been established, but surge arresters are often used to protect generators and motors against overvoltages.

The arresters used for this application are often non-standard and the requirements have to be defined by agreement between manufacturer and user. In particular, attention should be paid to the short-circuit capability of generator arresters because short-circuit currents may be appreciably higher than those covered in IEC 60099-4 for standard arresters.

For machines which are connected to overhead lines either directly or through short cables, capacitors (typically in the range 0,1 μF to 0,3 μF) and arresters should be installed between phase and earth as close as possible to the machine terminals to extend the overvoltage front to approximately 10 μs or more, and to provide additional protection. In addition, a second set of arresters on the overhead lines in front of the machine station or at an overhead line-cable junction point may be applied.

The characteristics of the surge arresters should be selected according to Clause 6 and the impulse strength of the insulation or the value recommended by the manufacturer should be compared to the protection level of the arrester. Generally, only small margins between protective levels and withstand voltages are achievable.

If sufficiently long cables connect the machine, or if capacitors of the values mentioned above are installed, machines connected to overhead lines through transformers may not require arrester protection beyond the standard transformer protection, if sufficiently long cables connect the machine, or if capacitors of the values mentioned above are installed. If a breaker is installed between the transformer and the rotating machine, the capacitors should be installed at the transformer terminals (generator winding).

For machines connected to star-delta transformers, additional phase-to-phase arresters can provide improved protection. Arresters installed at the machine or at the machine side of the transformer are not subjected to high lightning currents.

Large turbo generators have low surge impedances, rendering it important to avoid single-phase enclosed busbars and short circuits between phases. Surge arresters should not be installed phase-to-phase. Sufficient protection may be achieved by the arresters on the transformer high-voltage side.

NOTE Besides limiting the overvoltages entering the machine station, the arresters on the overhead line cause lower discharge currents through the arresters at the machine. The resulting lower residual voltages of these machine arresters provide an additional protection of the machine.

7.4 Surge arresters in parallel

7.4.1 General

7.4.1.1 Proliferation of arresters

In a large substation, a considerable number of arresters may have been installed in each phase. Reasons for a proliferation of arresters may be one or more of the following:

- To ensure sufficient protection at all locations of the station, which may not be possible with only one set of arresters due to distance effects and/or operation of the station.
- A single arrester may not be able to handle the decisive case energy.
- Rebuilding and extension of the station may have resulted in additional arresters at the new equipment and thus new arresters in parallel with old ones.

7.4.1.2 Protection considerations

From a protection point of view, having many parallel arresters in a station is not an issue, because addition of such arresters will never worsen the protection level. A common case is one arrester at the line entrance and one at the transformer. The arrester at the line entrance protects an open breaker and other equipment at the line entrance (for example, instrument

transformers). In addition the line entrance arrester improves the protection at the transformer since some of lightning current is shunted to earth via the line entrance arrester and thus the transformer arrester takes lower current than without the protection at line entrance. The lower discharge current of course will result in a lower protection level at the transformer.

7.4.1.3 Energy considerations

It cannot be assumed if no special measures are taken that the total arrester energy from a system event, such as a switching or fault event will be equally shared between arresters in parallel, even between arresters of the same make and rated voltage. It is common for arresters of the same make and rated voltage to have residual voltages at nominal discharge current that vary up to 3 % from each other. The spread may be even greater for lower currents that would be associated with switching impulses. With, for example, a 5 % difference in switching impulse residual voltage between two parallel arresters, the current sharing between the arresters could be mismatched by as much as 4:1 (i.e. the arrester with the lower residual voltage would take as much as 80 % of the total discharge current/energy). The large difference results from the high non-linearity of the current-voltage characteristics of the arresters. For arresters with the same rated voltage but of different makes, an even greater mismatch could result.

If a particular application requires that arresters share energy more evenly (for example, where it is known that the energy from the system event would exceed the energy handling capability of a single arrester), the user should specify this requirement to the manufacturer, who would then need to undertake special matching procedures during the manufacturing of the arresters. Such matching is normally not performed on standard arresters [48].

Unless specially matched arresters are used, each arrester in the station should be sized to individually withstand the decisive case energy. Alternatively, only one arrester sized to withstand the decisive case energy would be necessary provided that all other arresters in the station have at least 10 % higher residual voltage.

The energy sharing mismatch issue will typically be of even greater concern for temporary overvoltages (TOV). This is because TOV are likely to be quite close to the “kneepoint” of the arrester voltage-current characteristic, where the non-linearity of the characteristic is much greater than for currents in the range associated with switching impulses, making current matching between arresters even more challenging. Furthermore, the arrester’s non-linear resistance close to the “kneepoint” of the characteristic has a negative temperature coefficient, in contrast to the case for higher currents where the temperature coefficient is positive [49]. For these reasons, each arrester in the station should be selected so that it can individually withstand the expected worst case TOV.

7.4.2 Combining different designs of arresters

In a station with both gapped and gapless arresters, the gapless arrester will most often have a much lower SIPL and thus will take most of the energy from a switching surge (and will effectively protect the gapped arrester in that circuit). Thus, the energy capability for a new metal-oxide arrester to be installed in parallel with old SiC arresters shall be calculated ignoring any energy sharing with the older arresters.

7.5 Surge arresters for capacitor switching

Arresters are installed at capacitor banks due to a variety of reasons:

- To prevent capacitor failures in the event of a breaker restrike
- To limit the risk of repeated breaker restrikes if the circuit-breaker is not able to interrupt the capacitive current
- To prolong the service life of the capacitors by limiting high overvoltages
- To serve as an “insurance” against unforeseen resonance conditions which otherwise would lead to capacitor failures

- For overall limitation of transients related to capacitor bank switching which can be transferred further in the system and cause disturbances in sensitive equipment
- For upgrading of capacitors by preventing high overvoltages and/or for increasing the service voltage
- To serve as protection against lightning for capacitors banks connected to lines
- To protect series reactors with full or reduced insulation

Thyristor-controlled capacitors are usually equipped with a number of arresters. For these types of capacitors, detailed studies are typically performed. Therefore only breaker-switched equipment is dealt with here.

The possible arrester discharge energy is the most important parameter to consider. This energy depends on factors such as capacitor bank design (earthed or unearthed), arrester installation (phase-earth or phase-neutral) and breaker performance (restrike or no restrike).

As a rough estimation the arrester energy, W , will be:

$$W = \frac{1}{2} \times C \times \left[(3 \times U_0)^2 - (\sqrt{2} \times U_r)^2 \right] \quad (21)$$

where

C is the single-phase capacitance of the bank

U_0 is the phase-to-earth operating voltage (peak voltage)

U_r is the rated voltage of the arrester (r.m.s. value)

The factor “3” results from the assumption of a breaker restrike with full voltage of opposite polarity on the capacitor due to a previous break.

Furthermore, the operating voltage at the capacitor bank may be 5 to 10 % higher than at other locations if series reactors are used, either to limit current when switching-in with parallel banks or to form a filter with the capacitors. This increased voltage must be considered when selecting the continuous operating voltage of the arrester.

For an arrester protecting a series reactor in the bank or filter, a likely decisive case is a single phase to earth fault. If the reactor has less than full line-to-earth insulation, it would typically be protected with arresters having a corresponding low rated voltage. Proper sizing of the arrester with respect to energy capability is important because, in the event of a capacitor discharge into an earth fault the energy absorbed by the arrester may be vary large. The energy to be considered is approximately:

$$W = \frac{1}{2} \times C \times U_{sw}^2 \quad (17)$$

where

C is the single-phase capacitance of the bank;

U_{sw} is the slow front protection level phase-to-earth at the capacitor bank;

The duration and magnitude of the discharge may be different from those of long-duration current impulses used for arrester tests (such as prescribed in IEC 60099-4). For example, the duration may be shorter and the peak value may be much higher, and it may be necessary to use arresters with higher energy handling capability than would normally be used. The manufacturer should be consulted in such cases. The most severe case for the energy stress of an arrester is the sequence of a three phase break of capacitive load followed by multiple restrikes in two phases [68].

It should be considered that up to three restrikes can occur without sufficient cooling in between, resulting in increased energy absorption by the arrester. The arrester energy rating should be selected accordingly.

If the fundamental frequency across the arrester in a filter application is higher than the normal power frequency (50 Hz or 60 Hz), special attention must be paid since the power losses of a metal-oxide arrester increase with increasing frequency. The arrester U_c therefore may have to be derated for higher frequencies. If the U_c has to be derated, the relative protection level will usually be higher than for normal arrester applications. The manufacturer should be consulted in such cases.

7.6 Surge arresters for series capacitor banks

Surge arrester used in series capacitors are often called varistors and testing is not covered by IEC 60099-4. System studies are performed for the different fault scenarios [75].

Because the capacitors are placed in series with the line, a fault on the transmission system can cause the capacitors to see different overvoltages. The ZnO-varistor can be the sole protection or in combination with some bypass gap. These varistors are tested and selected according to IEEE Std. 824-2004 (IEEE Standard for Series Capacitor Banks in Power Systems) and/or IEC 60143-2 (Series capacitors for power systems – Part 2: Protective equipment for series capacitor banks).

8 Asset management of surge arresters

8.1 General

Clause 8 considers the factors associated with the ownership stage of surge arresters. It addresses metal-oxide surge arresters as defined in IEC 60099-4, 60099-6 and 60099-8. Although routine factory tests will demonstrate whether the surge arrester is satisfactorily manufactured, failure to follow manufacturer instructions regarding transport to site, storage and site assembly can cause deleterious effects to the surge arrester or provide less than optimal performance.

The surge arrester operational environment will also affect the performance, so issues such as environmental pollution and the integrity of the earthing system require attention. From an operational perspective, there are no serviceable or replacement components inside the surge arrester, so it is essentially sealed for life. Condition monitoring for gapless arresters is discussed describing diagnostic techniques and life limiting factors. However, on the whole, whenever a surge arrester fails or shows any signs of distress, the general recommendation would be to replace the whole surge arrester.

8.2 Managing surge arresters in a power grid

8.2.1 Asset database

It is recommended to establish a database with the main information and technical data of the surge arresters in the power grid or transmission system.

The information should at least include arrester manufacture and type, year of manufacturing, year and place of installation, numbers of arresters and electrical data.

8.2.2 Technical specifications

Technical specifications for surge arresters should be updated regarding system temporary over-voltages, energy stress and protection level.

8.2.3 Strategic spares

A failed arrester can be disconnected and the circuit returned to service, albeit with a lower degree of reliability until the replacement arrester can be acquired. The risk and implication of this are determined by the utility and a recommendation cannot be made here.

Although surge arresters are of relatively low cost compared to the cost of the equipment being protected, the lead time to replace a unit can make it worthwhile to stock a spare set of arresters. If a surge arrester fails or needs to be replaced a spare can make a significant positive impact on the reliability and availability of the circuit. It is normally not necessary to replace the arresters of the other two phases in case of one arrester failure.

The physical dimension and mounting requirements of the surge arrester should also be considered when determining which spares to hold. Where a 3-phase set of arresters is replaced, the replaced arresters could be placed in storage should a similar design require replacement. For diagnostic methods to check the conditions of an arrester, recommendations are given in Annex D.

8.2.4 Transportation and storage

The precautions specified by the manufacturer for transport and storage should be strictly followed. Porcelain-housed arresters are sensitive to transportation stress, which, for many arresters often represents the highest mechanical stress seen during the lifetime. In most cases transportation and storage in an upright position are specified.

Polymer-housed arresters may be sensitive to storage conditions. Growth of moss and fungi on the housing may be initiated or supported if the arresters are stored in the wrapping enclosure as used for transportation. The manufacturer usually gives clear instructions if the transportation enclosure should be removed for storage or not. The storage room or house should be kept free from rodents, mice, birds and other animals that could harm the soft polymeric material of the insulators.

8.2.5 Commissioning

The general recommendation is that no commissioning tests are needed for surge arresters.

If considered necessary one should follow the manufacturer's advice and seek their consultation on the site commissioning tests. This might include visual checks and basic impedance tests. This can be supplemented with a simple test prior to system energising. This commissioning test can be either an AC or DC characteristic test from a portable source. One commissioning test, however not common, is a DC U-I test to 'fingerprint' the surge arrester that will identify any non-characteristic issues and serve also as a future benchmark for condition assessment. This requires the installed surge arrester to be disconnected from earth and HV connections to carry out the test, then reconnection to return the arrester to service. This is very difficult to perform on GIS arresters, since it involves de-gassing of the GIS disconnecting the surge arrester, re-gassing to test and finally repeating the exercise to reconnect the arrester. Therefore, it is not usually requested.

NOTE It is very important to check that both earth and high voltage connections have been restored following any tests.

8.3 Maintenance

8.3.1 General

Surge arresters are basically maintenance free. There is no intrusive work necessary, principally because the device is a sealed solid-state design with no moving parts.

For arresters with rated voltages of 100 kV or above there are possible typical routine activities associated with surge arresters which includes visual inspection to ensure any

pressure relief vents are clear of debris and water is not collecting within the vent (normally there should be a drain hole). Moisture ingress is the main process leading to long term degradation of seals.

Check the integrity of the earthing system connected to the surge arrester. The surge arrester may be unable to perform its function, if the earthing system has been interfered with. There is no intrusive maintenance, but for porcelain surge arresters the insulation surface may require cleaning, but the frequency will depend on environmental conditions. Polymeric insulation should not be cleaned. If so desired, a condition assessment can be performed by a number of on-line or off-line testing techniques.

General maintenance activity may include:

- Testing of the surge counter where installed
- Visual inspection of the arrester body
- Confirm integrity of high-voltage and earth connection leads.
- Cleaning or re-greasing of the porcelain surface where necessary.

The condition of any corona or grading rings should be inspected, since failure of these elements can either damage the arrester if it breaks, or allow corona to establish, which may deteriorate the performance of the polymeric insulators.

Whenever a surge arrester fails or shows any signs of distress, the whole arrester shall be replaced. Single units of a multi-unit surge arrester cannot be replaced.

8.3.2 Polluted arrester housing

Pollution on the arrester housing may cause high temperature increase of the varistors inside. To prevent failures in polluted areas, arresters able to withstand the relevant polluted conditions shall be chosen. Although not explicitly specified in IEC 60099-4, arresters used in normal operating conditions should withstand the medium pollution stresses according to pollution level II of IEC 60071-2. If the area is exposed to high pollution, the surge arrester performance may be adversely affected. If arresters of inadequate design are used in heavy (pollution level III) or very heavy (pollution level IV) polluted areas, periodic cleaning, or greasing, or silicone coating (for porcelain-housed arresters) may be effective in preventing the events stated above. When live washing is intended, arresters designed for such service conditions are required.

Polymer-housed arresters generally require no cleaning, however the units should be occasionally inspected for evidence of dry-banding, which may occur under the sheds, as this area is where tracking may establish.

When live washing of the arrester is specified specialists should be consulted. Basically it is easier to wash MO arresters since no sparkover of internal series gaps can occur. However, experience and practice is needed to carry out live-washing in a safe way. Compared with washing insulators the only added risk concerns the heating of the MO resistors.

8.3.3 Coating of arrester housings

The application of palliative coatings to porcelain-housed arresters is possible, however not preferred. Correct selection of arrester creepage distance in the first place should avoid the necessity for greasing. However, where circumstances change after installation it may be required. Silicone grease and RTV Silicone rubber are the most common types of coating used on porcelain insulators. Under no circumstances is there a need to treat arresters in a different way than any other equipment.

8.3.4 Inspection of disconnectors on surge arresters

Disconnectors may be used on line and distribution arresters. Regular inspections will be necessary to spot any open disconnectors. There is no possibility to check the correct operation of disconnectors onsite.

8.3.5 Line surge arresters

Onsite inspection may be possible using thermal imaging but only for NGLA. For EGLA visual inspection is an option checking for physical integrity of gap and SVU.

8.4 Performance and diagnostic tools

Various diagnostic methods and indicators for assessing possible deterioration or failure of the insulating properties have been utilized since the introduction of surge arresters. The diagnostic methods range from fault indicators and disconnectors for indication of complete arrester failure (generally employed at distribution voltage levels), to instruments that are able to measure slight changes in the resistive component of the leakage current of metal-oxide arresters. These are discussed in detail in Annex D.

8.5 End of life

8.5.1 General

End of life is defined in IEC 62650 as “Life cycle stage of a product starting when it is removed from its intended use-stage”. Therefore, it is required that on request from the user, each manufacturer shall give enough information so that arrester components may be scrapped and/or recycled in accordance with international and national regulations.

The function of an arrester is to protect other equipment. However if it fails to protect, then the application is pointless in the first place. Therefore surge arrester lifetime should be considered from a functional perspective and where there is any concern regarding the capability of an arrester, then replacement with a new surge arrester should be considered. Utilities typically attribute primary plant economic lifetime to match other substation equipment, this can vary between 20 and 50 years. It is for the utility to determine the appropriate replacement interval of the surge arresters, based on business and technical factors. The assessment criteria should take into consideration that routine replacement is viable, since surge arresters do not require intrusive maintenance or refurbishment and are an insurance to avoid costly failure of more expensive equipment (e.g. GIS substations, power transformers, or critical circuits).

