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INTERNATIONAL STANDARD

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inside

Surge arresters –
Part 5: Selection and application recommendations

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FOREWORD

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International Standard IEC 60099-5 has been prepared by IEC technical committee 37: Surge arresters.

This third edition cancels and replaces the second edition published in 2013. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition regarding the new surge arrester classification introduced in IEC 60099-4:2014:

a) Expanded discussion of comparison between the old and new classification and how to calculate or estimate the corresponding charge for different stresses.
b) New annexes dealing with:
   - Comparison between line discharge classes and charge classification
   - Estimation of arrester cumulative charges and energies during line switching

The text of this standard is based on the following documents:

FDIS	Report on voting
37/437/FDIS	37/439/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

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

A list of all parts in the IEC 60099 series, published under the general title *Surge arresters*, can be found on the IEC website.

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

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- withdrawn,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

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

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

SURGE ARRESTERS –

Part 5: Selection and application recommendations

1 Scope

This part of IEC 60099 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 J, some aspects regarding the old type of SiC gapped arresters are discussed.

Surge arrester residual voltage is a major parameter to which most users have paid a lot of attention to when selecting the type and rating. Typical maximum residual voltages are given in Annex F. It is likely, however, that for some systems, or in some countries, the requirements on system reliability and design are sufficiently uniform, so 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.

Annexes H and I present comparisons and calculations between old line discharge classification and new charge classification.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60071-1:2006, *Insulation co-ordination – Part 1: Definitions, principles and rules*
IEC 60071-1:2006/AMD1:2010

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

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

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

IEC 60099-4:2014, *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 ceramic and glass insulators to be used on a.c. systems*

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

IEC 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 definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

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 pad mounted 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 disconnector
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

Note 1 to entry: Electrical connection may be made by sliding contact or by bolted devices; however, all separable arresters are dead-break arresters.

Note 2 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, defined in 3.57, 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 μs to 20 μs, and tail duration < 300 μs

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
slightly different definitions are used in different IEC 60099 arrester standards; they are repeated here for reference:

IEC 60099-4, IEC 60099-6 & IEC 60099-9: peak value of discharge current having a 4/10 impulse shape which is used to test the stability of the arrester on direct lightning strokes

IEC 60099-8: 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

Note 1 to entry: 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

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 60099-4:2014, 8.3.3).

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
type of arrester that is applied to overhead lines of power systems to reduce the risk of insulator flashover during lightning overvoltages

Note 1 to entry: This 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
average breaking load for porcelain or cast resin-housed arresters determined from tests

3.37
metal-oxide surge arrester with gapped structures
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
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 disconnector 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 60099-4:2014

combination of the following:

a) residual voltage for steep current impulse according to 8.3.1 of IEC 60099-4:2014;

b) residual voltage versus discharge current characteristic for lightning impulses according to 8.3.2 of IEC 60099-4:2014

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 of IEC 60099-4:2014;

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

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 of IEC 60099-6:2002;

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 of IEC 60099-6:2002;

c) residual voltage for switching impulse and the switching impulse sparkover according to 7.3.3 and 8.3.8.2 of IEC 60099-6:2002

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

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 MO resistor area for single column arresters.

3.50
reference voltage of an arrester

U_ref

peak value of power-frequency voltage divided by √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
repetitive charge transfer rating

Q_rs

maximum specified charge transfer capability of an arrester, in the form of a single event or group of surges that may be transferred through an arrester without causing mechanical failure or unacceptable electrical degradation to the MO resistors

Note 1 to entry: The charge is calculated as the absolute value of current integrated over time. For the purpose of this standard this is the charge that is accumulated in a single event or group of surges lasting for not more than 2 s and which may be followed by a subsequent event at a time interval not shorter than 60 s.

3.52
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.

3.53
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

3.54
routine tests

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

3.55
self-restoring insulation
insulation which, after a short time, completely recovers its insulating properties after a disruptive discharge during test

3.56
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

3.57
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

3.58
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

3.59
shielding failure rate
SFR
characteristics of an overhead line with respect to the number of shielding failures typically given per 100 km and year

3.60
shunt gap
intentional gap(s), between spaced electrodes, that is electrically in parallel with one or more metal-oxide resistors

3.61
slow-front overvoltage
SFO
transient overvoltage usually unidirectional, with time to peak between 20 μs to 5 000 μs, and tail duration $\leq$ 20 ms

3.62
sparkover of an arrester
disruptive discharge between the electrodes of the gaps of an arrester

3.63
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

3.64
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.

3.65

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 no longer than 20 µs

3.66

surface current of SVU

current that flows on the surface of the SVU

3.67

switching impulse withstand voltage

SIWV

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

3.68

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

3.69

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.

3.70

terminal line force

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

3.71

thermal charge transfer rating

Q_{th}

maximum specified charge that may be transferred through an arrester or arrester section within 3 minutes in a thermal recovery test without causing a thermal runaway

Note 1 to entry: This rating is verified by the operating duty type test.

3.72

thermal energy rating

W_{th}

maximum specified energy, given in kJ/kV of U_{r}, that may be injected into an arrester or arrester section within 3 minutes in a thermal recovery test without causing a thermal runaway

Note 1 to entry: This rating is verified by the operating duty type test.

3.73

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

3.74
thermal stability of an arrester
state of an arrester 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

3.75
time to sparkover of an arrester
the time interval between virtual origin and the instant of sparkover of the arrester expressed in microseconds

3.76
torsional loading
each horizontal force at the top of a vertically mounted arrester housing which is not applied to the longitudinal axis of the arrester

3.77
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.

3.78
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.

3.79
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

3.80
very-fast-front overvoltage
VFFO
transient overvoltage usually unidirectional, with time to peak $\leq$ 0,1 μs, and with or without superimposed oscillations at frequency 30 kHz $< f <$ 100 MHz

4 General principles for the application of surge arresters

The principle of insulation coordination for an electricity system is given in IEC 60071-1 and IEC 60071-2. Basically the insulation coordination process represents 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 arresters helps to achieve a system and equipment insulation level while still maintaining an acceptable risk and the best economy 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 equipment and surge arresters.

IEC 60071-1 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 800 kV

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 60071-1):

- 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

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

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 about 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 former 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. These 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 [19][20][22][23][24][26][27][38][39][40][55][56].

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, 1 200 kV) [21][23]. 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.

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 (SF_6) at high operating pressures. Furthermore, there exist some other very specific housing technologies for distribution applications.

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

- SiC surge arresters with internal series gaps, porcelain-housed: IEC 60099-1 (withdrawn 2013);
- MO surge arresters without gaps, all housing technologies: IEC 60099-4;

- MO distribution surge arresters of 52 kV rated voltage or less, with internal series gaps, porcelain or polymer-housed: IEC 60099-6;
- externally gapped line arresters (EGLA) for application in distribution or transmission overhead lines, porcelain or polymer-housed: IEC 60099-8;
- Metal-oxide surge arresters without gaps for HVDC converter substations: IEC 60099-9.

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 J 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.

The active part of a gapless 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).

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 5.2.2.2, 5.2.2.3, 5.2.2.4, 5.2.2.5 and 5.2.2.6.