Technically, providing MO resistor elements are not overstressed, a long lifetime is achievable from the active component. However, it is the enclosure and seals that are more likely to be the lifetime determining factors.

For the hollow tube surge arrester designs (porcelain and polymeric), when the sealing system has deteriorated to a level which is no longer capable of isolating the active element from external meteorological influence, moisture ingress could weaken the dielectric strength of the surge arrester active element assembly. The reliable lifetime associated with the seals is in the region of 20-30 years. The operational and climatic environment will also play a major role in whether the arrester will achieve this lifetime.

Polymer-housed arresters of wrapped and caged design came to the market in the 1980s. As such the lifetime is still being evaluated, but estimates suggest that at least 25 years should be achievable.

8.5.2 GIS arresters

These are enclosed units within SF₆, and should see a lifetime of at least 30 years.

8.6 Disposal and recycling

On request from users, each manufacturer shall give enough information so that all the arrester components may be scrapped and/or recycled in accordance with international and national regulations. All arrester units should be checked for which type of gas was used for filling. GIS units which have operated in SF₆ should be handled with care in case any tracking or arcing may have occurred which could generate contaminants in particular associated with SF₆ breakdown.

The internal design may be under compression, so caution should be exercised when removing internal parts from their housing and disposed of.

Annex A (informative)

Determination of temporary overvoltages due to earth faults

The earth fault factor k is the ratio of the highest r.m.s. phase-to-earth power frequency voltage on a sound phase at a particular location during a fault to earth (affecting one or more phases at any point) to the r.m.s. phase-to-earth power frequency voltage which should be obtained without the fault (see 3.17 of IEC 60071-1:2006).

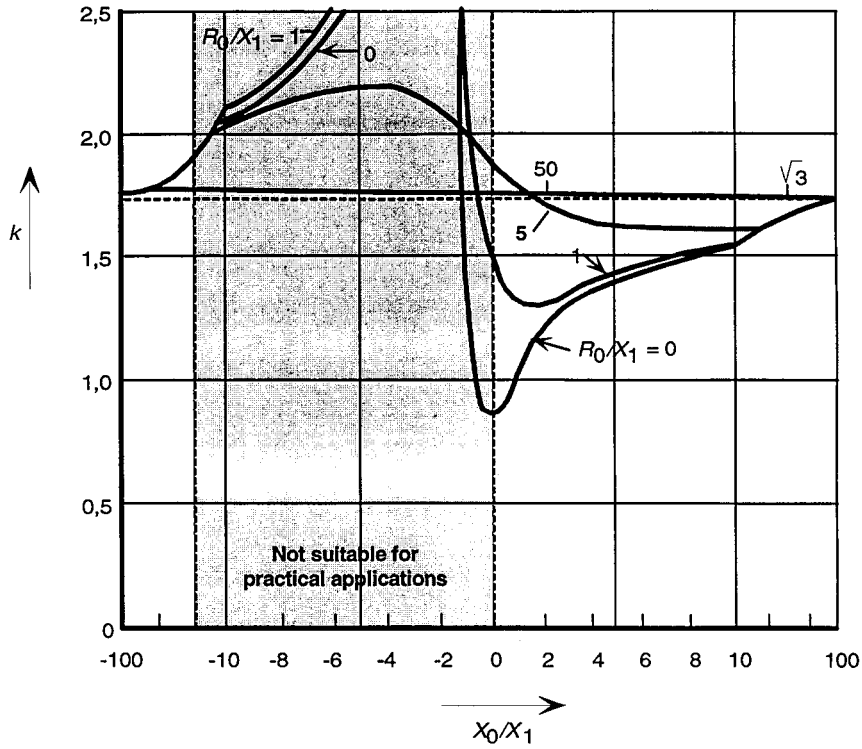
The earth fault factor is calculated using the complex impedances Z_1 , Z_2 and Z_0 of the positive, negative and zero sequence systems, taking into account the fault resistance R . The following applies:

$Z_1 = Z_2 = R_1 + jX_1$: resistance and reactance of positive and negative sequence system;

$Z_0 = R_0 + jX_0$: resistance and reactance of zero sequence system.

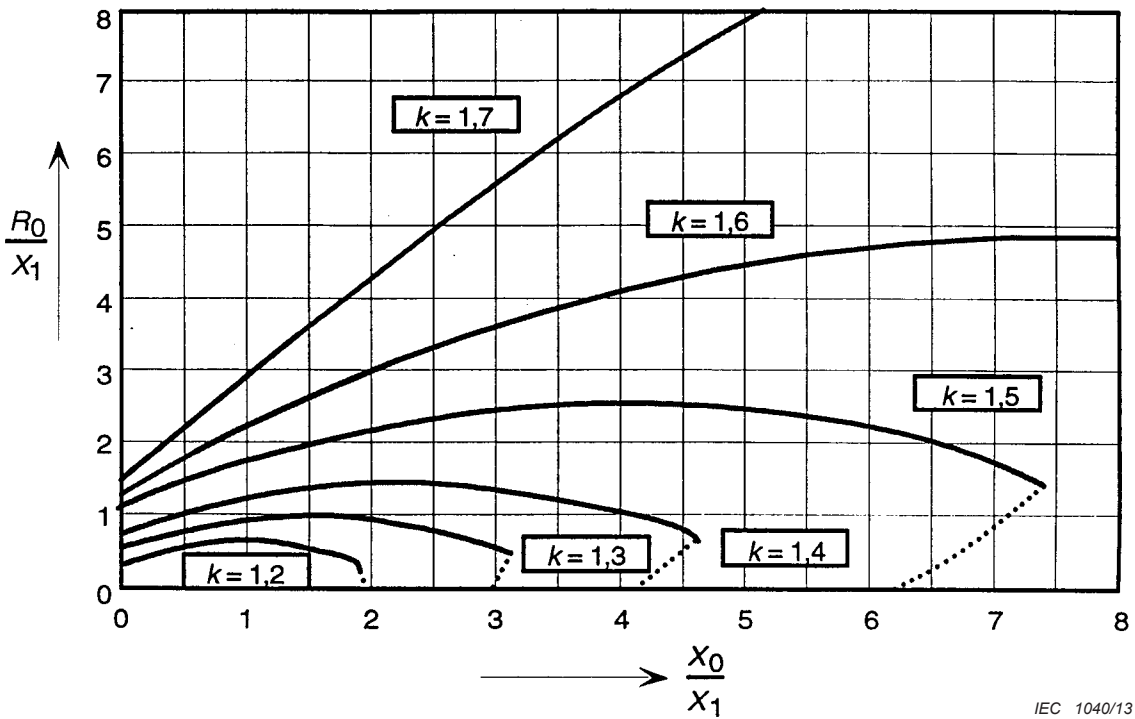
NOTE It should be observed that, in extended resonant earthed networks, the earth fault factor might be higher at other locations than at the fault.

The earth fault factors are calculated for the location of the fault. Figure A.1 shows the overall situation, when $R_1 \ll X_1$ and $R_1 = 0$. The range of high values for X_0/X_1 , positive and/or negative, applies to resonant earthed or isolated neutral systems. The range of low values of positive X_0/X_1 is valid for earthed neutral systems. The range of low values of negative X_0/X_1 , shown hatched, is not suitable for practical application due to resonant conditions. For earthed neutral systems, Figures A.2 through A.5 show the earth fault factors as families of curves applicable to particular values of R_1/X_1 . The curves are valid for fault resistance values giving the highest earth fault factors.



IEC 1039/13

Figure A.1 – Earth fault factor k on a base of X_0/X_1 , for $R_1/X_1 = R_1 = 0$



IEC 1040/13

Figure A.2 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth fault factor k where $R_1 = 0$

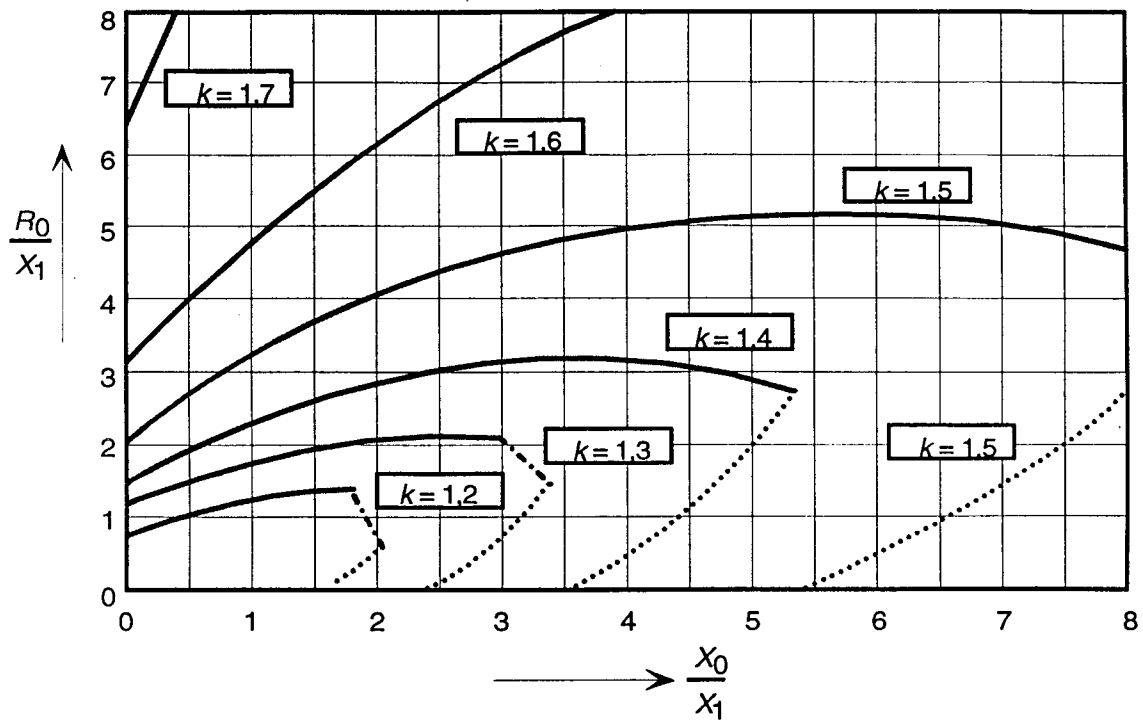
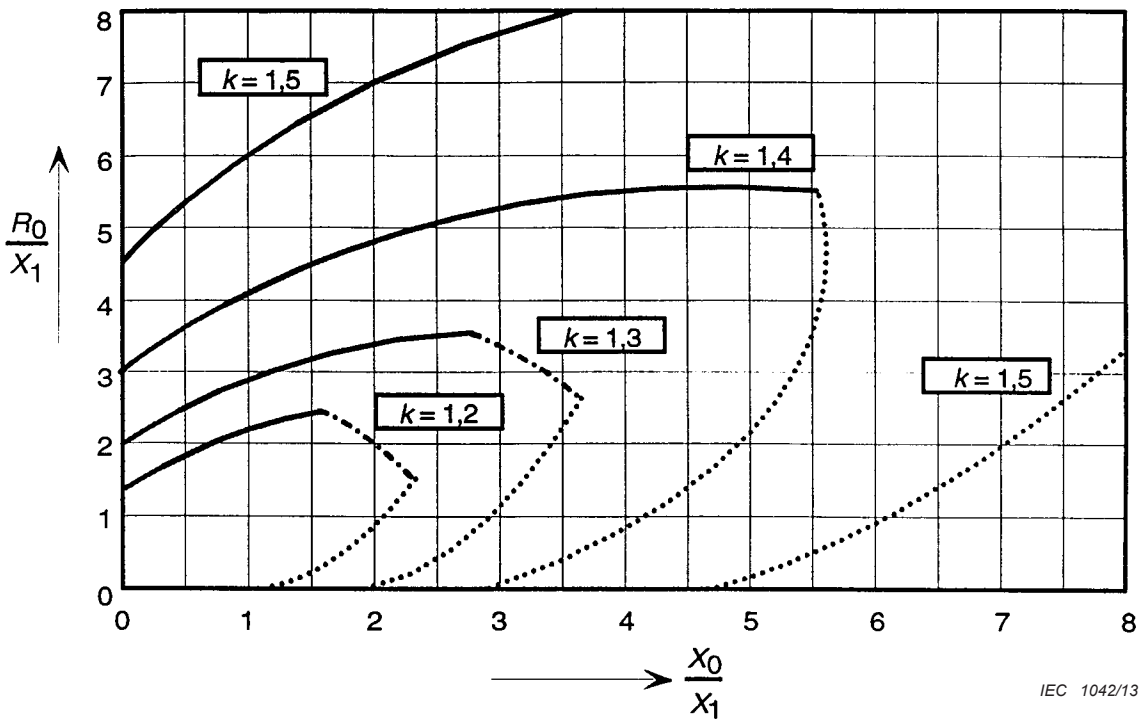


Figure A.3 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth fault factor k where $R_1 = 0,5 X_1$



IEC 1042/13

Figure A.4 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth fault factor k where $R_1 = X_1$

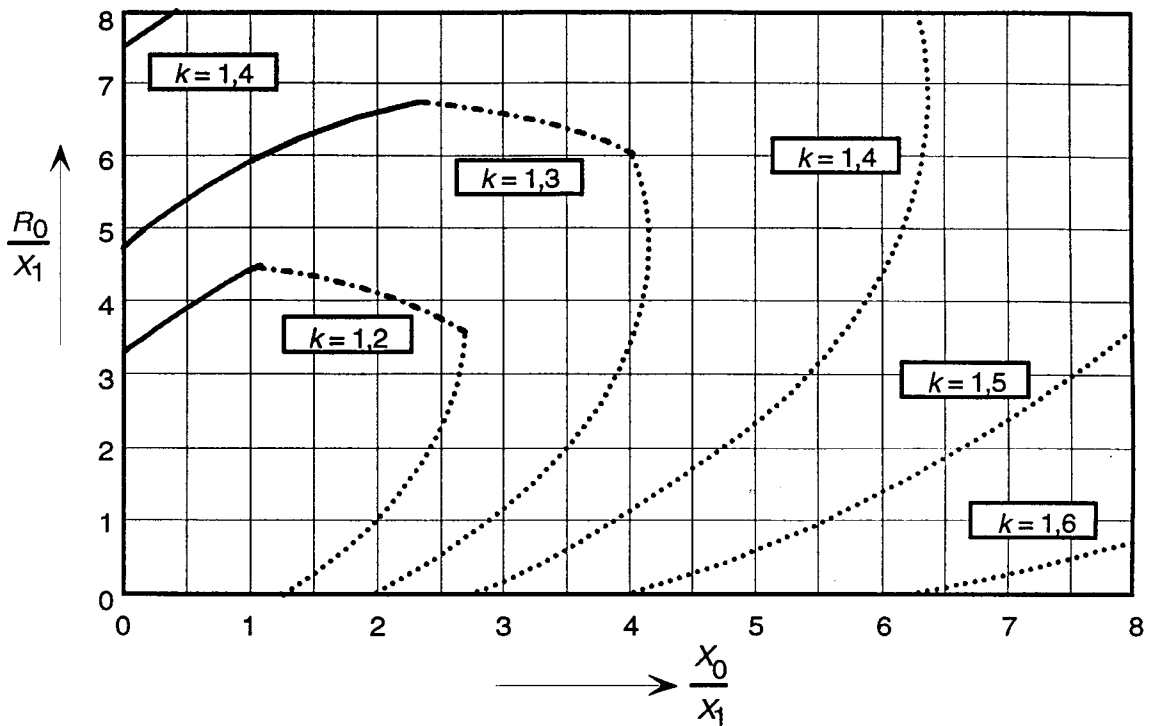


Figure A.5 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth fault factor k where $R_1 = 2X_1$

In Figures A.2 to A.5, the curves are divided into regions representing the most critical conditions by the following methods of presentation:

- maximum voltage occurs during a phase-to-earth fault on the phase which leads the faulted phase;
- maximum voltage occurs during a phase-to-earth fault on the phase which lags the faulted phase;
- - - - - maximum voltage occurs during a phase-to-earth fault on the unfaulted phases.