5.2.2.2 Porcelain-housed arresters

The gap between the active part of stacked MO resistors 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. SF_6, are used it should be checked that all relevant tests as per IEC 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 shall 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 60071-1:2010 (Tables 2 and 3) 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 = 1,1 × $e^{m\times 1\,000/8\,150}$ times the switching impulse protection level (U_{ps}) of the arrester for substation class arresters for use in systems of $U_{\mathrm{s}} > 245$ kV, where $m = 1$ in case of 245 kV $< U_{\mathrm{s}} \leq$ 800 kV, and in case of $U_{\mathrm{s}} >$ 800 kV m is taken from IEC 60071-2:1996, Figure 9, phase-to-earth insulation, with the value on the abscissa being 1,1 times the switching impulse protection level (U_{ps}) of the arrester
- PFWV (peak value) = 1,06 times the switching impulse protection level (U_{ps}) of the arrester for substation class arresters for use in systems of $U_{\mathrm{s}} \leq 245$ kV
- PFWV (peak value) = 0,88 times the lightning impulse protection level (U_{pl}) of the arrester for distribution class arresters.

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 lightning impulse protection level U_{pl} = 825 kV

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

- required LIWV for surge arrester housing: LIWV = 1,3 × 825 kV = 1 073 kV
- required SIWV for surge arrester housing: SIWV = 1,24 × 700 kV = 868 kV

Often users are not aware of this special situation for surge arresters and would require the standard values of IEC 60071-1:2010 (Tables 2 and 3). This leads to unnecessarily tall arrester housings, which is not only a problem of geometrical dimensions but also results in an adverse axial voltage distribution and possibly in 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.

Limit of unit length is not only given by mechanical and electrical reasons but also for manufacturing or transportation reasons. Therefore, the length of a single arrester unit usually is limited to less than two meters. Arresters for system voltages higher than 245 kV usually comprise more than one unit in series. Beginning from a length of about 1,5 m to 2 m, external grading rings may 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 substation layout perspective they shall not be omitted during installation, because the arrester might then fail within short time by a thermal runaway (i.e. electrical power losses exceed thermal heat dissipation capability).

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 applied 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 preimpregnated 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. 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. 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 ≥ 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. Many cases will still 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-propylene-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 substation layout, e.g. in case of extremely low clearances to neighbouring 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 of IEC 60099-4:2014.

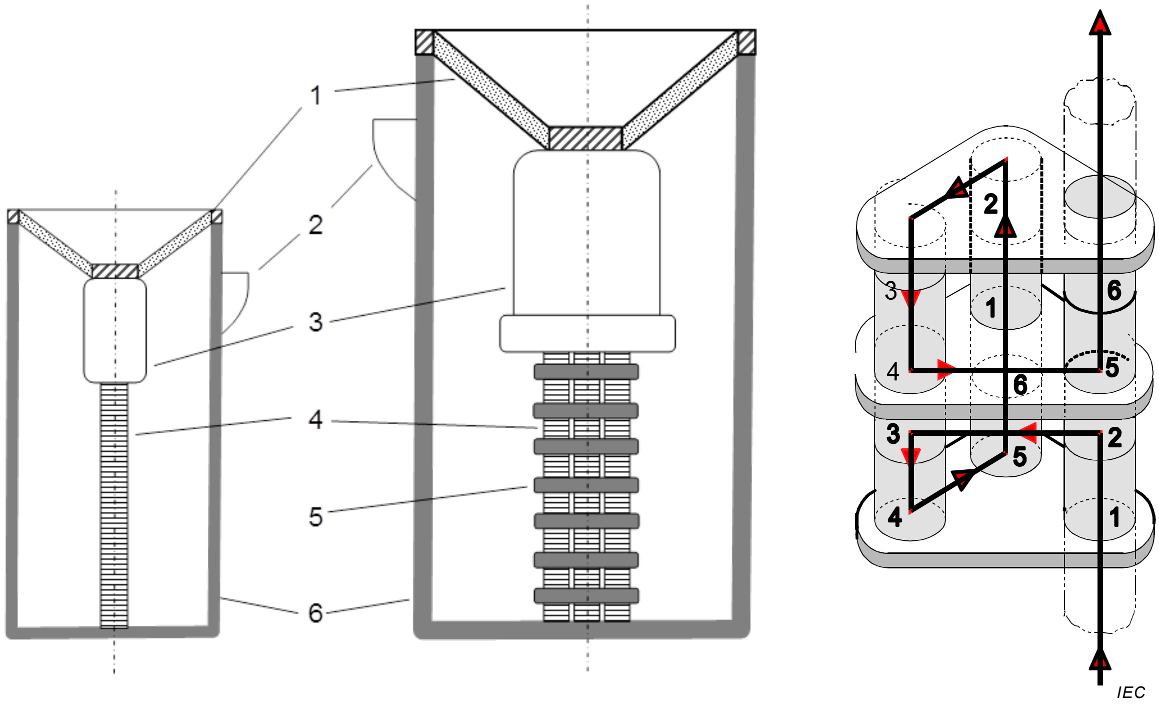
Recent developments have been that, even for EHV systems, arresters of mechanical and electrical single column design are used, which make use of high voltage gradient MO resistors (i.e. MO resistors of more "volts per millimetre length"), and UHV arresters with extremely low protection levels by connecting 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 quite similar to those for AIS arresters (LIWV = 1,3 times U_{pl}, SIWV = 1,25 times U_{ps}, PFWV = 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, also phase-to-phase withstand voltages are important.

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 μH/m length is assumed, while the value for AIS arresters is 1 μH/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 IEC 62271-203 and if it has no additional internal pressure relief system, no short-circuit test needs to be performed during type tests. Otherwise, the internal pressure relief system shall be tested in a short-circuit test.

Special care shall 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 shall be removed during these tests, or the integrated disconnectors, which are incorporated in some arrester designs, shall be opened [50][51][52].



Key

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

Figure 1 – Example of 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)

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 are used. 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 means that the power system shall 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 and common in the USA, always have shielded housings, as shown in Figure 2. They are usually installed in underground and pad mounted distribution equipment and circuits, and they are often of the load-break type, i.e. they can be installed and removed under voltage.

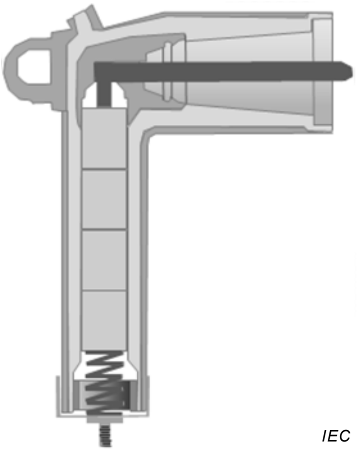


Figure 2 – Typical deadfront arrester

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 60071-1 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 60099-4:2014).

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 IEC 60099-4, 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 E of IEC 60099-4:2014 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 13.8.10 of IEC 60099-4:2014). [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. For given continuous operating and rated voltages, different types of arresters, and therefore different protection levels, exist. Further characteristics, which have to be considered are impulse and thermal energy handling capability rated short-circuit current and pollution withstand capability. Mechanical characteristic data are the specified long-term load and the specified short-term load.

With the publication of edition 3 of IEC 60099-4 in 2014 a transition was performed from the line discharge class system towards a purely charge and energy based classification system in terms of repetitive charge transfer rating and thermal energy or charge transfer rating. This application guide addresses these new approaches. However, Annex H of this application guide and Annex L of IEC 60099-4:2014 give information how to convert from the former line discharge classification to the new charge and energy classification. This may help users who have been familiar with the old system to adopt the new approaches.

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, and is normally (1.05 x system voltage/√3) in solidly earthed neutral systems. This is the recommended minimum value of U_c. Higher values may be adopted (e.g. for achieving better operation stability in case of severe pollution conditions), but for the price of increased protection levels. In isolated, impedance earthed or compensated neutral systems the arresters’ U_c should be at least the same as the highest system voltage, U_s.

5.2.2.7.3 Rated voltage, U_r

The rated voltage U_r is the power frequency voltage that is applied in the operating duty test for 10 s. It represents the minimum 10 s temporary overvoltage capability of the arrester after injection of rated thermal energy or charge. It is often used as a reference parameter to establish arrester characteristics.

Standard rated voltages are defined in steps of 1,3, 6, 12, 18, or 24 kV according to IEC 60099-4:2014. Other values may be accepted.

5.2.2.7.4 Nominal discharge current, I_n

The nominal discharge current I_n is used for the surge arrester classification. Four standard nominal discharge currents exist according to IEC 60099-4:2014, Table 1, with an increasing number indicating increased duties and requirements (2,5 kA, 5 kA, 10 kA, 20 kA). The nominal discharge current is the main parameter for the protective characteristics and the classification of the arrester. Its choice has also an impact on the whole procedure of insulation coordination, because the lightning impulse protection level (U_{pl}) of an arrester is specified as its residual voltage during discharge of a current equal to I_n.

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 Repetitive charge transfer rating, Q_{rs}

This characteristic quantity was introduced in IEC 60099-4:2014. It replaces, together with a second characteristic quantity (either W_{th} or Q_{th}, see 5.2.2.7.7), the line discharge class of an arrester, which had been in use so far. Charge has been chosen as a typical characteristic parameter for the purpose of better comparison between different makes of MO resistors. The repetitive charge transfer rating is related to a certain very low failure probability and is thus not a deterministic but a statistical value.

Repetitive charge transfer capability, given in C (Coulomb), is specified as an impulse current stress that can be withstood by the MO resistors of an arrester twenty times without mechanical or unacceptable electrical damage. One impulse current stress is considered to represent a charge transfer event that may occur under real system conditions. The charge, according to definition 3.51, may be accumulated in a single event or group of surges lasting for not more than 2 s, and which may be followed by a subsequent event at a time interval not shorter than 60 s.

An arrester shall be assigned a Q_{rs} value from a list given in 8.5.4 of IEC 60099-4:2014. Other requirements may apply for different types of arresters such as NGLA and EGLA.

5.2.2.7.7 Thermal energy rating, W_{th}, and thermal charge transfer rating, Q_{th}

These ratings were introduced in IEC 60099-4:2014. They replace, together with the repetitive charge transfer rating (Q_{rs}, see 5.2.2.7.6) the line discharge classes of substation class arresters, which had been in use so far, or are used to classify distribution class arresters, respectively.

A substation class arrester shall be assigned a W_{th} value from a list given in 8.7.3 of IEC 60099-4:2014. This value, given in kJ/kV of rated voltage, is used to specify the thermal energy handling capability of substation class arresters. It is the (specific) energy that has to be injected by any number of individual current impulses within a period of three minutes in the operating duty test.

A distribution class arrester shall be assigned a Q_{th} value from Table 5 in 8.7.3 of IEC 60099-4:2014. This value given in C, is used to specify the charge that can be transferred by a distribution class arrester without becoming thermally unstable at U_{c}. It is the charge, which has to be transferred during the operating duty test in the form of two 8/20 lightning current impulses.

5.2.2.7.8 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.

Since publication of IEC 60099-4:2014 it is required that every arrester shall have a short-circuit rating. Only for applications with expected short-circuit currents below 1 kA the rated value “zero” may be claimed. In this case “0” shall be indicated on the name plate, but the arrester must still pass a short-circuit test. In this case amplitude and duration shall be agreed between user and manufacturer.

Users should be aware that short-circuit testing according to IEC 60099-4:2014 does not address the ability of a failed arrester to withstand subsequent reclosing events.

5.2.2.7.9 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 test procedure for multi-unit porcelain-housed arresters is given in Annex C of IEC 60099-4:2014. 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 MO resistor elements or to the internal mounting elements. No related test procedure exists so far [42].

5.2.2.7.10 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 have to be demonstrated in a “weather aging test”. This test is a 1 000 hours salt fog test with permanent exposure to salt fog of a given salt mass concentration under applied continuous operating voltage. 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 from the radial field stress (puncture of the housing, effects of internal partial discharges) that may be imposed by the permanently changing potential distribution on the housing.

Resistance against solar UV radiation stress is verified by a separate material test.

5.2.2.7.11 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.

5.2.2.7.12 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 needs 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 AC distribution systems (rated voltages 52 kV and below), housed in either porcelain or polymeric housings.

5.2.3.2 Different types and designs

IEC 60099-6:2002 covers series gapped MO surge arresters. The internal series gap design (see Figure 3) has been in use since the late 1970s in Japan and USA. It combines the characteristics of the oldest arrester design component, a series gap, with the latest arrester design component, a MO resistor stack [18]. The MO resistor stack is similar to a standard MO arrester and has got roughly the same characteristics. 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 silicon 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 needs 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.

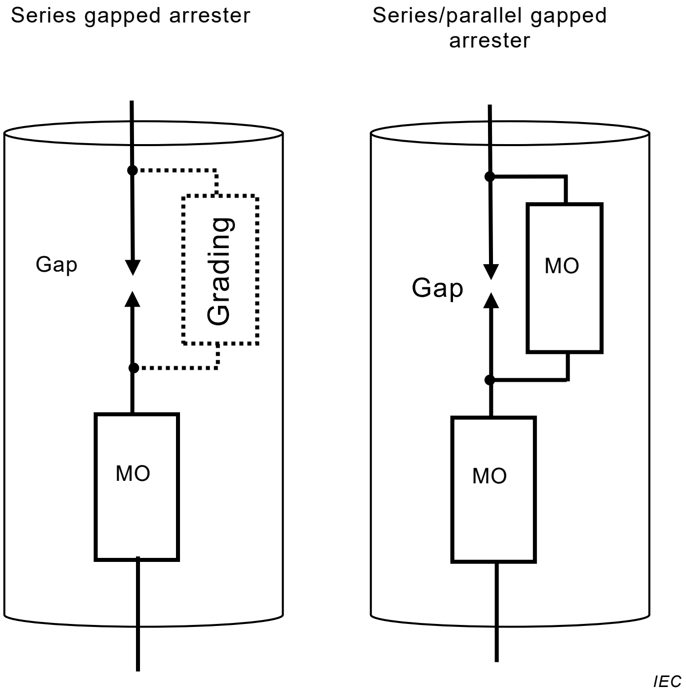


Figure 3 – Internally gapped metal-oxide surge arrester designs

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 (according to the former definition in IEC 60099-4, up to Edition 2.2 (2009), after which the line discharge class system was replaced by other approaches). 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. However, the test procedures are still in accordance with 60099-4:2009. A new revision of 60099-6, which is currently under work, will refer to the new requirements and test procedures of 60099-4:2014.

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 characteristic 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

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][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. 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 attach the electrodes of the EGLA's external gap across an insulator in series with the SVU, but this design is not covered by IEC 60099-8.