Annex B (informative)

Current practice

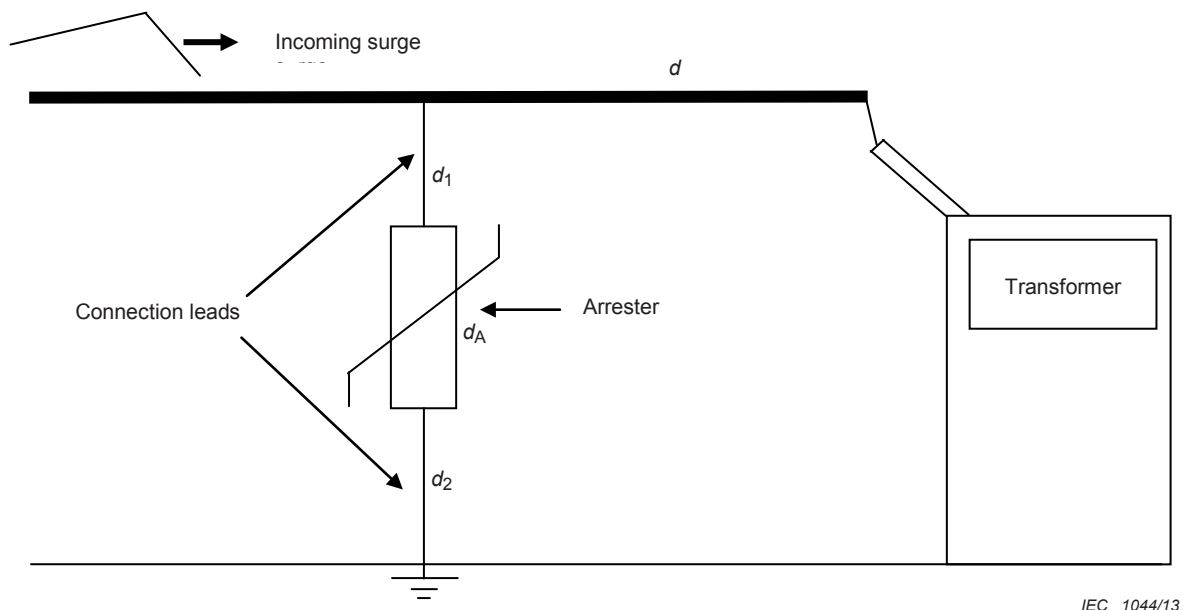
For the power supply systems within some countries, the application of this standard may result in tables of consistently used surge arrester characteristics. For the use of this standard within such countries, tables containing these characteristics may be added to this Annex B, without deviating from the standard.

Annex C (informative)

Arrester modelling techniques for studies involving insulation coordination and energy requirements

C.1 Arrester models for impulse simulations

In Figure C.1 a normal installation of an arrester is shown (compare Figures 8 and 9). For insulation coordination studies the arrester with its connection leads must be modelled in a suitable way. An equivalent model of the arrester must be used which ideally takes into account both the increase in residual voltage as function of the steepness of the current as well as inductive effects. Normally the arrester height d_A and connection leads d_1 and d_2 shall be taken into account with inductances. For the purposes of insulation coordination studies, a conservative figure for AIS arresters in most cases will be $1 \mu\text{H/m}$ of arrester length. The same inductance per meter is also recommended to be used for any connection leads. For GIS arresters a lower inductance, $0,3 \mu\text{H/m}$, is suggested due to the coaxial design. For critical cases, more accurate calculations of inductances may be used. It must also be noted that the inductance given here is related to the magnetic field surrounding the arrester and connection leads. The so called internal inductance of a conductor is much smaller. Therefore, the shape of the conductors e.g. using thin flat conductors instead of cylindrical conductors makes no significant difference.



IEC 1044/13

Key

d length of conductor between transformer busing and point of connection of arrest line lead

d_1 length of arrester line lead

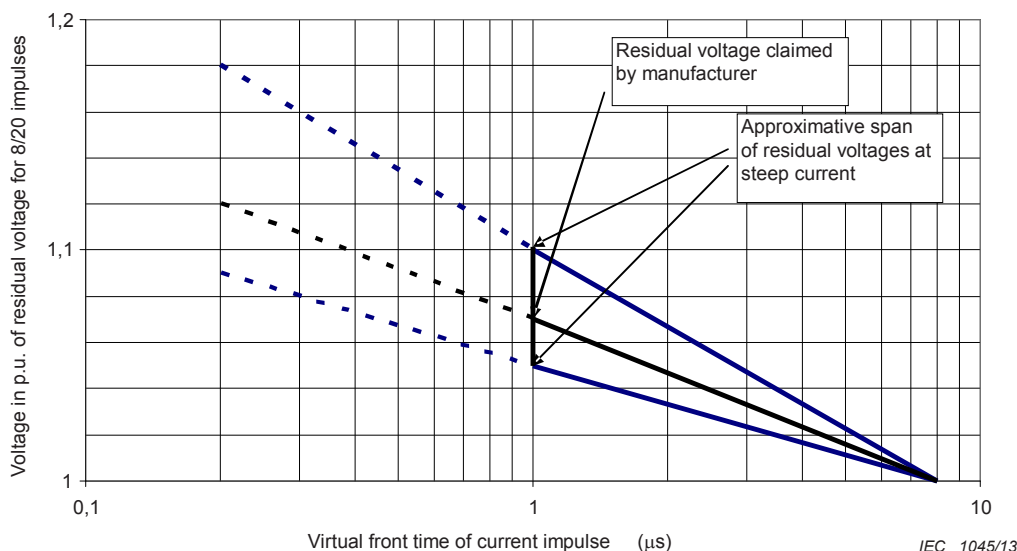
d_A height of arrester

d_2 length of arrester ground lead

Figure C.1 – Schematic sketch of a typical arrester installation

For insulation coordination studies, including steep lightning surges, different models to consider the increase in residual voltage have been suggested. However, it is quite complicated to model the response of the metal-oxide material in a precise way, and no

models have so far shown to be very accurate. Therefore, a simplified practical approach is suggested here. A first calculation is made with the arrester modelled with the 8/20 μs characteristic plus an inductance of $1\mu\text{H}/\text{m}$ arrester length and connection leads in order to check the steepness of the current through the arrester. Based on the obtained current steepness the primary used characteristic is adjusted correspondingly and another calculation is made and so on. A typical increase in residual voltage as function of the virtual current front time is shown in Figure C.2. Note that the increase is assumed to be the same independent of current amplitude.



NOTE Illustrates only material response without any inductive effects. Values for shorter than $1\mu\text{s}$ only indicate the estimated trend. When more accurate values are needed, the manufacture should be consulted.

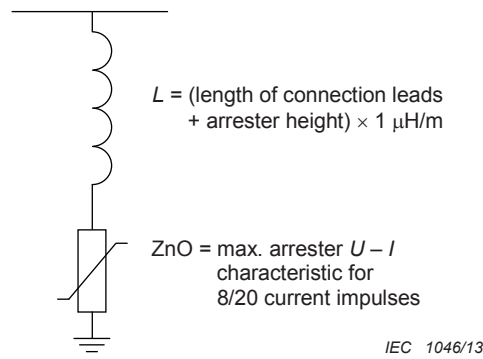
Figure C.2 – Increase in residual voltage as function of virtual current front time

C.2 Application to insulation coordination studies

Normally, decisive cases involve virtual current front times through the arrester of approximately $1\mu\text{s}$. As an option, therefore, a first calculation could be done with a characteristic 5 to 10 % higher than the 8/20 μs characteristics. Based on the obtained current steepness, the primary used characteristic is then adjusted correspondingly and another calculation is made and so on. For studies involving insulation coordination, the maximum characteristic is important. However, when calculating arrester energy stresses from switching operations, normally a higher energy is obtained for a lower characteristic. For such studies, therefore, a minimum characteristic should be used. As an approximation a 5 to 10 % lower characteristics than maximum given in the manufacturer catalogues could be used if no more accurate information is available. For lightning related energies, on the other hand, the maximum characteristic may give the highest arrester energy, since the source in this case generally could be seen as a current source. For switching surge studies, the 30/60 characteristic should be used. Normally, no series inductance element is needed to model the arrester length and connection leads because of the negligible effect of the slow impulse.

C.3 Summary of proposed arrester models to be used for impulse applications

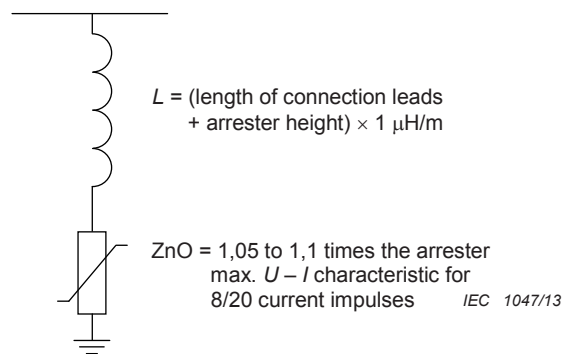
To summarise, the following models as shown in Figures C.3 to C.5 are proposed for use under impulse conditions.



The steepness of the current surge (virtual front time of wave) is determined from the preliminary calculation. The $U-I$ characteristics is then adjusted accordingly and the calculations repeated.

NOTE For GIS arresters the inductance is set to 0,3 $\mu\text{H/m}$.

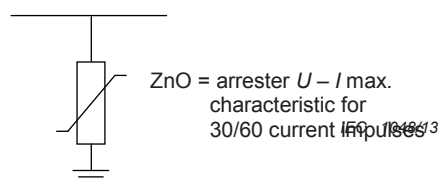
Figure C.3 – Arrester model for insulation coordination studies – fast-front overvoltages and preliminary calculation (Option 1)



The steepness of current surge (virtual front time of wave) is determined from the preliminary calculation. The $U-I$ characteristics is then adjusted accordingly, and the calculations repeated.

NOTE For GIS arresters the inductance is set to 0,3 $\mu\text{H/m}$.

Figure C.4 – Arrester model for insulation coordination studies – fast-front overvoltages and preliminary calculation (Option 2)



For studies of arrester energy stresses, the maximum characteristic is replaced by an estimated minimum characteristic.

Figure C.5 – Arrester model for insulation coordination studies – slow-front overvoltages.

Annex D (informative)

Diagnostic indicators of metal-oxide surge arresters in service

D.1 General

D.1.1 Introduction

Apart from brief occasions when a surge arrester is functioning as an overvoltage-limiting device, it is expected to behave as an insulator with very low leakage current. The insulating properties are essential for the arrester life expectancy and for the power system operation reliability.

Various diagnostic methods and indicators for revealing signs of deterioration or possible failure of the arrester have been utilized since the introduction of ZnO surge arresters. The diagnostic methods range from fault indicators and disconnectors, which indicate complete arrester failure, to instruments that are able to measure small changes in the resistive leakage current and/or power loss of gapless metal-oxide arresters.

The aim of this annex is to provide guidance to the user if use of any diagnostic method is considered, and to present an overview of common diagnostic methods. It also gives detailed information about leakage current measurements on metal-oxide arresters.

Diagnostic devices should be designed and handled while providing personal safety during measurement. Permanently installed devices should be designed and installed with the operational and short-circuit stresses taken into consideration.

For several diagnostic methods, an insulated earth terminal is required on the arrester. The earth terminal should have a sufficiently high withstand voltage level to account for the inductive voltage drop appearing between the terminal and the earthed structure during an impulse discharge.

D.1.2 Fault indicators

Fault indicators give a clear visual indication of a failed arrester, without disconnecting the arrester from the line. The device may be an integrated part of the arrester, or a separate unit installed in series with the arrester. The working principle is usually based on the amplitude and duration of the arrester current, or on the temperature of the non-linear metal-oxide resistors.

D.1.3 Disconnectors

Disconnectors, often used on medium-voltage arresters, give a visual indication of a failed arrester by disconnecting it from the system. The typical working principle is an explosive device triggered by the fault current; however, the disconnector is not intended to extinguish the fault current. The disconnector may be an integral part of the arrester or insulating bracket, or a separate unit installed in series with the arrester. The advantage of the device is that the line remains in operation after disconnection of the arrester. The major disadvantage is the lack of overvoltage protection until the failed arrester has been discovered and replaced.

D.1.4 Surge counters

Surge counters operate at impulse currents above certain amplitude or above certain combinations of current amplitude and duration. If the interval between discharges is very short (less than 50 ms), surge counters may not count every current impulse. Some counters

require power follow current, and may not count the short impulse currents through metal-oxide arresters.

Depending on the operating principle and sensitivity of the counter, it may give an indication about overvoltages appearing in the system, or it may provide information on the number of discharges corresponding to significant arrester energy stresses. The counter provides no specific information about the condition of the arrester.

For safety reasons, the surge counter should be installed beyond easy reach of personnel; it shall be located where it can be read from ground level with the arrester in service. The installation should be done without considerably lengthening the earth connection or reducing its cross-section. The arrester shall be equipped with an insulated earth terminal and a conductor between the arrester and counter that is insulated from earth.

D.1.5 Monitoring spark gaps

Monitoring spark gaps are used to indicate the number and to estimate the amplitude and duration of discharge currents through the arrester. Special experience is necessary to interpret properly the marks on the gap. Some spark gaps can be examined with the arrester in service, while other types require that the arrester is de-energized. It is required that the arrester is equipped with an insulated earth terminal. Alternatively, the device may be an integral part of the arrester. Spark gaps give no direct information about the actual condition of the arrester, but may help to make decisions about continued operation.

D.1.6 Temperature measurements

Remote measurement of the arrester temperature can be carried out by means of thermal imaging methods. Advances in thermal imaging instruments have resulted in making this method of on line arrester condition assessment very popular worldwide. The reason this method is effective is that during steady state conditions the arresters operate relatively close to ambient temperature and the measurement is fast and accurate. The best way to determine if an arrester is not operating properly with this method is to compare the temperature of nearby similar vintage and type arresters. If the temperature difference between the similar units is more than 10 K, then there may be a problem with the hot arrester.

Direct measurement of the metal-oxide resistor temperature gives a fairly accurate indication of the arrester condition, but it requires that the arrester is equipped with special transducers at the time of manufacturing. Therefore, this method is used only in special arrester applications [40].

D.1.7 Leakage current measurements of gapless metal-oxide arresters

D.1.7.1 General

Any deterioration of the properties of a metal-oxide arrester will cause an increase in the resistive leakage current or power loss at given values of voltage and temperature. The majority of diagnostic methods for determining the condition of gapless metal-oxide arresters are based on measurements of the leakage current.

The measurement procedures can be divided into two groups: a) on-line measurements, when the arrester is connected to the system and energized with the service voltage during normal operation, and b) off-line measurements, when the arrester is disconnected from the system and energized with a separate voltage source on site or in a laboratory.

Measurements carried out on-line under normal service voltage are the most common method. For practical and safety reasons, the leakage current is normally accessed only at the earthed end of the arrester. To allow measurement of the leakage current flowing in the earth connection, the arrester must be equipped with an insulated earth terminal.

Off-line measurements can be made with voltage sources that are specially suited for the purpose, e.g. mobile a.c. or d.c. test generators. Good accuracy may be obtained using the off-line methods provided that a sufficiently high-magnitude test voltage is used. The major disadvantages of the off-line methods are the cost of the test equipment and the need for disconnecting the arrester from the system.

NOTE The insulation of the earth terminal, even after long-term degradation, shall be sufficient to prevent circulating currents caused by electromagnetic induction, since these currents may interfere with the measurement of the leakage current.

On-line leakage current measurements are usually made on a temporary basis using portable or permanently installed instruments. Portable instruments are usually connected to the earth terminal of the arrester by means of a clip-on, or permanently installed, current transformer. Long-term measurements of the leakage current may be necessary for closer investigations, especially if significant changes in the condition of an arrester are revealed by temporary measurements. Remote measurements may be implemented in computerized systems for supervision of substation equipment.

[29] [30] [31] [32] [33] [34] [35] [36] [37].

D.1.7.2 Properties of the leakage current of non-linear metal-oxide resistors

D.1.7.2.1 General

The a.c. leakage current can be divided into a capacitive and a resistive part, with a predominant capacitive component and a significantly smaller resistive part. This can be seen in Figure D.1, which shows a typical laboratory measurement of the leakage current of a single, non-linear metal-oxide resistor when energized at a voltage equivalent to U_c for the complete arrester.

Figure D.2 shows the results of leakage current measurements carried out on two different arresters in service at voltage levels slightly below U_c . Figure D.2 also illustrates the influence of different levels of harmonic content in the system voltage.