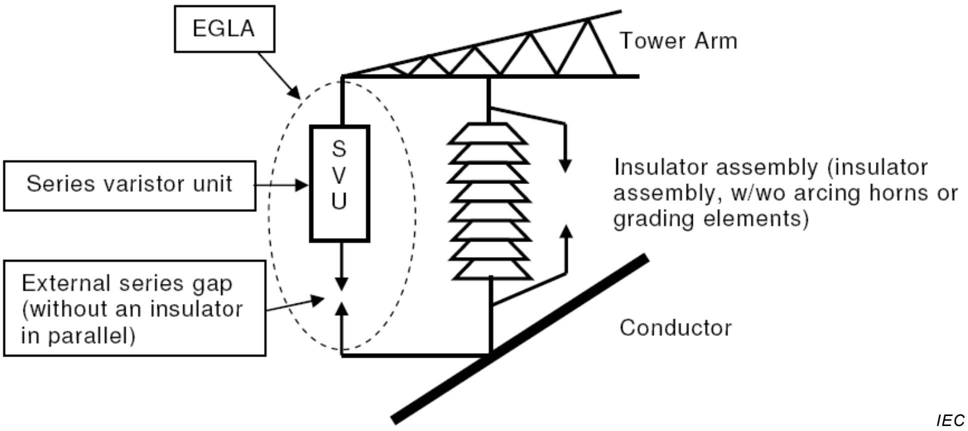


Figure 4 – Components of an EGLA acc. to IEC 60099-8

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 substation 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. Examples of such data are forces due to short-circuit current and line vibration.

The following sub clauses 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 H of IEC 60099-4:2014. The current wave shape is approximately sinusoidal with a time duration of 200 to 230 μs, which results in a current wave shape of about 90/200 μs. Eighteen impulses have to be applied 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 the charge transfer capability in C (this value must be shown 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 across 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 flashover 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 60815-1, "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, having a conductivity according to the specified SDD level.

"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 concession in the present standards should be noted carefulluy since many areas below transmission or distribution lines are open to the public.

Users should be aware that short-circuit testing according to IEC 60099-8 does not address the ability of a failed SVU of an EGLA to withstand subsequent reclosing events.

5.2.4.2.9 Mechanical performance

As for substation 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. The basic requirement is a number of one million oscillations of 1 × g at the SVU’s free end. It is also mentioned in a note that such a test should also be performed on the gap assembly.

5.2.5 Application considerations

5.2.5.1 General

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 be strictly followed. In particular, 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.

Grading rings or corona rings should not be omitted under any circumstances.

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

5.2.5.2 Connection leads

The national specifications and the requirements of the system user are in principle to be observed for the connections. The connecting lead cable and termination shall be adequately rated for the impulse duty associated with the rated short circuit current. The diameter of the connections shall be chosen in such a way that at least the short circuit current for the respective arrester (kA range for the given short circuit current duration of µs to s) 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 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 leads will see only a few mA of leakage current during steady state conditions. 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.

5.2.5.3 Inductive voltage drops

5.2.5.3.1 Connection leads and arrester height

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 kA/µs of a lightning current impulse can be expected. Under these conditions the inductive voltage drop shown in the arrangement of Figure 5 is:

$$U_{\mathrm{i}} = L \times \frac{di}{dt} = 10\ \mu\mathrm{H} \times 5\ \mathrm{kA/\mu s} = 50\ \mathrm{kV} \qquad (1)$$

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).

5.2.5.3.2 Separation distances

Due to their possible high rate-of-rise, travelling wave effects between arrester and equipment cannot be neglected for fast-front overvoltages (whereas they do not play a role for slow-front overvoltages within substations). Generally, fast-front overvoltages at the protected equipment are expected to be higher than the arrester residual voltage. The overvoltage at an open terminal or a terminal with a high surge impedance (such as a transformer terminal) 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 distances between arrester and major equipment. Maximum protection distances are typically only a few meters in distribution systems and several ten meters in high voltage systems. 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 substation and overhead lines are adequately shielded.

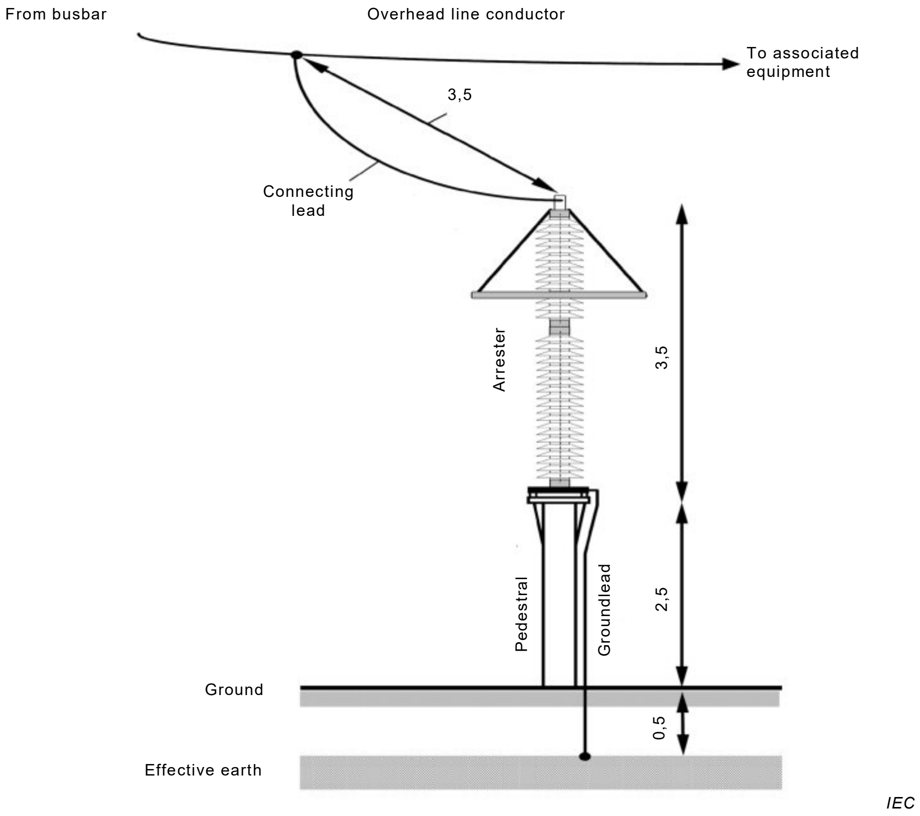


Figure 5 – Typical arrangement of a 420 kV arrester

5.2.5.4 High-voltage substation arresters

5.2.5.4.1 Installation considerations

Multi-unit high-voltage 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 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 60099-4:2014, Annex F.

In the case of an arrester with grading rings the manufacturer's declared minimum clearances to earthed or live parts measured 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 system volatges 550 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 6 shows examples of HV arresters equipped with grading and corona rings.