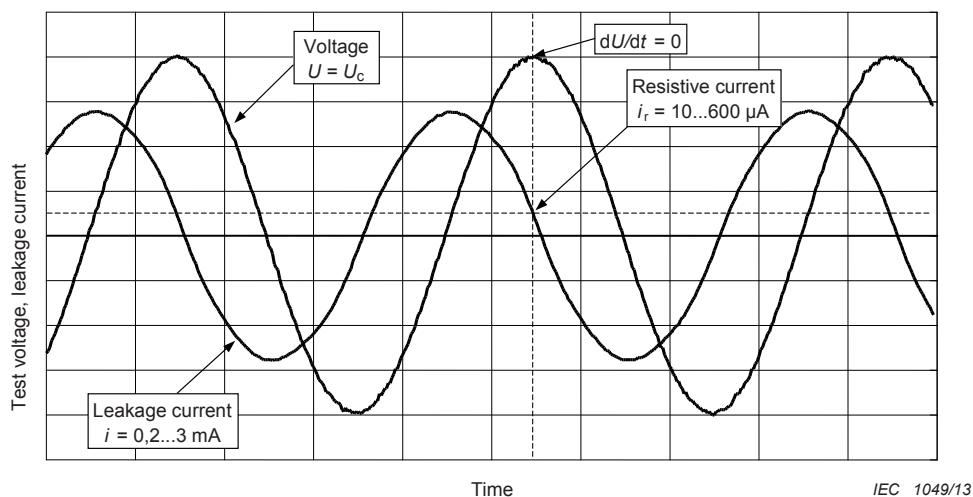


Figure D.1 – Typical leakage current of a non-linear metal-oxide resistor in laboratory conditions

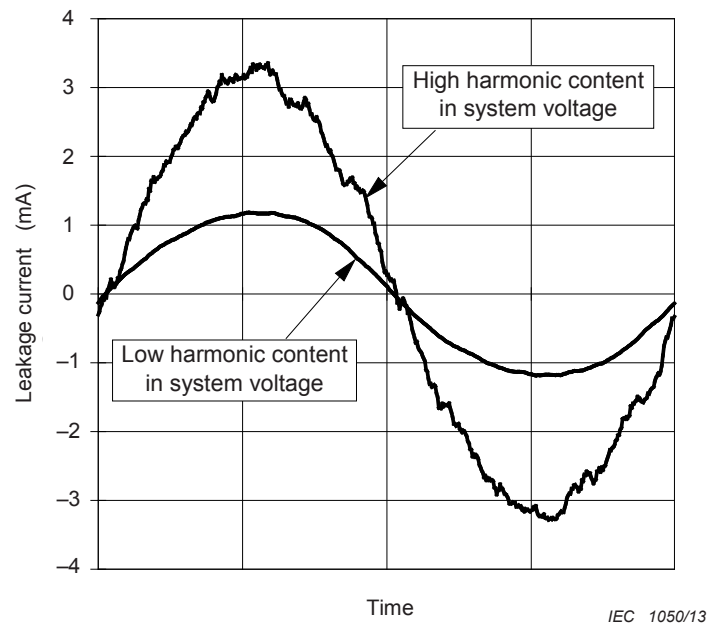


Figure D.2 – Typical leakage currents of arresters in service conditions

D.1.7.2.2 Capacitive leakage current

The capacitive leakage current measured at the earth terminal of an arrester is caused by the permittivity of the non-linear metal-oxide resistors, the stray capacitances and the grading capacitors, if applied. The specific capacitance of a resistor element is typically 60 pF.kV/cm^2 to 150 pF.kV/cm^2 (rated voltage), resulting in a capacitive peak leakage current of about 0,2 mA to 3 mA under normal service conditions.

There is no evidence that the capacitive current would change significantly due to deterioration of the voltage-current characteristic of the non-linear metal-oxide resistors. Therefore, it is unlikely that measurements of capacitive current can reliably indicate the condition of metal-oxide arresters.

D.1.7.2.3 Resistive leakage current

At given values of voltage and temperature, the resistive component of the leakage current is a sensitive indicator of changes in the voltage-current characteristic of non-linear metal-oxide resistors. Therefore, the resistive current can be used as a tool for diagnostic indication of changes in the condition of metal-oxide arresters in service. Typical resistive and capacitive voltage-current characteristics for a.c. voltages are shown in Figure D.3. For comparison, typical characteristics for d.c. voltages are also shown in Figure D.3.

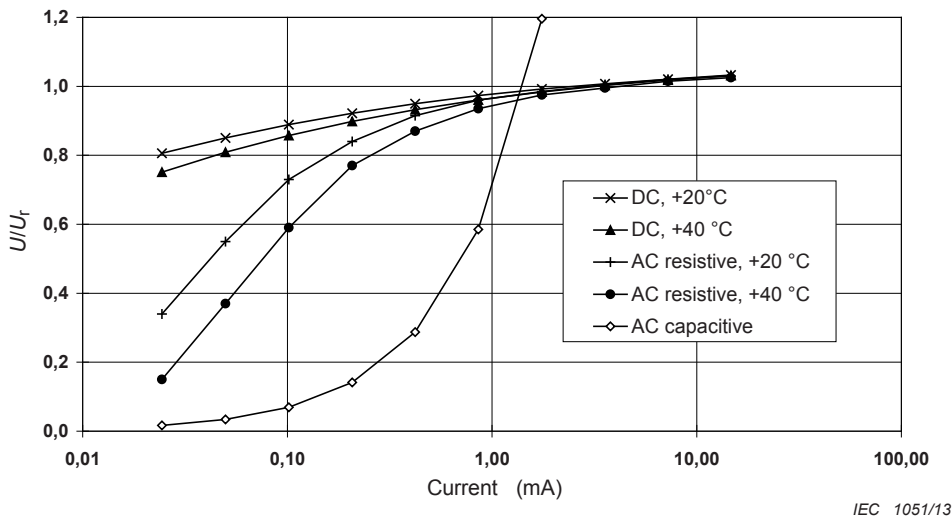


Figure D.3 – Typical voltage-current characteristics for non-linear metal-oxide resistors

The resistive component under a.c. voltage is defined as the current level at the instant of voltage maximum ($dU/dt = 0$), as indicated in Figure D.1. The resistive leakage current of a non-linear metal-oxide resistor is in the order of 2 % to 20 % of the capacitive current under normal operating conditions, corresponding to about 10 μ A to 600 μ A peak resistive current at a temperature of +20 °C.

In the leakage current region, the resistive current depends on the voltage and temperature. Typical values of voltage and temperature dependencies under a.c. voltage are indicated in Figures D.4 and D.5, normalized to U_c and at +20 °C, respectively.

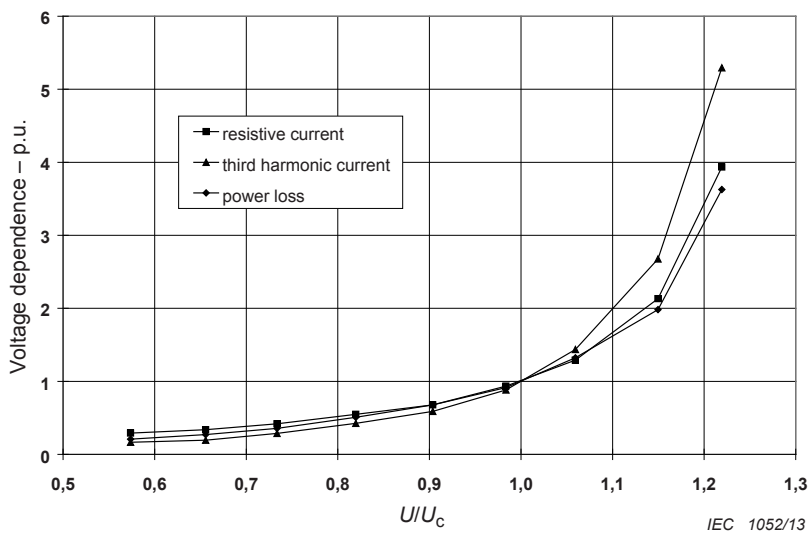


Figure D.4 – Typical normalized voltage dependence at +20 °C

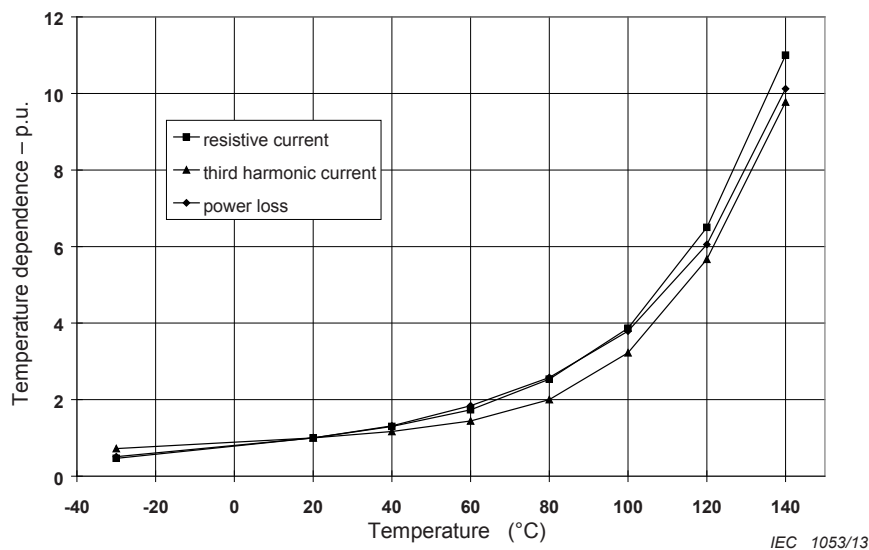


Figure D.5 – Typical normalized temperature dependence at U_c

Uncertainties in resistive current measurement may arise for long arrester columns. This may be caused by the non-uniform voltage distribution along an arrester, primarily due to the influence of stray capacitances and to adjacent equipment. The voltage across the non-linear metal-oxide resistors at the earthed end of the arrester may, therefore, deviate in both magnitude and phase from the full voltage across the complete arrester. This phenomenon affects the measurement of the resistive leakage current in two ways: Firstly, the resistive current measured in the earth connection is affected by the magnitude of the voltage across the non-linear metal-oxide resistors at the earthed end, therefore, the measured resistive current may differ from the average resistive current along the arrester; Secondly, the phase shift of the voltage across the non-linear metal-oxide resistors at the earthed end influences the result of resistive current measurement for methods that are using the voltage across the complete arrester as a reference for the phase angle.

In addition, the capacitive current induced in the earth lead of the arrester by the adjacent phases may introduce small changes in the measured current.

D.1.7.2.4 Harmonics in the leakage current

The non-linear voltage-current characteristic of a metal-oxide arrester gives rise to harmonics in the leakage current when the arrester is energized with a sinusoidal voltage. The harmonic content depends on the magnitude of the resistive current and the degree of non-linearity, which is a function of voltage and temperature. As an example, the third harmonic content of the resistive current is typically 10 % to 40 % of the resistive current component. Therefore, the harmonic content can be used as an indicator of the resistive current. Typical values of voltage and temperature dependencies under a.c. voltage are indicated in Figures D.4 and D.5, respectively, with magnitudes normalized to voltage U_c and temperature +20 °C. Another source of harmonics, beside negligible ones, that may considerably influence the measurement of harmonics in the leakage current, is the harmonic content in the system voltage. The capacitive harmonic currents produced by the voltage harmonics may be of the same order of magnitude as the harmonic currents created by the non-linear resistance of the arrester. An example of harmonics in the leakage current caused by system voltage harmonics is seen in Figure D.2.

D.1.7.2.5 Power loss

Power loss may be used for diagnostic indication of arresters in the same way as the resistive leakage current. Typical values of power losses are 5 mW/kV to 300 mW/kV (rated voltage) at U_c and +20 °C. The temperature and voltage dependencies are practically the same as for the resistive current, as seen in Figures D.4 and D.5.

D.1.7.3 Surface leakage current

As with any other outdoor insulator, external surface leakage current may temporarily occur on the arrester housing under rain or under conditions of high humidity combined with surface pollution. In addition, internal surface leakage current may appear due to moisture penetration. During measurements, the surface currents may interfere with the leakage current of the resistors, however, the sensitivity to external and internal surface currents may be different for the various measurement methods. The influence of the external surface leakage current can be avoided, either by performing the measurements in dry conditions, or by any other suitable method, e.g. bypassing the surface leakage current to earth.

D.2 Measurement of the total leakage current

The total leakage current depends mainly on the capacitive current, since the resistive part is only a fraction of the capacitive current component. Furthermore, the capacitive and resistive current components differ in phase by 90°; therefore, a large increase in the resistive current of the non-linear metal-oxide resistors is needed before a significant change can be noticed in the total leakage current level. In addition, the total leakage current is sensitive to the installation, since the capacitive current depends on the stray capacitances.

On-line measurements of the total leakage current are extensively used in practice by means of conventional mA-meters built into the surge counters or into portable instruments, showing the r.m.s., mean or peak value of the total leakage current. The sensitivity of the r.m.s, mean, and peak values of the total leakage current to variations in the resistive current is illustrated in Figure D.6.

Because total leakage current is not sensitive even to critical changes in the resistive current component, it is in general not suitable as a diagnostic indicator of gradual degradation of the resistor elements.

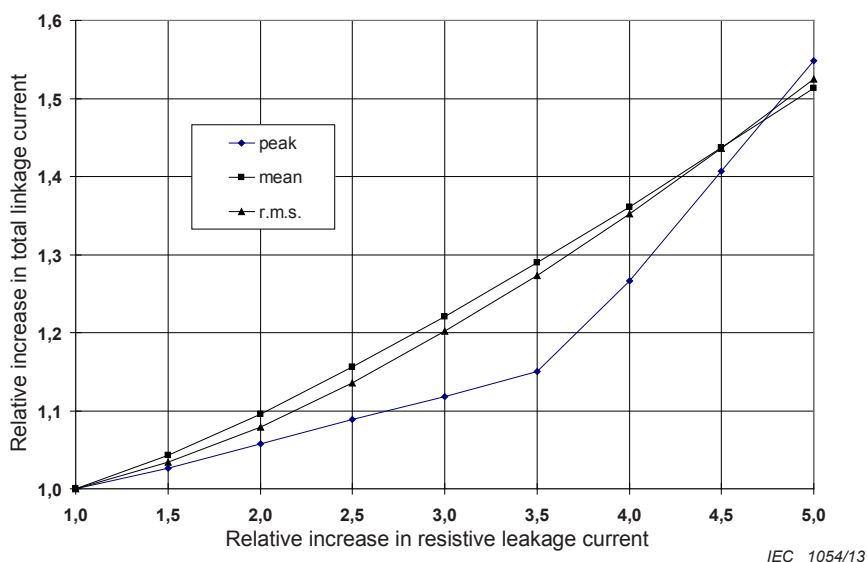


Figure D.6 – Influence on total leakage current by increase in resistive leakage current

D.3 Measurement of the resistive leakage current or the power loss

D.3.1 General

The resistive component of the total leakage current or the power loss can be determined using several methods. Three main principles can be identified, which can be further divided into different groups:

Method A: Direct measurement of the resistive leakage current: This method can be divided into four groups depending on the method of extracting the resistive component of the leakage current:

- A1 Using the applied voltage signal as a reference for direct peak resistive current reading or total leakage current discrimination
- A2 Compensating the capacitive component of the leakage current by using a voltage signal
- A3 Compensating the capacitive component of the leakage current without using of a voltage signal
- A4 Compensating the capacitive components of the leakage current by combining the currents of the three phases

Method B: Indirect determination of the resistive component by means of harmonic analysis of the leakage current: This method can be divided into three different groups:

- B1 Third order harmonic analysis of the leakage current
- B2 Third order harmonic analysis with compensation for harmonics in the system voltage
- B3 First order harmonic analysis of the leakage current

Method C: Direct determination of the power losses.

D.3.2 Method A1 – Using the applied voltage signal as a reference

a) Direct peak resistive current reading

The method relies on using a reference signal representing the voltage across the arrester. The reference signal can be used for direct reading of the resistive component of the leakage current at the instant when the voltage is at its peak ($dU/dt = 0$). The voltage and the resistive current level can be read with an oscilloscope or similar device. This method is commonly used in the laboratory for accurate determination of the resistive current since the reference signal is easily accessible through a voltage divider having a sufficiently small phase-shift.

In practice, the accuracy is limited mainly by the phase-shift of the reference signal and by the deviations in magnitude and phase of the voltage across the non-linear metal-oxide resistors at the earthed end of the arrester, as discussed above in D.1.7.2.3. The presence of harmonics in the voltage may further reduce the accuracy of the method.

A restriction on the method during in-service measurements is the need for a reference signal. Temporary connection to the secondary side of a potential transformer or to the capacitive tap of a bushing is necessary, and may be complicated to obtain. The capacitive currents induced in the earth connection of the arrester by adjacent phases may reduce the accuracy during in-service measurements, as discussed in D.1.7.2.3.

b) Total leakage current discrimination

The ZnO element may be represented by a parallel RC circuit, both R and C being non-linear, and the current can be resolved into conduction and capacitive components. A point-on-wave method, which requires voltage and current traces, has identified variations during the voltage cycle not only in the equivalent resistance of the sample, but also in its capacitance. The method is based on the expression of the average power and assumes a single valued voltage-conduction current characteristic.

The total current for an RC parallel equivalent circuit is

$$I_t(t) = I_c(t) + I_r(t) = C \frac{dU(t)}{dt} + I_r(t) \quad (D.1)$$

where I_c and I_r are the capacitive and resistive components of the total leakage current I_t .

The instantaneous resistive current magnitude at two instants t_1 and t_2 corresponding to the same level of voltage on the cycle can be expressed as

$$I_r(t_1) = I_r(t_2) = \left(\frac{1}{2} (I_t(t_1) + I_t(t_2)) \right) - \left(\frac{1}{2} (I_t(t_1) - I_t(t_2)) \right) \left(\frac{\frac{dU(t_1)}{dt} + \frac{dU(t_2)}{dt}}{\frac{dU(t_1)}{dt} - \frac{dU(t_2)}{dt}} \right) \quad (D.2)$$

Equation (D.2) allows the calculation of the resistive current around the cycle for any wave shape. If the voltage is sinusoidal with no harmonic content or with only odd harmonics without phase shift, the following simplified equation applies

$$I_r(t_1) = I_r(t_2) = \frac{1}{2} (I_t(t_1) + I_t(t_2)) \quad (D.3)$$

Figure D.7 shows typical examples obtained with this discrimination technique on a 15 kV-rated surge arrester in the low and high conduction regimes. As can be seen, both the resistive and capacitive components show non-linearities. In-service, however, measurements of voltage and currents with the required accuracy may be challenging.

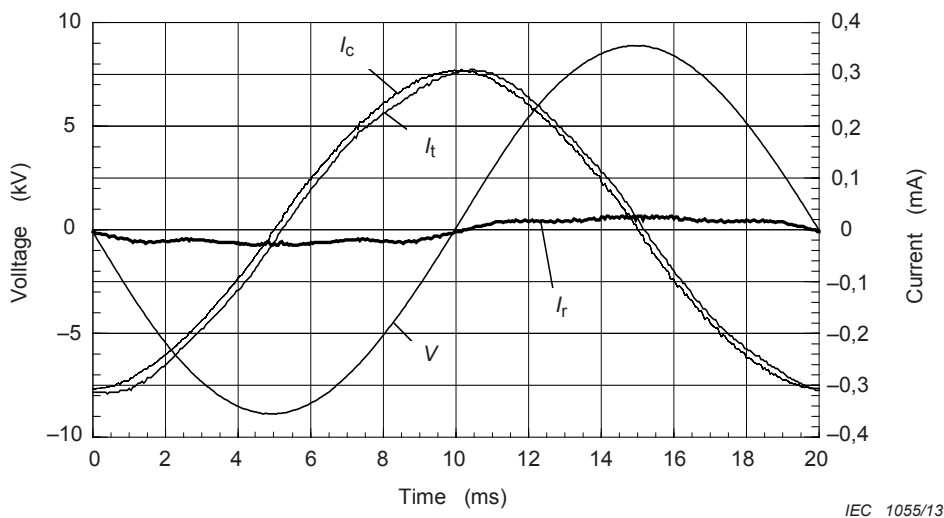
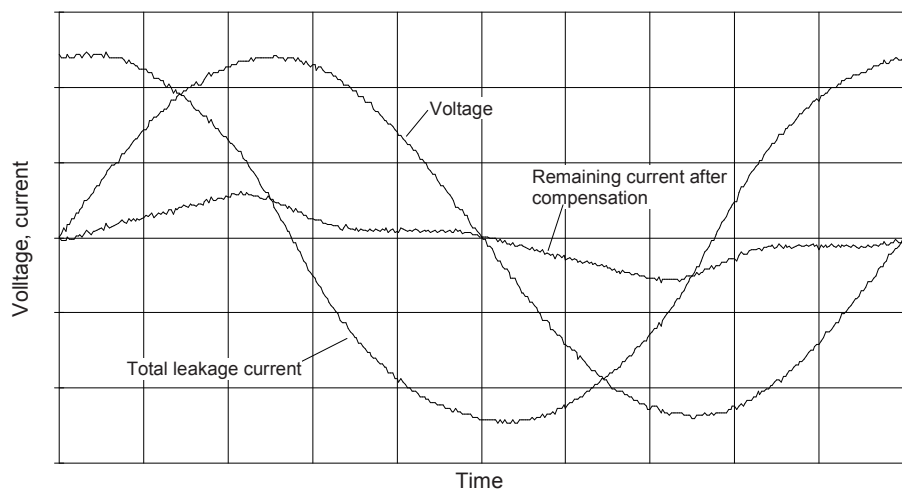


Figure D.7 – Measured voltage and leakage current and calculated resistive and capacitive currents ($V = 6,3$ kV r.m.s)

D.3.3 Method A2 – Compensating the capacitive component using a voltage signal

By using a voltage signal to compensate the leakage current for its capacitive component, the sensitivity in the measurement of the resistive component may be further increased. The basic principle is a HV bridge where the capacitive-resistive arm is adjusted to balance the capacitive component of the leakage current so that only the non-linear resistive part contributes to the output voltage, which can be studied with the help of an oscilloscope.

The bridge is balanced when the voltage is close to zero and with the capacitive current being at its peak. Since the differential capacitance of the arrester is voltage dependent (the capacitance increases with voltage), while the bridge capacitance is constant, the remaining current after compensation comprises not only the resistive component, but also a capacitive part. This approach is illustrated in Figure D.8. As for method A1 (i), the true resistive component is found at the instant when the voltage is at its peak. However, it is worth noting that zinc oxide material is found to exhibit a non-linear capacitance, especially around the knee of conduction. Since the method requires a reference voltage, which may be difficult to access in service, the method is generally restricted in the same way as method A1 (i). Similarly, the accuracy may be reduced by phase shifts in voltages and currents due to the influence of adjacent phases.



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Figure D.8 – Remaining current after compensation by capacitive current at U_c

D.3.4 Method A3 – Compensating the capacitive component without using a voltage signal

This is a compensation method where the need for a voltage signal is eliminated. The basic principle is that a reference signal of fundamental frequency is created synthetically by means of information derived from the leakage current. By proper adjustment of the amplitude and phase angle, which can be done automatically or by using an oscilloscope, the reference signal can be made to compensate the capacitive component of the leakage current.

A potential problem is the presence of harmonics in the voltage, which cause harmonic capacitive currents that may interfere with the resistive component. Furthermore, the compensating signal represents the current in a linear capacitance, which implies the same type of accuracy problem as with method A2. Phase shifts in voltages and currents caused by the adjacent phases may also reduce accuracy as with other methods.

D.3.5 Method A4 – Capacitive compensation by combining the leakage current of the three phases

The method is based on the assumption that the capacitive currents are cancelled if the leakage currents of the arresters in the three phases are summed up. The resulting current is composed of the harmonics of the resistive currents from the three arresters, since the fundamental components are also cancelled as long as they are equal in magnitude. If there is an increase in the resistive current of any of the arresters, the capacitive currents remaining constant, the increase will appear in the summed current. A voltage reference signal is not needed.

For measurements in service, the main disadvantage with the method is that the capacitive currents of the three phases are not generally equal. Only well-controlled geometries such as arresters in gas-insulated switchgear, combined with equal capacitances of the arresters, will provide the necessary symmetry. Another concern is the influence of harmonics in the system voltage, which will cause harmonics in the added current.

D.3.6 Method B1 – Third order harmonic analysis

The method is based on the fact that harmonics are created in the leakage current by the non-linear voltage-current characteristic of the arrester. No voltage reference is needed since it is assumed that all harmonics arise from the non-linear resistive current. However, this assumption is not valid as the capacitive current is observed to show non-linear behaviour. The harmonic content depends on the magnitude of the resistive current and on the degree of non-linearity of the voltage-current characteristic, i.e., the harmonic content varies also with the voltage and temperature of the arrester, as indicated for the third order harmonic in Figures D.4 and D.5.

In the upturn region of the V-I characteristic, the third harmonic is the largest harmonic component of the resistive current, and it is commonly used for diagnostic measurements. The conversion from harmonic to resistive current level, if required, relies on information supplied by the arrester manufacturer or from measurements in the laboratory, and large errors may be introduced in this process. This is seen in Figure D.9, where the error in the evaluation of the third harmonic in the leakage current is given as a function of the third harmonic content in the system voltage. The figure includes the effects of different voltage-current characteristics and capacitances, as well as the influence of the phase angle of the third harmonic in the voltage.

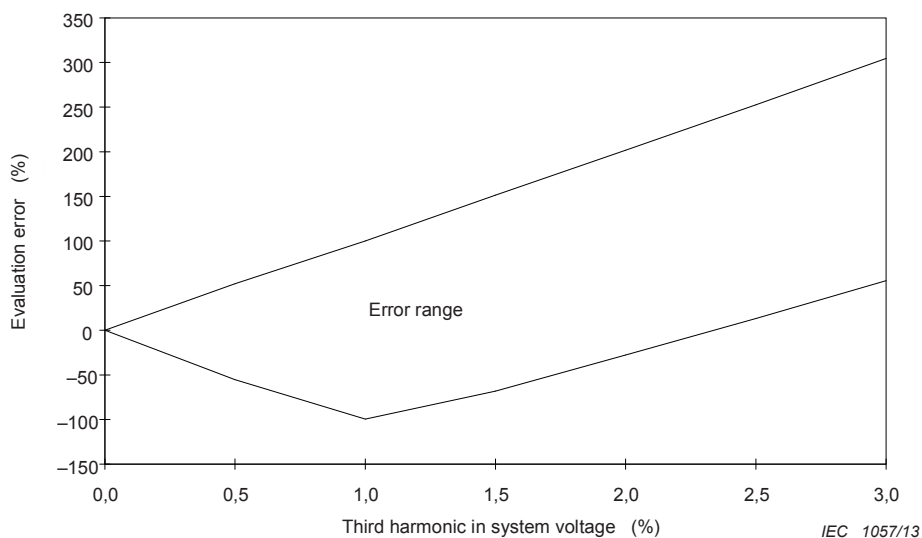


Figure D.9 – Error in the evaluation of the leakage current third harmonic for different phase angles of system voltage third harmonic, considering various capacitances and voltage-current characteristics of non-linear metal-oxide resistors

The main problem is the sensitivity to harmonics in the system voltage. The harmonics in the voltage may generate capacitive harmonic currents that are comparable in size with the harmonic currents generated by the non-linear resistance of the arrester. As a result, the error in the measured harmonic current may be considerable if the harmonic content in the voltage is high.

D.3.7 Method B2 – Third order harmonic analysis with compensation for harmonics in the voltage

The method is based on the same principle as method B1, but the sensitivity to harmonics in the voltage is greatly reduced by the introduction of a compensating current signal for the capacitive third harmonic current in the arrester. The compensating current signal is derived from a "field probe" positioned at the base of the arrester. After proper scaling, the harmonic current induced in the probe by the electric field is subtracted from the total harmonic current. The result is the harmonic current generated by the non-linear resistive current of the arrester. The conversion from third harmonic to resistive current requires additional information from the arrester manufacturer, as for method B1. The method is suitable for measurements in service.

D.3.8 Method B3 – First order harmonic analysis

The fundamental component of the resistive current is obtained by filtering and integration of the leakage current, yielding a signal proportional to the resistive component.

The influence of harmonics in the system voltage during in-service measurements is practically eliminated by using only the fundamental components of voltage and current. The main limitation of the method is the need for a voltage signal obtained, e.g. from the secondary side of a potential transformer. The accuracy depends on phase shifts in the voltages and currents, in the same way as for other methods.

D.3.9 Method C – Direct determination of the power losses

The average power loss is the integral of the product of the instantaneous values of the voltage and leakage current over one cycle divided by the period. The power loss may be expressed in terms of the product of the r.m.s. value of the resistive component of leakage current and the r.m.s. value of the voltage across the arrester. The influence of the harmonics in the voltage is greatly reduced by the multiplication and integration procedure. The main disadvantage is the need for a voltage signal. The accuracy during in-service measurements may be limited due to phase shifts in voltages and currents, caused by the adjacent phases.

D.4 Leakage current information from the arrester manufacturer

The measured leakage current data may be compared with information supplied by the arrester manufacturer. To utilize this information, it is important that the operating voltage and the ambient temperature are known at the time of measurement.

For efficient use of the diagnostic methods described above, the arrester manufacturer may provide information relevant to the various methods. The information may comprise the resistive current, third harmonic current and power loss data for each arrester type as functions of voltage and temperature.

For practical use, the voltage dependence may be expressed as a function of the service voltage divided by U_r . The information should preferably cover operating voltages from 0,40 to 0,90 of U_r . The resistive and third harmonic currents should be given as peak values, while the power loss should be expressed as a specific value based on the rated voltage.

The temperature dependence should be given as a function of the ambient temperature, assuming a certain over-temperature of the resistor elements, since it is difficult to obtain the actual resistor temperature during in-service measurements. The ambient temperature range should preferably be from -10 °C to $+40\text{ °C}$.

NOTE The actual varistor temperature may be higher than normal due to energy absorption, solar radiation and other heat sources.

Two different types of information from the arrester manufacturer are of main interest in the evaluation of the measurement results:

Firstly, information for comparison of results obtained under different operating conditions in terms of service voltage and ambient temperature. By converting the measured results to a set of “standard” operating conditions, e.g. a service voltage of $0,70 U_r$ and an ambient temperature of $+20\text{ °C}$, it is possible to compare the results from measurements made on different occasions. The information from the manufacturer could be given as correction multipliers, as indicated in Figures D.10 and D.11.

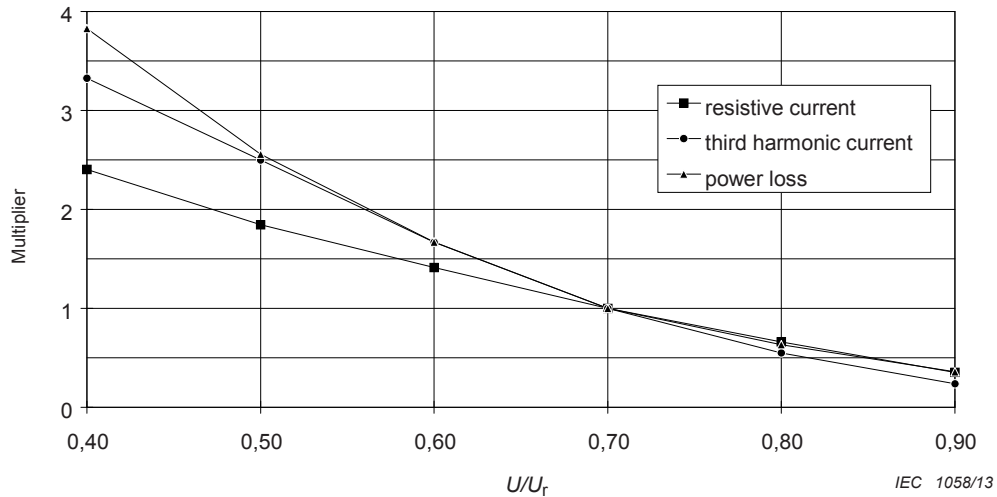


Figure D.10 – Typical information for conversion to "standard" operating voltage conditions

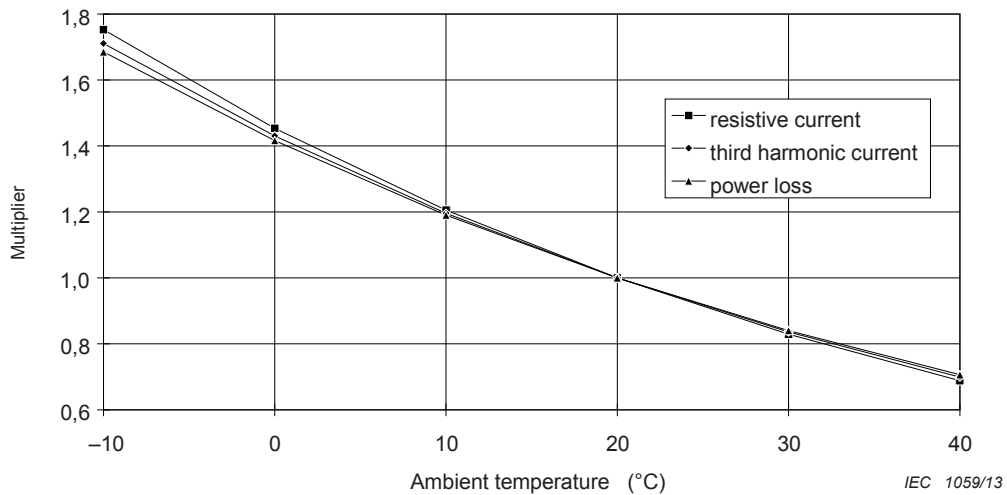


Figure D.11 – Typical information for conversion to "standard" ambient temperature conditions

Secondly, the arrester manufacturer may give limits for the measured quantities after conversion to “standard” operating conditions, as described above. If the limits are exceeded, the manufacturer should be consulted for further advice. The limits may be given as absolute values and/or relative changes with time.

Due to the complexity of the measurement methods, it is recommended that the arrester manufacturer be consulted in order to avoid misinterpretation of the measurement results.

The determination of the third harmonic current data may be influenced by harmonics in the laboratory test voltage. Therefore, the requirements on the test equipment should be considered.

D.5 Summary of diagnostic methods

The service experiences with the different diagnostic methods are summarized in Table D.1. The sensitivity, diagnostic efficiency and service experience with the various leakage current measurement methods are indicated in Table D.2.