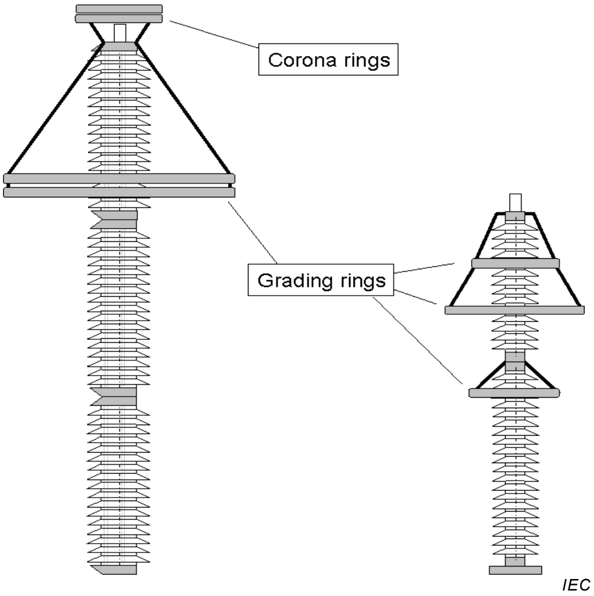


Figure 6 – Examples of UHV and HV arresters with grading and corona rings

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 oriented as on a pedestal. Figure 7 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.

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.

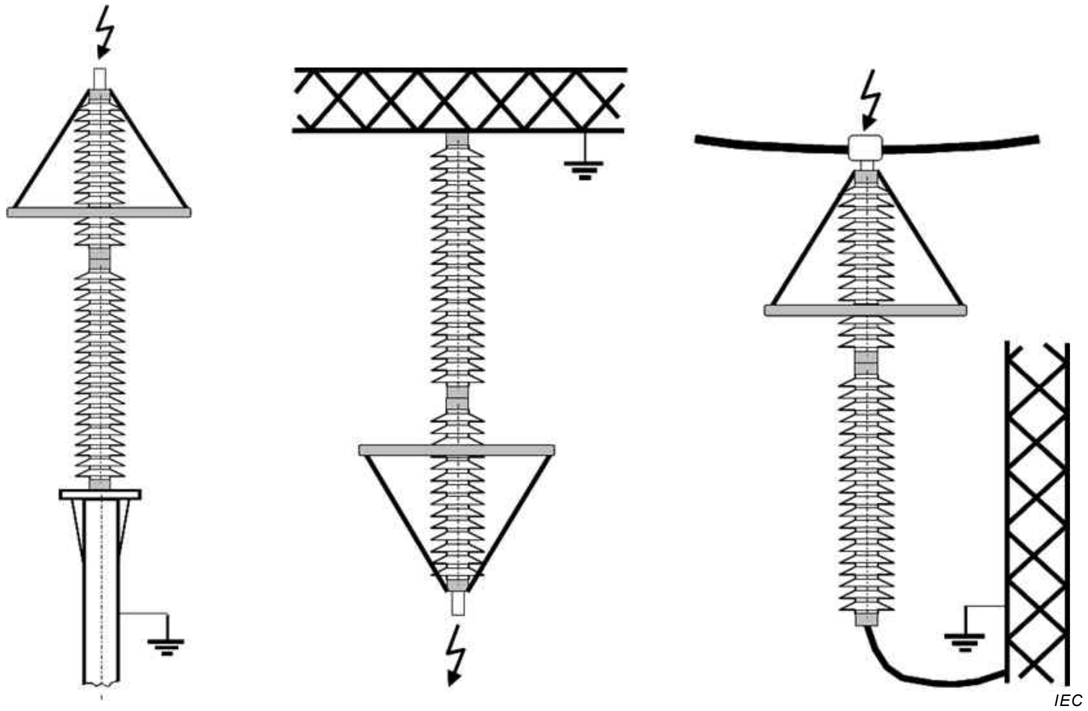


Figure 7 – Same type of arrester mounted on a pedestal (left), suspended from an earthed steel structure (middle) or suspended from a line conductor (right

If the arrester is 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.

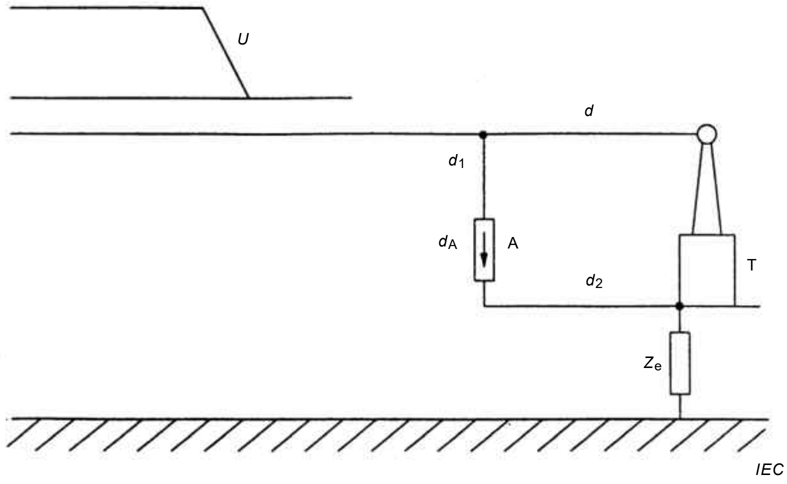
5.2.5.4.2 Earthing considerations

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 8 and Figure 9). 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. Figure 8 and Figure 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.

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 else where and introduce safety risks.

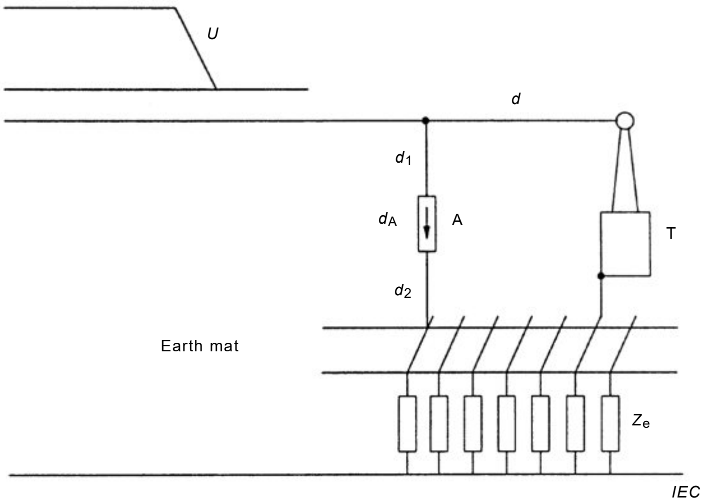
For inverted or under hung arresters the earth connection can be very long, with lengths over 20 m. This shall be taken into account when establishing the design protective margin.



Key

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

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



Key

U	incoming surge voltage	d_A	height of arrester
d	length of conductor between transformer bushing 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 earthing system 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 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.

5.2.5.4.3 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 F_{min} values in Table 1 can serve as a guideline for the necessary static head loads (F_{min} corresponds to SLL according to IEC 60099-4 – see Figure 10). 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, guidance for calculation is given in Clause G.5 of IEC 60099-4:2014.

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.

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 fixed ratio between dynamic and static load is specified in the standard IEC 60099-4:2014, special care should be taken when comparing catalogue values and technical data sheets. Figure 10 (from IEC 60099-4:2014) shows the different approaches for porcelain and cast resin housed as well as for polymer-housed arresters.

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

Highest system voltage U_{s} (kV)	$F_{\text{min, static}}$ **(N) ("SLL")**	$F_{\text{min, dynamic}}$ **(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

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.