Table D.1 – Summary of diagnostic methods

Diagnostic method	Service condition		Service experience
	off-line	on-line	
Surge counter		x	extensive
Monitoring spark gap		x	extensive ^{a)}
Temperature measurement		x	limited
Leakage current measurement – using a separate voltage source	x		see Table D.2
– using service voltage		x	see Table D.2
^{a)} In certain countries.			

Table D.2 – Properties of on-site leakage current measurement methods

Leakage current measurement method	Method No.	Sensitivity to			Diagnostic efficiency		Service experience
		harmonics in the voltage	phase shift in measurement of voltage or current	surface currents	information quality	handling complexity	
Separate d.c. voltage source		n.a.	n.a.	high	high	high	limited
Service voltage or separate a.c. voltage source							
Measurement of total leakage current		low	low	mean	low	low	extensive
Measurement of resistive current							
– using voltage reference	A1	mean	high	high	mean	high	limited
– using capacitor compensation	A2	mean	high	high	mean	high	limited
– using synthetic compensation	A3	mean	high	high	mean	low	n.i.a.
– using capacitive current cancellation	A4	high	high	high	low	low	limited
Harmonic analysis of leakage current							
– using third harmonic	B1	high	low	low	mean	low	extensive
– using third harmonic with compensation	B2	low	low	low	high	mean	extensive
– using first order harmonic	B3	low	high	high	mean	high	limited
Measurement of power loss	C	low	high	high	mean	high	n.i.a.

Annex E (informative)

Typical data needed from arrester manufacturers for proper selection of surge arresters

Table E.1 shows the typically needed arrester data in order to make a proper selection of surge arresters for the usual application of protection of transformers or other substation equipment.

Table E.1 – Arrester data needed for the selection of surge arresters

Arrester data	Denomination
Rated voltage, U_r	kV(rms value)
Continuous operating voltage, U_c	kV(rms value)
Nominal discharge current, I_n	kA
Line discharge class ^{a)}	1, 2, 3, 4, or 5
Lightning impulse protective level, LIPL	kV(crest value)
Switching impulse protective level, SIPL ^{a)}	kV(crest value)
Rated short-circuit current, I_s	kA(rms value)
Insulation withstand voltage	According to IEC 60099-4
Specified long-term load, SLL	N
Specified short-term load, SSL	N
^{a)} Typically used for HV-arresters only.	

Annex F (informative)

Typical maximum residual voltages for metal-oxide arresters without gaps according to IEC 60099-4

Tables F.1 and F.2 provide information regarding typical residual voltages for different classes of metal-oxide arresters without gaps.

**Table F.1 – Residual voltages for 20 000 A and 10 000 A arresters
in per unit of rated voltage**

Rated voltage U_r	20 000 A kV (peak)/ U_r			10 000 A kV (peak)/ U_r			
	kV r.m.s.	Steep	Lightning	Switching	Steep	Lightning	Switching
3 – 29					2,6 – 4,0	2,3 – 3,6	2,0 – 2,9
30 – 132	2,6 – 3,1	2,3 – 2,8	2,0 – 2,3	2,6 – 3,7	2,3 – 3,3	2,0 – 2,6	
144 – 342	2,6 – 3,1	2,3 – 2,8	2,0 – 2,3	2,6 – 3,7	2,3 – 3,3	2,0 – 2,6	
360 – 756	2,6 – 3,1	2,3 – 2,8	2,0 – 2,3	2,6 – 3,1	2,3 – 2,8	2,0 – 2,3	
780 – 900	2,1 – 2,8	1,9 – 2,4	1,6 – 2,0				

NOTE The table gives the range of maximum residual voltages normally available. Low values refer normally to arresters with high line discharge class and vice versa.

**Table F.2 – Residual voltages for 5 000 A, 2 500 A and 1 500 A
arresters in per unit of rated voltage**

Rated voltage U_r	5 000 A kV (peak)/ U_r		2 500 A kV (peak)/ U_r		1 500 A kV (peak)/ U_r	
	kV r.m.s.	Steep	Lightning	Steep	Lightning	Steep
0,175 – 2,9	2,7 – 4,0	2,4 – 3,6	3,7 – 5,0	3,3 – 4,5	4,5 – 6,7	4,0 – 6,0
3 – 29	2,7 – 4,0	2,4 – 3,6	4,0	3,6		
30 – 132	2,7 – 3,7	2,4 – 3,6	4,0	3,6		

NOTE The table gives the range of maximum residual voltages normally available.

Annex G (informative)

Steepness reduction of incoming surge with additional line terminal surge capacitance

G.1 General

Presence of surge capacitance at the line terminal or station entrance can reduce the steepness of the incoming surge. The degree of reduction is dependent on the size of the surge capacitance relative to the original steepness defined by the line corona distortion factor and surge distance from the station as derived from adopted equipment failure rate or mean return time of damaging surges.

For simple estimation, steepness of the incoming voltage surge can be related to charging of capacitor through the line surge impedance. Following this concept, an equivalent capacitance can be estimated based on the original incoming surge steepness. Then, the level of surge steepness reduction becomes dependent on the size of the line terminal capacitance relative to the equivalent capacitance evaluated from the original surge.

G.2 Basic formula

The basic formula for a capacitor voltage response when it is being charged through a line surge impedance Z is given by G.1:

$$u(t) = 2,0 \times U_s \times \left(1 - e^{-\frac{t}{Z \times C}} \right) \quad (\text{G.1})$$

where

Z : Line surge impedance (real value; i.e. lossless) in Ω

C : Total capacitance in F

U_s : Incoming surge magnitude, in V, based on attenuation and corona distortion

(U_s estimate: $U_s \approx 1,2 \times \text{CFO}$ of the line insulators)

Steepness S_0 of the capacitor voltage as derived from formula G.1 becomes:

$$S_0 = \frac{du(t)}{dt} = \frac{2,0 \times U_s \times e^{-\frac{t}{Z \times C}}}{Z \times C} \quad (\text{G.2})$$

When parameters U_s , Z and $\left(\frac{t}{Z \times C}\right)$ are assumed to be constant, the ratio f_s of steepness S_0 , related to the equivalent capacitance C_0 as derived from the original surge and modified steepness S_s due to the presence of line terminal capacitance C_s becomes:

$$f_s = \frac{S_s}{S_0} = \frac{C_0}{C_0 + C_s} \quad (\text{G.3})$$

Steepness of the original incoming surge S_0 associated with line corona factor and accepted equipment failure rate distance from station in G.4:

$$S_0 = \frac{A \times \frac{C_0}{2}}{L_{sp} + L_f} \text{ in kV}/\mu\text{V} \quad (\text{G.4})$$

where

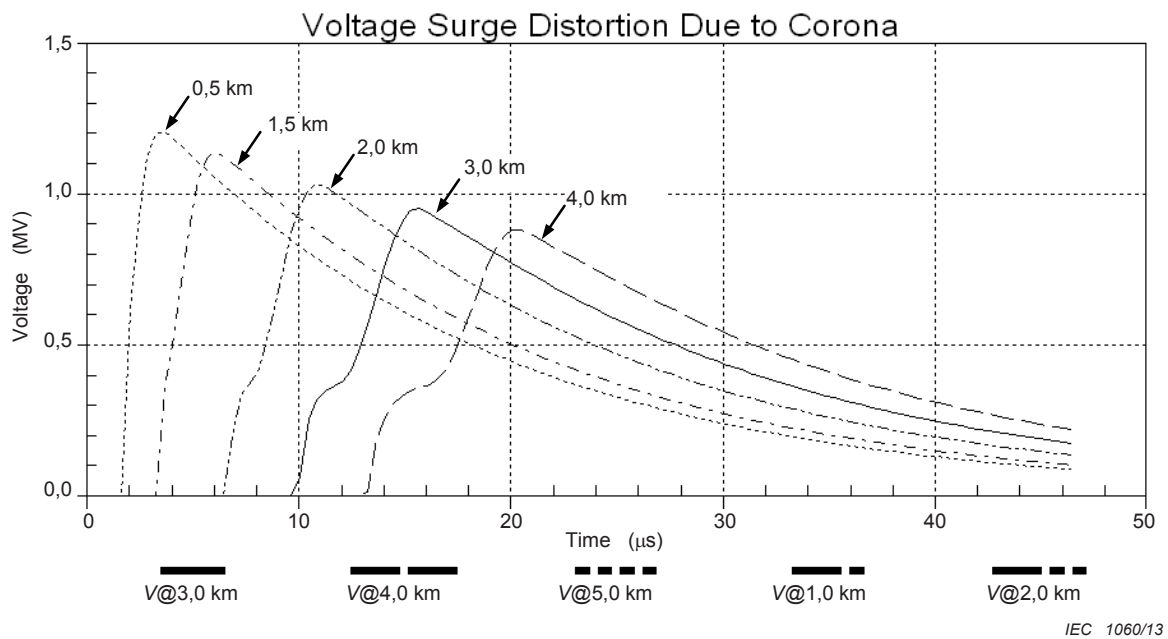
A: From IEC 60071-2:1996, Table F.2, in kV

C_0 : Speed of light = 0,3 km/ μs

L_{sp} : Line span length in km

L_f : Line section, in km, with outage rate equal to the adopted return rate (failure rate)

Figure G.1 shows typical line voltage distortion due to corona versus distance travelled.



Line voltages at 0,5 km – 1,0 km – 2,0 km – 3,0 km – 4,0 km

NOTE In the above figure V is used for the voltage instead of U.

Figure G.1 – Surge voltage waveforms at various distances from strike location (0,0 km) due to corona

G.3 Equivalent capacitance associated with incoming surge fronts

G.3.1 General

The equivalent capacitance C_0 , associated with the original incoming surge with steepness S_0 can be estimated by keeping $t_0/(Z \times C_0)$ fixed at 0,5 value and equating the time t_0 , taken by corresponding surge with steepness S_0 to attain a capacitor voltage $U_c(t_0)$ from formula G.1 as follows:

a) instant in time, t_0 , when

$$\frac{t_0}{Z \times C_0} = 0,5 \quad \text{or} \quad t_0 = 0,5 \times Z \times C_0$$

and

b) time, t_0 , taken by incoming line surge with steepness S_0 to attain voltage $U_c(t_0)$:

$$t_0 = \frac{U_c(t_0)}{S_0}$$

$$U_c(t_0) = U(0,5 \times Z \times C_0) = 2 \times U_s \times (1 - e^{-0,5}) = 0,8 \times U_s$$

$$t_0 = \frac{0,8 \times U_s}{S_0}$$

Solve for equivalent capacitance C_0 by equating the above two formulas for t_0 :

$$t_0 = 0,5 \times Z \times C_0 = \frac{0,8 \times U_s}{S_0}$$

Equivalent capacitance:

$$C_0 = \frac{1,6 \times U_s}{Z \times S_0} \quad (\text{G.5})$$

Estimate of the steepness reduction ratio f_s based on the original surge steepness S_0 and the modified steepness S_s due to addition of line terminal capacitance C_s at an instant of time when $t_0/(Z \times C_0)$ fixed at a value of 0,5:

$$f_s = \frac{S_s}{S_0} = \frac{C_0}{C_0 + C_s} = \frac{1}{1 + \frac{C_s}{C_0}}$$

Therefore, modified steepness S_s is related to f_s and S_0 as follows in formula G.6:

$$S_s = f_s \times S_0 \quad (\text{G.6})$$

G.3.2 Examples of incoming surge steepness change, f_s , using typical 550 kV & 245 kV circuit parameters

$$V(t) = 2,0 \times V_s \times (1 - e^{-[\frac{t}{Z \times C}]})$$

$$A(t) \times \frac{t_0}{Z \times C_0} = 0,5; \quad e^{-0,5} = 0,6; \quad 1 - e^{-0,5} = 0,4$$

When

$$u(t_0) = 0,8 \times U_s; \quad t_0 = \frac{0,8 \times U_s}{S_0} = 0,5 \times Z \times C_0$$

$$S_0 = \frac{K_c}{d}; \quad K_c = A \times \frac{C_0}{2}; \quad C_0 = 0,3 \text{ km}/\mu\text{s}; \quad d \text{ (km)} = \text{strike distance from station}$$

Therefore

$$\frac{0,8 \times U_s}{S_0} = 0,5 \times Z \times C_0 \quad \text{or} \quad C_0 = \frac{1,6 \times U_s}{Z \times C_0}$$

Table G.1 – C_s impact on steepness ratio f_s and steepness S_n

									$S_0 = f_s \times S_0$
CFO=1900	$U_s \sim 1,2 \times \text{CFO}$		$S_0(\text{kV/us}) = K_c/d$		$C_0(\text{nF}) = 10^3 \times 1,6 \times U_c / (Z \times S_0)$			$F_s = C_0 / (C_0 + C_s)$	
U_{class}	$U_s(\text{kV})$	Z(typical)	$K_c(\text{kV-km/us})$	d(km)	$S_0(\text{kV/us})$	$C_0(\text{nF})$	$C_s(\text{nF})$	$f_s(S_n/S_0)$	$S_c(\text{kV/us})$
500	2280	320	1700	0,50	3400	3,4	0,0	1,0	3 400
							1,0	0,8	2 619
							2,0	0,6	2 130
							3,0	0,5	1 794
500	2280	320	1700	1,00	1700	6,7	0,0	1,0	1 700
							1,0	0,9	1 479
							2,0	0,8	1 309
							3,0	0,7	1 175
									$S_0 = f_s \times S_0$
CFO=1200	$U_s \sim 1,2 \times \text{CFO}$		$S_0(\text{kV/us}) = K_c/d$		$C_0(\text{nF}) = 10^3 \times (1,6 \times U_c) / (Z \times S_0)$			$F_s = C_0 / (C_0 + C_s)$	
U_{class}	$U_s(\text{kV})$	Z(typical)	$K_c(\text{kV-km/us})$	d(km)	$S_0(\text{kV/us})$	$C_0(\text{nF})$	$C_s(\text{nF})$	$f_s(S_n/S_0)$	$S_0(\text{kV/us})$
230	1440	450	1000	0,5	2000	2,6	0,0	1,0	2 000
							1,0	0,7	1 438
							2,0	0,6	1 123
							3,0	0,5	921
230	1440	450	1000	1,0	1000	5,1	0,0	1,0	1 000
							1,0	0,8	837
							2,0	0,7	719
							3,0	0,6	631

G.3.3 Change in coordination withstand voltage, U_{cw} , with steepness reduction, f_s :

$$U_{cw} = U_{pl} + \frac{A \times f_s}{N} \times \frac{L_t}{L_{sp} + L_f}$$

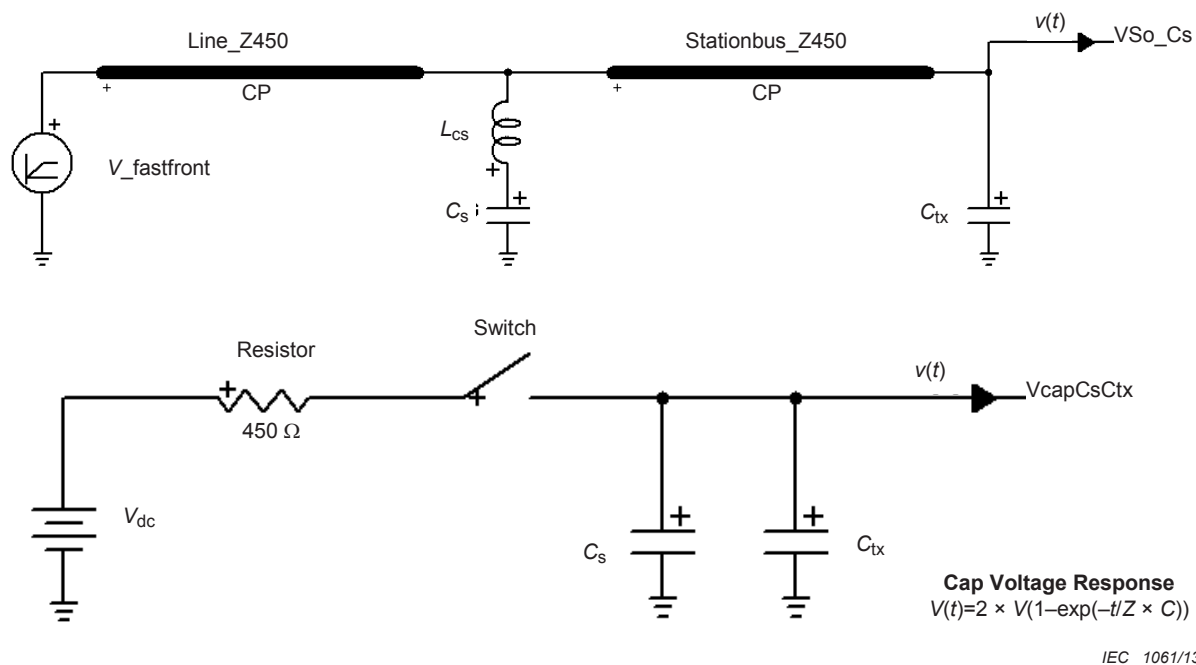
Table G.2 shows how U_{cw} changes for different surge steepness S_0 and steepness reduction f_s .

Table G.2 – Change in coordination withstand voltage, U_{cw} ,

N = 1 $U_{sa} = 192 \text{ kV}$ $U_{pl} = 2 \times U_{sa}$						
A(kV)	$L_{sp} + L_f$ (km)	L_t (km)	U_{pl} (kV)	S_0 (kV/us)	f_s	U_{cw} (kV)
7000	0,5	0,02	384	2100	1	664
7000	0,5	0,02	384	2 00	0,5	524
7000	1	0,02	384	1050	1	524
7000	1	0,02	384	1050	0,5	454

G.4 EMTP & capacitor charging models for steepness change comparisons at line open terminal

Two cases are shown in Figures G.2 and G.3.



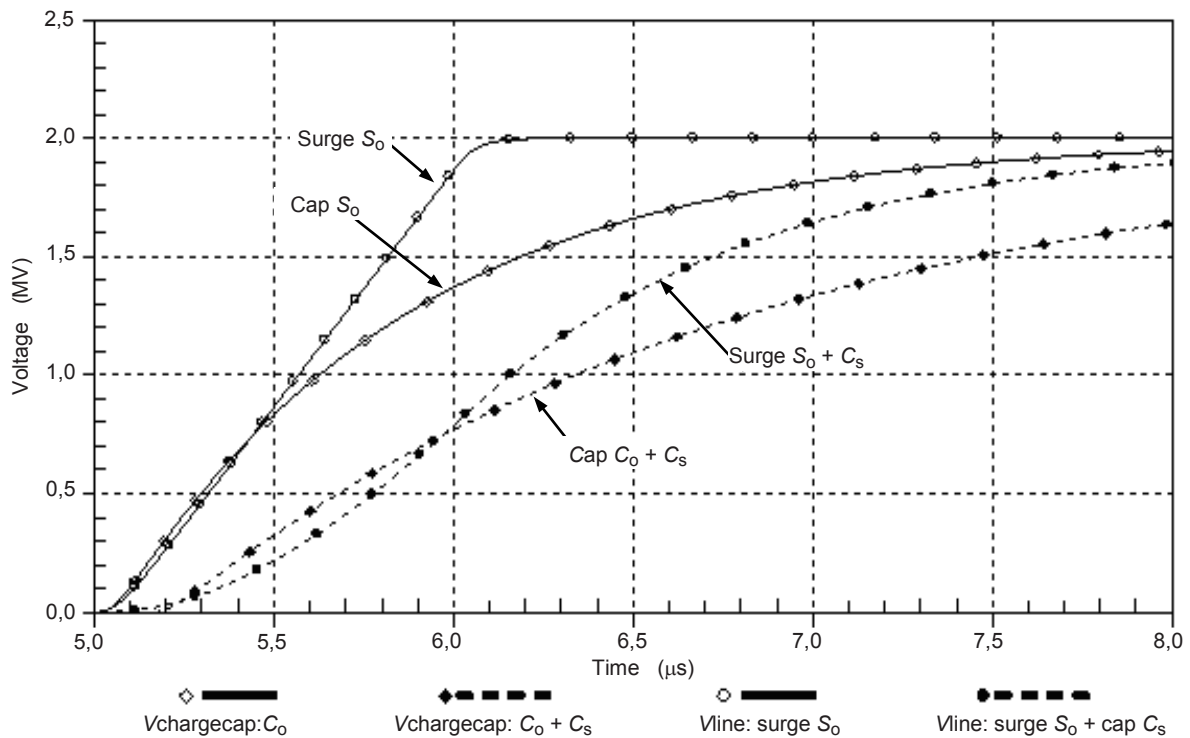
Example: $U_s = 1\,000\text{ kV}$, $Z_c = 450\ \Omega$, $S_0 = 2\,000\text{ kV}/\mu\text{s}$

C_0 (corona equivalent) = $1,6 \times U_s / (Z \times S_0) = 1,78\text{ nF}$, $C_{tx} = 0,1\text{ nF}$

$C_0 = 1,78\text{ nF}$, C_s (in addition) = $1,78\text{ nF}$, $C_{total} = 3,76\text{ nF}$

NOTE In the above figure, V is used for the voltage instead of U .

Figure G.2 – Case 1: EMTP Model: Thevenin equivalent source, line (Z,c) & station bus (Z,c) & Cap(C_s)



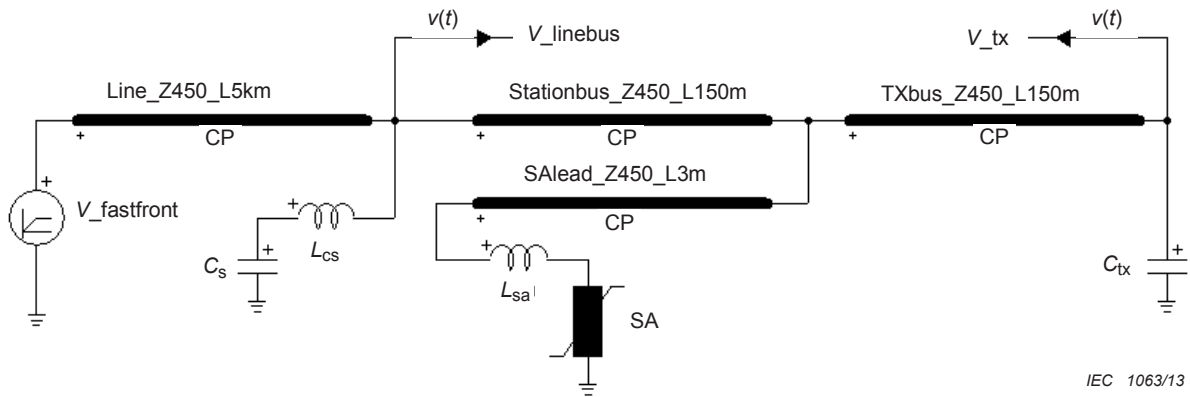
IEC 1062/13

- Surge S_0 (no C_s): Surge with $U_c = 1\,000$ kV, $S_0 = 2\,000$ kV/ μ s
- Surge $S_0 + C_s$ (with C_s): Surge with $U_c = 1\,000$ kV, $S_0 = 2\,000$ kV/ μ s and $C_s = C_0 = 1,8$ nF,
- Cap C_0 : Capacitor $C_0 = 1,8$ nF charged through $Z = 450$ Ω ,
- Cap $C_0 + C_s$: Capacitors $C_0 = 1,8$ nF and $C_s = C_0$ charged through $Z = 450$ Ω

Figure G.3 – Case 2: Capacitor Voltage charge via line Z: $u(t) = 2 \times U_s \times (1 - \exp[-t/(Z \times C)])$

G.5 Typical steepness ($S_0 = 1000$ kV/ μ s), change comparisons with C_0 & C_s

Figure G.4 shows the EMTP model used for a faster steepness example, and Figures G.5 and G.6 show the results of the simulated surge analysis.



Distances; Surge arrester – Transformer = 20 m, Surge arrester – Linebus = 150 m

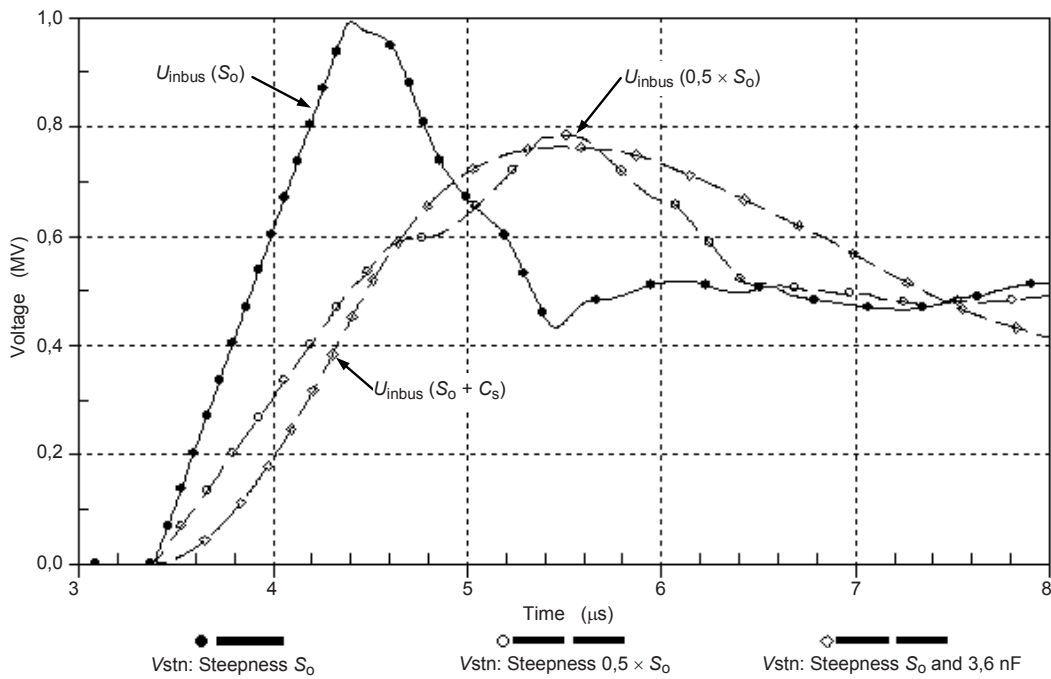
1st: $S_0 = 1\,000\text{ kV}/\mu\text{s}$, $U_s = 1\,000\text{ kV}$, $Z = 450\ \Omega$, $C_0 = 1,6 \times U_c / (Z \times S) = 3,6\text{ nF}$

2nd: $S = S_0/2 = 500\text{ kV}/\mu\text{s}$ $U_s = 1\,000\text{ kV}$

3rd: $S_0 = 1\,000\text{ kV}/\mu\text{s}$ and additional $C_s = C_0 = 3,6\text{ nF}$ at line terminal

NOTE In the above figure V is used for the voltage instead of U .

Figure G.4 – EMTP model



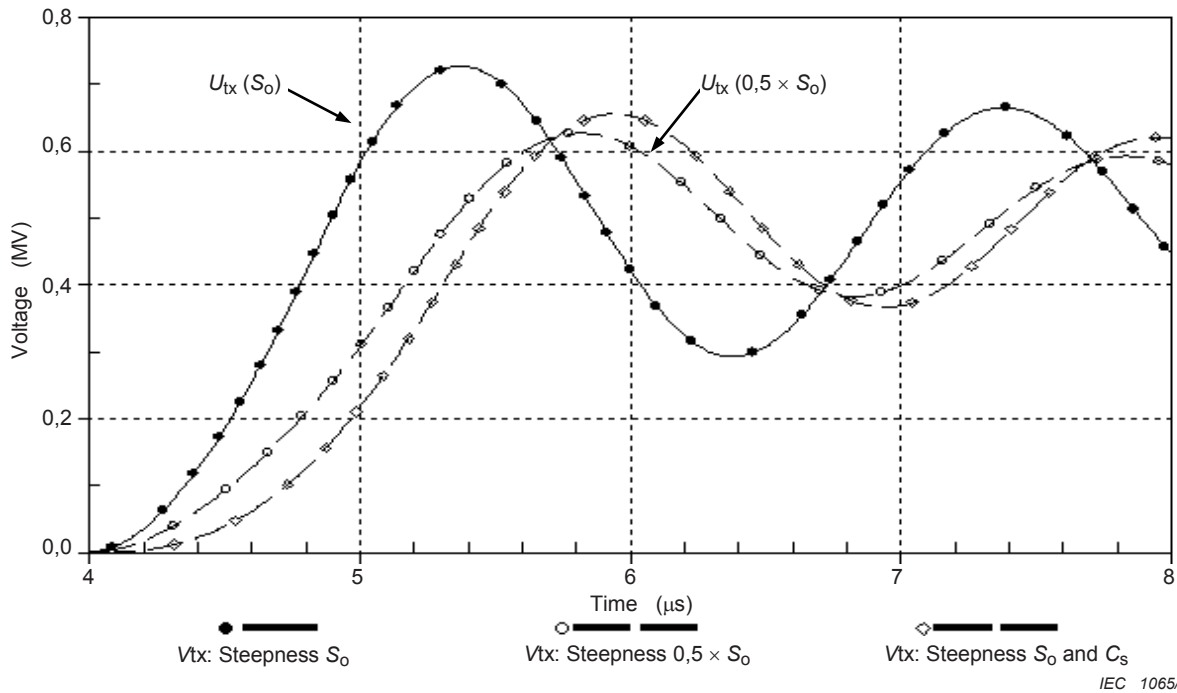
Distance: Surge arrester – Line station bus interface = 150 m

Graph 1: $S_0 = 1\,000\text{ kV}/\mu\text{s}$

Graph 2: $S_0/2 = 0,5 \times S_0 = 500\text{ kV}/\mu\text{s}$

Graph 3: $S_0 + C_s = S_0 + C_s(3,6\text{nF})$

Figure G.5 – Simulated surge voltages at the line-station bus interface



IEC 1065/13

Distance: Surge arrester – Transformer = 20 m

Graph 1: $S_0 = 1\ 000\ \text{kV}/\mu\text{s}$

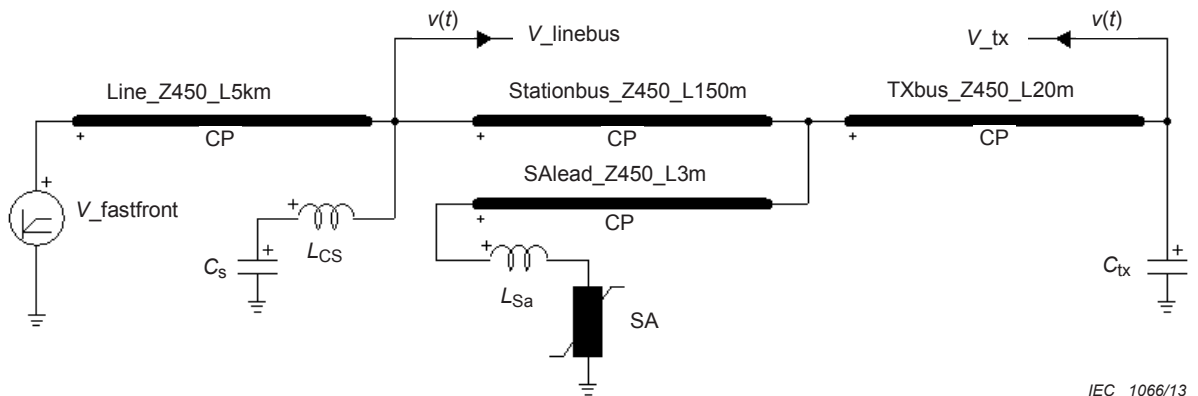
Graph 2: $S = S_0/2 = 0,5 \times S_0 = 500\ \text{kV}/\mu\text{s}$

Graph 3: $S_0 + C_s = S_0 + C_s$ (3,6 nF)

Figure G.6 – Simulated Surge Voltages at the Transformer

G.6 Faster steepness (2000 kV/µs), change comparisons with C_0 & C_s

Figure G.7 shows the EMTP model used for a faster steepness example, and Figures G.8 and G.9 show the results of the simulated surge analysis.