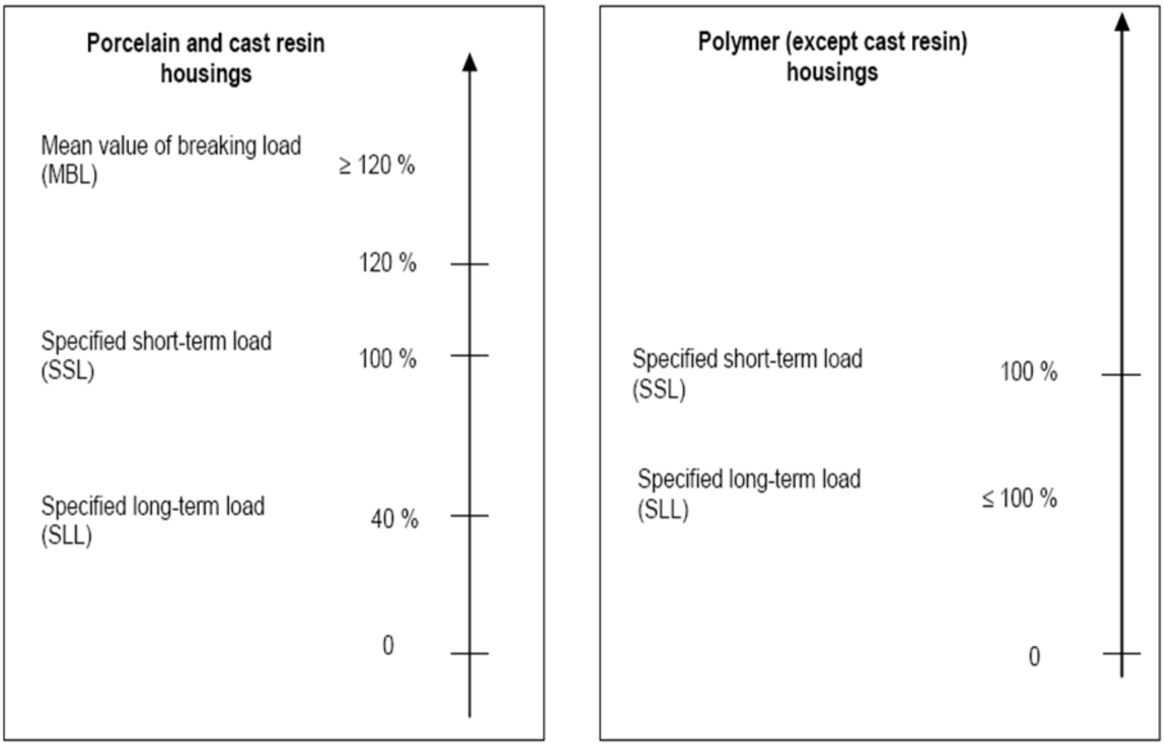


Figure 10 – Definition of mechanical loads according to IEC 60099-4:2014

5.2.5.4.4 Connection leads

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 substation and overhead lines are adequately shielded.

5.2.5.5 Distribution arresters

5.2.5.5.1 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), see Figure 11.

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 frequently inspect the line in order to replace the arresters that are out of order and were disconnected from the system as quickly as possible.

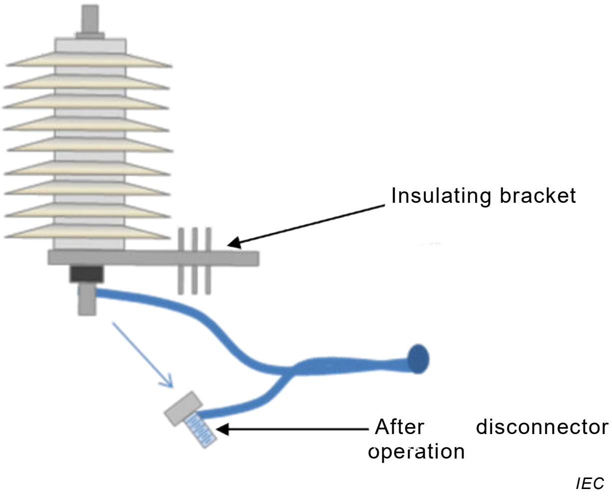


Figure 11 – Distribution arrester with disconnector and insulating bracket

Insulating brackets 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.

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 address this issue.

5.2.5.5.2 Earthing considerations

At distribution voltage levels ($U_s \leq 52$ 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).

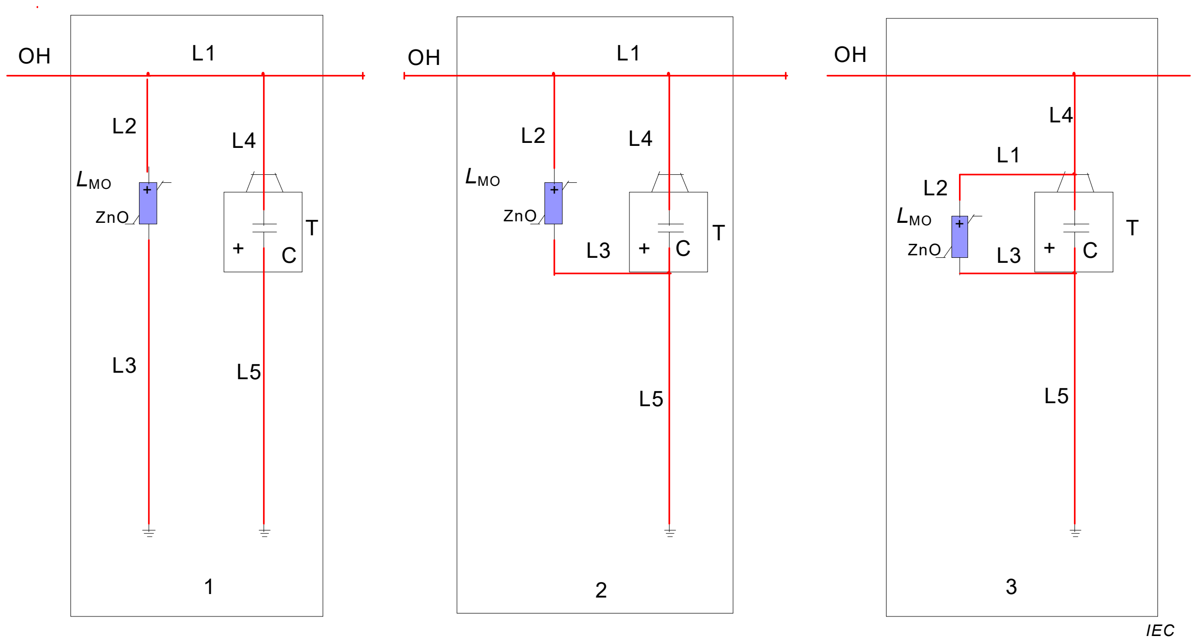
Low earth resistances is essential and should be as small as possible in order to limit the earth potential rise at the earth terminal, and hence mitigate safety hazards and flashover on the low voltage side of the transformer. A value of earth resistance $\leq 10\ \Omega$ is considered to be sufficient. 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.

5.2.5.5.3 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.

5.2.5.5.4 Connection leads

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-inductance 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 do not contain an inductive voltage drop corresponding to 1 μH/m of arrester length, then the arrester height must be considered.



Key:

1	Poor. The connection leads are too long and in (1) the transformer and arrester do not have the same earthing point. The loop L1 + L2 + L3 + L4 + L5 + L_{MO} is too long.
2	Good. Common earth of arrester and transformer, and the loop L1 + L2 + L3 + L4 + L_{MO} is much shorter than the loop L1 + L2 + L3 + L4 + L5 + L_{MO} in 1.
3	Very good. The arrester is earthed directly at the transformer tank. The loop L1 + L2 + L3 + L_{MO} is short. In this way, the inductances are kept to a minimum.
L1 – L5	length of connection leads
L_{MO}	height of arrester
OH	overhead line. Is assumed to be of infinite length before and after the transformer and arrester connection point.
C	internal capacitance of transformer
T	transformer

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

The additional inductive voltage is consequently calculated as:

$$U_\mathrm{i} = L \times \frac{di}{dt} \tag{2}$$

A voltage of U_i = 10 kV per meter of connection lead results from a steep current impulse with a rise time of 1µs 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 A 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 percent to avoid nuisance fuse blowing under normal arrester operation.

5.2.5.5.5 Liquid immersed arresters

Distribution transformers may be equipped with MO resistors installed within the transformer tank, giving optimized protection for such transformers. The primary drawback is that if the arrester fails due to lightning overload or any other reason, the whole transformer has to be replaced. Hence, the use of such arresters is more predominant in relatively low kVA single phase transformers.

5.2.5.6 Line surge arresters (LSA)

5.2.5.6.1 Installation considerations

LSA in transmission lines sometimes named TLA (transmission line arresters) 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 externally-gapped line arresters (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 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.

5.2.5.6.2 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 inductive voltage drop under fast-front overvoltages. NGLA usually have a disconnector in the earth lead. This is important when LSA are installed to protect line insulation with reduced withstand voltage, e.g. for increasing clearance of overhead conductors to ground or upgrading of existing systems.

5.2.5.6.3 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 is suspended at the cross-arm, the correct orientation of the weather sheds shall be regarded (see Figure 7).

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 concession in the present standards should be noted carefully since many areas below distribution or transmission lines are open to the public.

5.2.5.6.4 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 disconnector 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; transmission lines and substations. Line insulation coordination deals primarily with prevention of line faults from lightning and line switching operations, while substation coordination deals predominantly with protection of substation equipment from incoming lightning surges on lines and impact on local and remote equipment during substation switching operations. In modern insulation coordination practices, application of surge arresters is considered a fundamental and economical method of achieving the desired performance equipment protection and/or system [1][2][3][4][5][6][7][12][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 [84].

6.2.3 Overvoltages

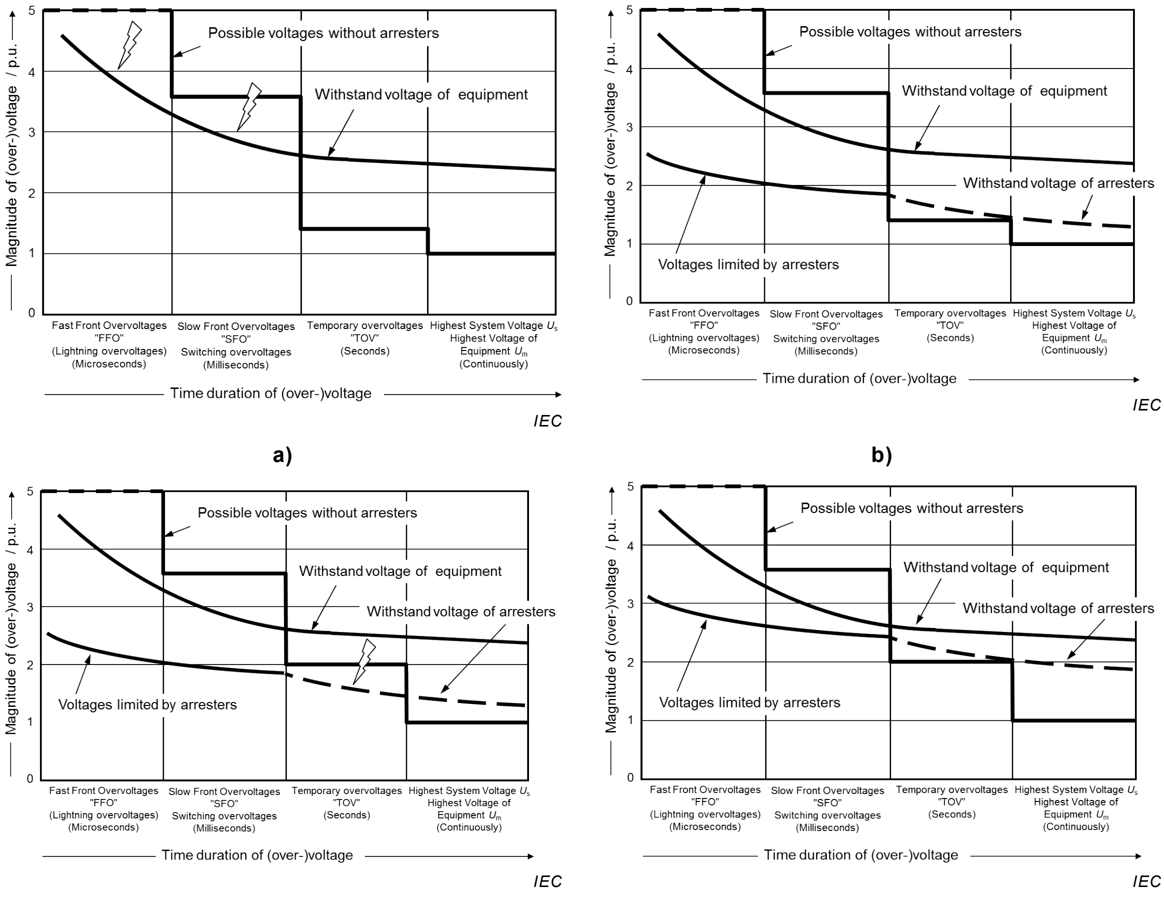
6.2.3.1 General

Overvoltages occur in power systems as a result of system disturbances such as faults, lightning strikes and of 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][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].

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.

A 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].



a)

b)

c)

d)

a) Example of a solidly earthed system without surge arrester application. Equipment withstand voltage is exceeded in SFO and FFO regions.

b) Example of a solidly earthed system with correctly dimensioned arresters. Arresters limit voltages in SFO and FFO regions to below equipment withstand voltages.

c) Example of an isolated neutral system with same arresters as before. Arresters provide same protection as before, but system overvoltages exceed arrester withstand voltages in TOV region (arrester will fail by TOV).

d) Example of an isolated neutral system with higher rated arresters. Arrester withstand voltages exceed system voltage in TOV region while still providing adequate protective margin to equipment in SFO and FFO regions.