IEC 1066/13

Distances; Surge arrester – Transformer = 20 m, Surge arrester – Linebus = 150 m

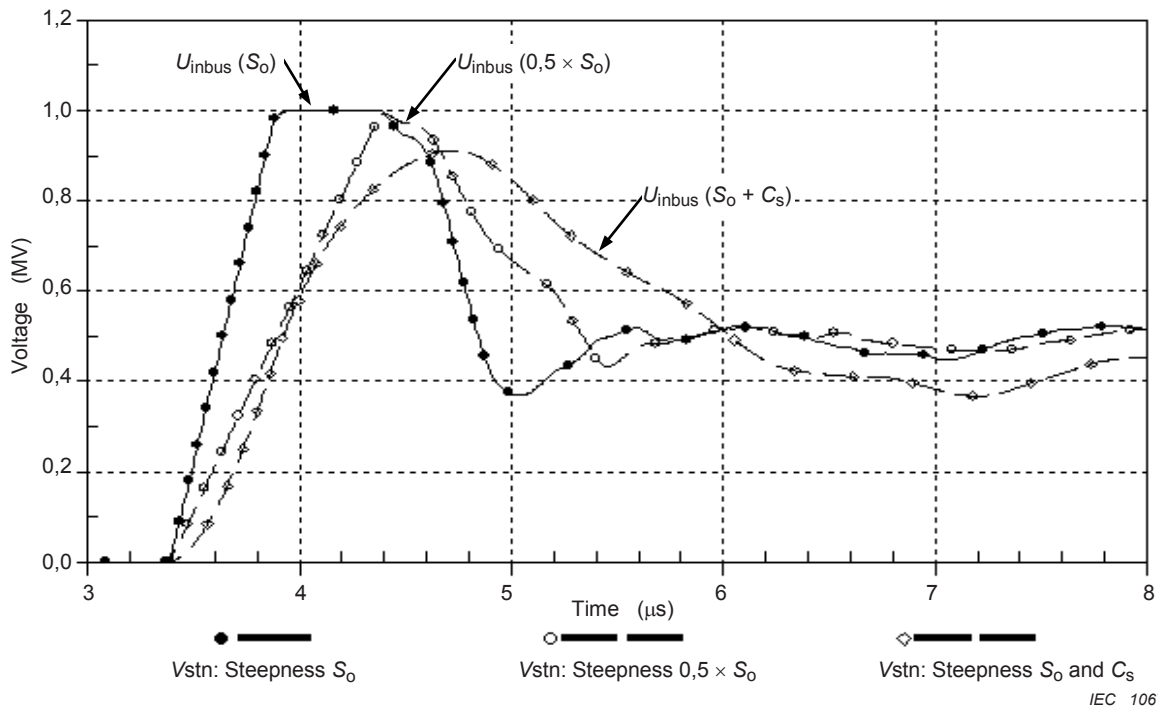
1st: $S_0 = 2\ 000\ \text{kV}/\mu\text{s}$, $U_s = 1\ 000\ \text{kV}$, $Z = 450\ \Omega$, $C_0 = 1,6 \times U_C/(Z \times S) = 1,8\ \text{nF}$, $C_{tx} = 1\ \text{nF}$

2nd: $S = S_0/2 = 1\ 000\ \text{kV}/\mu\text{s}$ $U_s = 1\ 000\ \text{kV}$

3rd: $S_0 = 2000\ \text{kV}/\mu\text{s}$ and additional $C_s = C_0 = 1,8\ \text{nF}$ at line terminal

NOTE In the above figure V is used for the voltage instead of U.

Figure G.7 – EMTP Model



IEC 1067/13

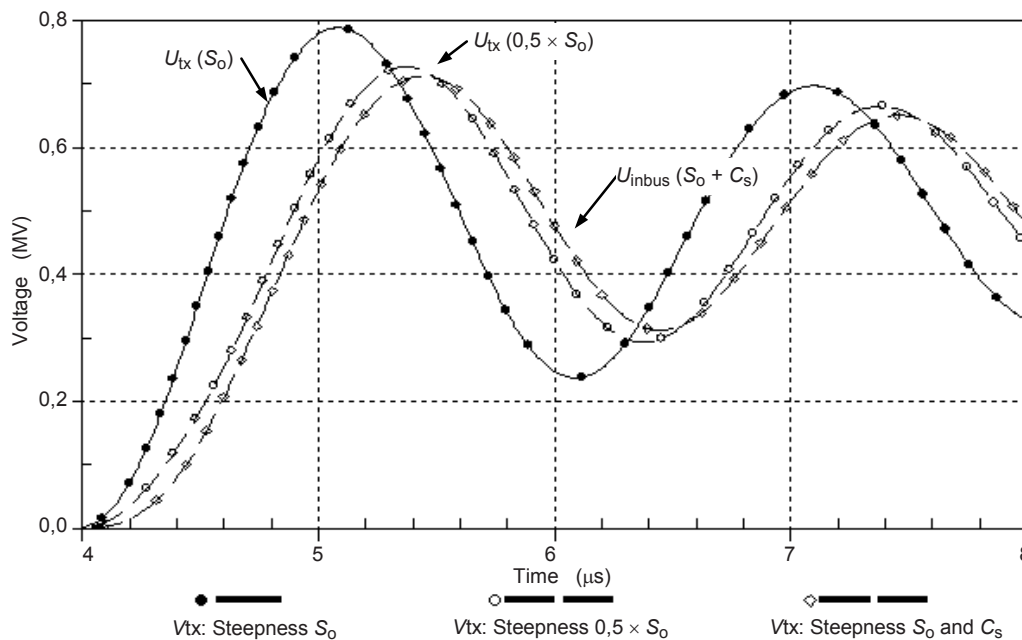
Distance: Surge arrester – Line station bus interface = 150 m

Graph 1: $S_0 = 2\,000\text{ kV}/\mu\text{s}$

Graph 2: $S = S_0/2 = 0,5 \times S_0 = 1\,000\text{ kV}/\mu\text{s}$

Graph 3: $S_0 C_s = S_0 + C_s (1,8\text{ nF})$

Figure G.8 – Simulated surge voltages at the line-station bus interface



IEC 1068/13

Distance: Surge arrester – Transformer = 20 m

Graph 1: $S_0 = 2\,000\text{ kV}/\mu\text{s}$

Graph 2: $S = S_0/2 = 0,5 \times S_0 = 1\,000\text{ kV}/\mu\text{s}$

Graph 3: $S_0 C_s = S_0 + C_s (1,8\text{ nF})$

Figure G.9 – Simulated surge voltages at the transformer

Annex H (informative)

End of life and replacement of old gapped SiC-arresters

H.1 Introduction

Since the late seventies, gapless metal-oxide arresters have replaced the earlier generation of gapped silicon carbide (SiC) arresters. Despite this, a large number of gapped SiC-arresters still remain in service all over the world. Most of them are now more than 25 years old and rapidly approaching the end of both their economical as well as physical lifetime.

H.2 Design and operation of SiC-arresters

The internal design of SiC-arresters was much more complex than that of today's gapless ZnO-arresters. There were basically two different designs of the gaps, passive or active gaps. The active gaps could take up higher energies achieved by magnetically moving the arc away from the sparkover point, in order to be as long as possible so that resealing started before the zero-passage of the power frequency current. The magnetic forces came from inductances in series with the gaps. Active gap designs were typically used for all EHV installations, for long transmission lines and capacitor banks used at lower system voltages. Passive gaps were typically using a design of simple electrode plates. All SiC-arresters did have to reseal at the first zero passage of the power frequency current otherwise, the gaps could never reseal, and the arrester would be short-circuited.

The continuous service voltage was taken up by the gaps, as the SiC varistors could not withstand it. The SiC arresters are designed so that if one small gap sparked over, the sparkover of the remaining gaps would follow. The sparkover voltage is usually a few kV per gap. Hence, grading components were used in order to ensure good voltage grading across the individual gaps inside the gap stacks as well as for achieving a uniform voltage distribution along the total height of multi-unit arresters. The grading components were typically small SiC-resistors and ceramic capacitors.

There was also a limitation in voltage stress across the internal components so that for high-voltage arresters the internal stack had to be built in a zigzag pattern, in order to reduce the arrester height. This, then, led to significantly larger diameter porcelains, compared to those used for ZnO-arresters, especially for EHV arresters. A typical internal SiC-stack with active gaps is shown in Figure H.1. The internal stacks were then put in porcelain housings with flanges, sealed with special gaskets. In order to avoid corrosion on the electrodes of the gaps each porcelain unit was sealed off with a closed inert atmosphere, mostly dry nitrogen although some designs used dry air.

H.3 Failure causes and aging phenomena

H.3.1 General

There are many potential causes for possible malfunction and/or failure because of the number of components used for these arresters.

H.3.2 Sealing problems

This has been the most common failure reason for SiC arresters, a typical construction of which is illustrated in Figure H.1. Not only do gaskets/seals become brittle and aged over time, but also the whole sealing system was not designed for more than 20 to 30 years lifetime depending on the flange design. Following moisture ingress, the arrester fails due to internal corona and tracking.

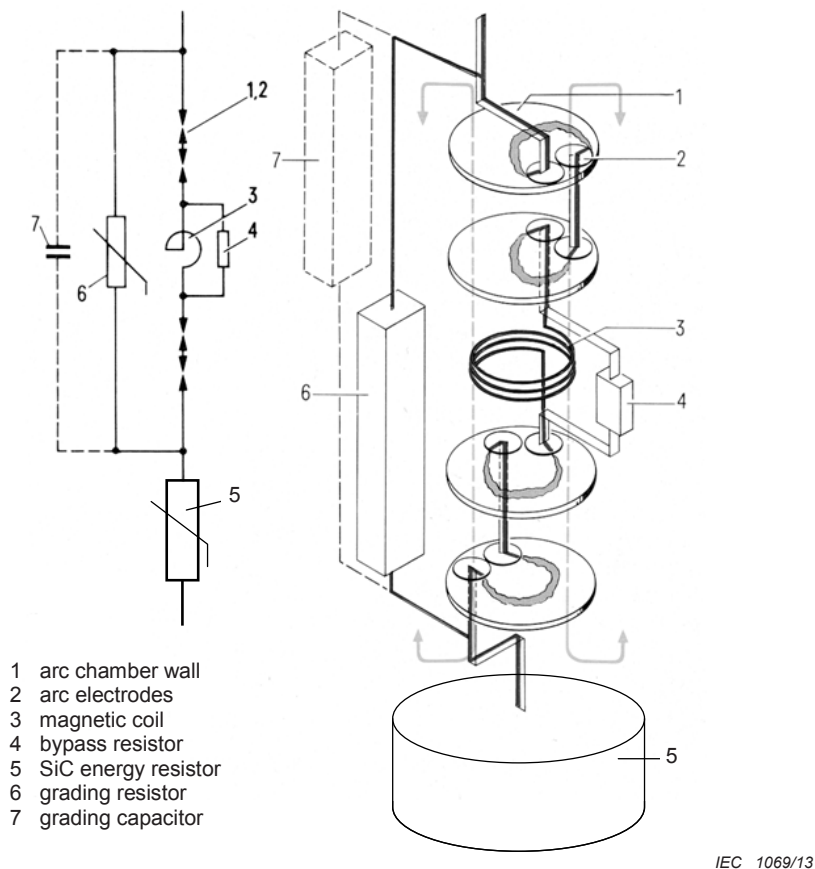


Figure H.1 – Internal SiC-arrester stack

H.3.3 Equalization of internal and external pressure and atmosphere

Even if the gaskets operate well, just by diffusion, the internal gas will escape after some 25 years. Moisture ingress by diffusion of oxygen and humidity will contaminate or change the original atmosphere and cause internal corona and tracking which may lead to sparkover for TOV or even at operating voltage. This, in turn, results in arrester failure, as the gaps will never be able to reseal.

Some arrester designs were also filled with a slight overpressure in order to facilitate leakage detection. If the actual outer air pressure is different from the originally filled, equalization of pressure may lead to internal corona affecting operation of the arrester and/or diminish the protection margins for the equipment. For operation at high altitudes, the arresters are designed and constructed with a lower internal pressure at the manufacturing stage.

H.3.4 Gap electrode erosion

This is a dangerous phenomenon as this may cause the sparkover voltage of the arrester to either increase or decrease. Therefore, even if the arrester does not actually fail, it may no longer ensure the adequate protective margins as it did originally.

Electrode erosion can have two causes; firstly, the number of arrester operations alone may change the electrode performance. Typically, a gapped arrester should not see more than 50-100 sparkover with significant surge currents involved. Secondly, since the sealing system will allow change of internal atmosphere in 20 to 25 years for these arresters; after which humidity may start to corrode the electrodes, and this is expected to influence all SiC-arresters after the expected lifetime.

H.3.5 Ageing of grading components

The characteristics of both grading resistors and grading capacitors change over time, leading to possible changes of the sparkover voltage. Sparkover voltage may either increase or decrease, causing the same risks as for electrode erosion. Field experience has shown that direct failures are more likely to occur on the grading capacitors than on the grading resistors. However, ageing was observed for both types of grading elements. When these arresters were designed, there was no requirement of any ageing test of the grading components, which all are under the continuous voltage stress of the service voltage (equivalent of U_c today). Very few of these components would pass today's 1 000 hours ageing test used for ZnO-blocks without change of characteristics.

H.3.6 Changed system conditions

Changed system conditions will influence the performance of SiC-arresters. Typical changes that do influence them are installation of capacitor banks and/or line expansion. In general, SiC-arresters do not have a good performance for energy discharges from capacitor banks. As a result, the gaps must be able to reseal which they can only achieve at zero power frequency current. As a consequence of the discharge, they will take both the whole energy from the capacitor discharge as well as the follow current from the service voltage. Furthermore, their energy capability for capacitor discharges is significantly lower than that of ZnO-arresters, which is further limited in high energy applications since SiC-arresters cannot share any energy between them. Expanding and/or strengthening the system may increase the short-circuit current of the system beyond the original arrester requirement and capability. Line extension will increase the line discharge energy from line switching, and may demand a higher IEC line discharge class than was originally specified.

H.3.7 Increased pollution levels

The characteristics that sparkover of one of the small gaps triggered a total sparkover of the arrester made them very sensitive to pollution events as the scintillations on the porcelain surface could easily trigger the sparkover of one internal gap. Therefore, an increase of industrial pollution or use of fertilizers in farming area, presents a potentially high risk of arrester failures.

H.4 Possibility to check the status of the arresters

Permanent monitoring is not a reasonable approach. In general, monitoring schemes are not economically viable. Costs for monitoring procedures can easily be higher than upgrading to new ZnO arresters. In addition, when the arresters have been in-service for over 20 years, replacement will still be needed in the near future

If checking of the arresters is decided upon the recommended procedures is to check some arresters from a population and make a decision from the test result. Power-frequency voltage sparkover tests are recommended as a minimum. The arresters should be opened to check the status of grading component and gaps and traces for sealing problems. A replacement plan is made based on the investigation. The arresters tested must not be returned to the field. Cost for investigations should be compared with replacement costs and the importance and number of the old arresters considered.

Strategy could include make, type, manufacturing year, importance of installation, consequence of a failure.

H.5 Advantages of planning replacements ahead

H.5.1 General

A well-planned replacement programme gives many advantages.

H.5.2 Improved reliability

Lower protection levels with ZnO-arresters, which gives better safety margins and/or increased protective distances. No steep overvoltage spikes from gap sparkover.

Minimising unplanned outages due to arrester malfunction.

H.5.3 Cost advantages

Prolonging lifetime of old transformers. Some utilities estimate this to be about 7 years longer lifetime.

Cost savings by avoiding emergency exchange of failed old arresters compared to planned replacements.

H.5.4 Increased safety requirements

Arresters are the first line of protection against system events of low probability for which the systems designed withstand capability is exceeded. They still protect the system from overvoltages but will see energies beyond their capability. In this case, the arrester will fail by an internal short-circuit. Arresters are designed to fail in a non-violent way verified by pressure relief or short-circuit tests as specified in the relevant IEC arrester standards. However, the requirements in these old standards for SiC-arresters were much less stringent than current IEC specifications, so old arresters may not function satisfactorily for all short-circuit currents. In particular very long units may represent a high risk. Beware that even today, this test is not mandatory as an arrester can be sold according to IEC 60099-4 but have no claimed short-circuit current capability. Note also that for some arresters manufactured before 1970, some arrester designs, especially for lower system voltages, were not provided with any pressure-relief mechanism for safe operations during an internal short-circuit. Such arresters will likely fail violently in the event of malfunction.

The design of arrester is however, such that there is;

- Less risk for personnel injury in the event of a catastrophic arrester failure;
- Less risk for damage to nearby equipment in the event of a catastrophic arrester failure.

H.6 Replacement issues

H.6.1 General

All old SiC-arresters cannot be exchanged at the same time, so it is important to prioritise the replacement in such a way that risks and planned outages are minimised. Whenever there is a planned maintenance outage at an older substation, it is advisable to check if there are any old type arresters that should be replaced.

H.6.2 Establishing replacement priority

The following priority replacement list may be used as guidance;

- Arresters without pressure relief
- All critical installations should be exchanged first. There have been cases when nuclear plants, which mostly were built during the SiC arrester-era, have been shut down due to failures of old SiC-arresters.
- Systems/lines where capacitor banks have been added afterwards, since the nearby arresters may not be dimensioned to handle actual capacitor discharges.
- Installation with very old arresters, since the statistical chance of a malfunction is higher for those.

- Systems/lines with changed operation conditions like new industrial pollution or longer lines.
- Installations with old equipment that, since new MO arresters can actually extend the lifetime of plant e.g. old transformers.

H.6.3 Selection of MO arresters for replacement installations

If specifications for gapless MO arresters exist for the actual system voltages, this should be used. Otherwise, for specific applications the following guidelines are helpful:

- **Selection of rated voltage:** Usually, the same rated voltage as for the SiC-arrester can be selected. The only exception might be for unearthed systems, having high TOV-requirements. In this case, a slightly higher rated voltage should be selected.
- **Selection of line discharge class:** Unless shunt banks have been added or the system has been extended, there is no need to change the line discharge class. Whenever system conditions have changed, a revised arrester specification is recommended.
- **Mechanical considerations:** Today's MO arresters will most likely be both shorter and have a smaller porcelain diameter and hence a smaller drilling plan than the old SiC-arresters. These larger diameter porcelain housings may have started already at 145 kV systems and above, due to the complexity of the internal structure. Manufacturing of adapter-plates in advance will facilitate to use existing drilling plans.

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