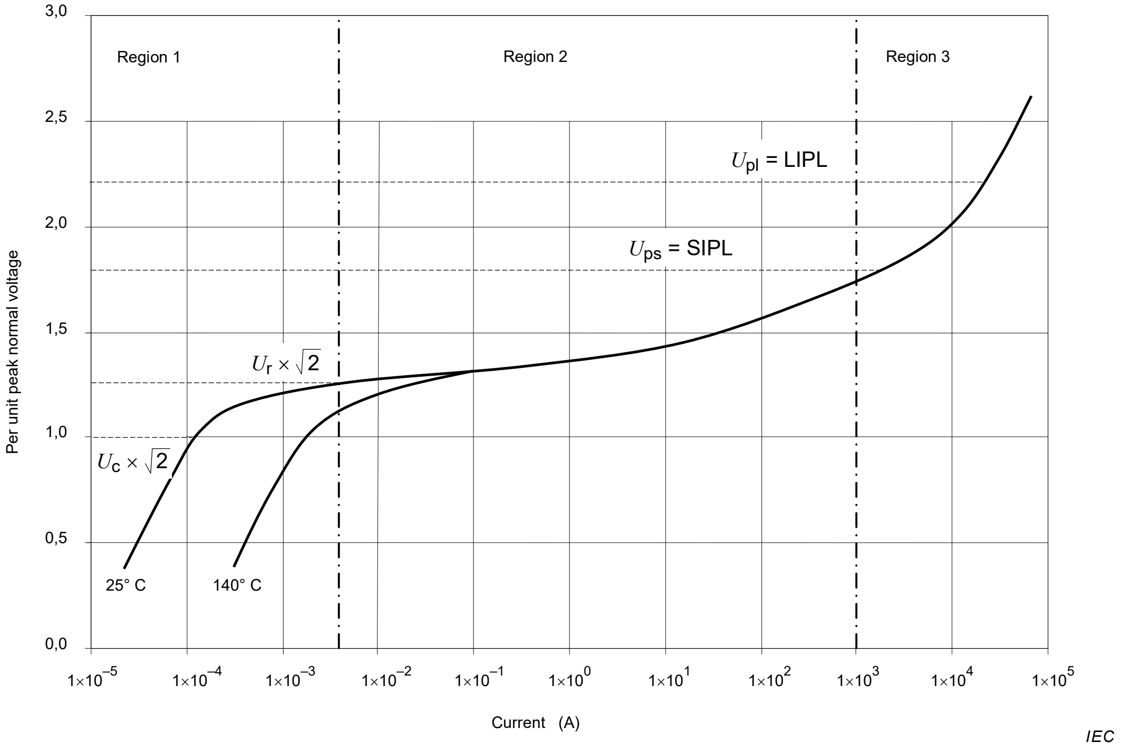
NOTE 1 p.u. = $\sqrt{2} \times U_s/\sqrt{3}$

Figure 13 – Typical voltages and duration example for differently earthed systems

Sources	**Typical p.u. Range** (1 p.u.=$\sqrt{2} \times U_s/\sqrt{3}$)	**Breaker RRRV** kV/μs
Temporary Overvoltages:		
• Single-Line-To-Earth Faults:		
Solidly Earthed Neutral System	1,3 to 1,4	
Isolated Neutral System	$\geq\sqrt{3}$	
Impedance Earthed Neutral System	up to 2,9	
• Load Rejection	1,2 to 1,5	
• Ferranti Effect:		
200 km line	1,02	
300 km line	1,10	
• Closing of Transformer Terminated Line	1,2 to 1,8	
Slow-front Overvoltages:		
• Line Energization		
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	
Shunt Capacitor Switching:		
• Earthed: breaker condition without restrike	1,7	
• Isolated:		
breaker with restrikes, no surge arrester	> 3,0	
breaker with restrikes, with surge arrester	~ 2 to 3[a]	
([a] specific overvoltages are dependent on arrester ratings and installation.)		
Circuit Breaker Transient Recovery Voltages (TRV) & Rate-of-Rise-of-Recovery Voltages (RRRV; kV/μs):		
• 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
• Fast-front Line surges Entering Substations:		
Unshielded Line	> 4,0	
Shielded lines	< 4,0	

IEC

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



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 1.05 x $U_s/\sqrt{3}$.

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=Ups: Arrester switching protective level i.e. the maximum residual level at the specified switching impulse currents.

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

Figure 15 – Arrester voltage-current characteristics

6.2.3.2 Very-fast-front overvoltages

Very-fast-front overvoltages, VFFO, with rise times below 0,1 µs are typically produced by disconnector operation or faults within gas insulated substations (GIS) due to the rapid breakdown of the SF_6 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.

VFFO are especially a concern for UHV GIS systems [81].

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 μs to 20 μs and tails as long as 300 μs.

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.

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 substation, except direct strikes which are usually prevented by shielding of the substation, more frequently will be determined by the strike distance on a line from the substation, since only a small percentage of surges generated by lightning strikes arrive at the substation with sufficient magnitudes and fast-fronts to cause problems. Other factors such as the substation 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 substation equipment [7].

Fast-front overvoltages may also occur during reactive equipment switching with short connections to the switchgear. Disconnector 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 μs 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, remote distance lightning strikes or transient overvoltages in case of earth faults.

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 [85].

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 [25]:

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 substations 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), where T_D is the keraunic level, expressed as thunder storm days per year. 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.

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

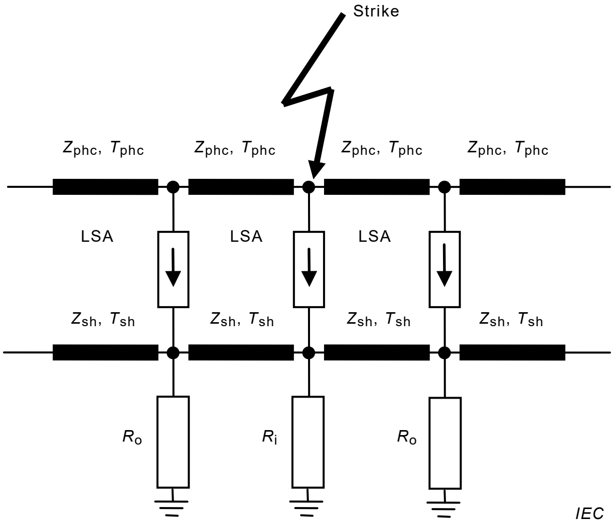
The effect of a flashover depends on protective relaying practices and in the case of wooden poles also on the possibility of arc quenching. Line performance evaluation can be done accounting for the benefits of line arrester installations. Factors to consider when evaluating lightning performance include 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 faults per 100 km per year) 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.



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

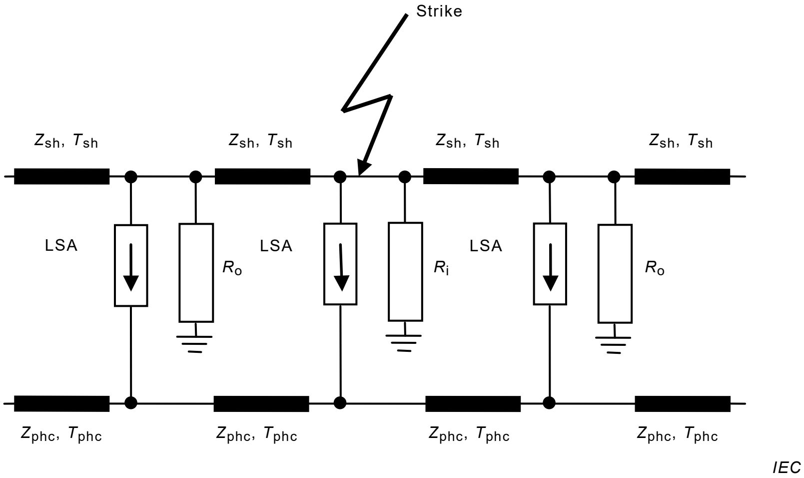
Since a surge from a lightning strike terminating somewhere along a span travel in two directions, LSA must be at both structures to prevent flashover. For this reason, it may be considered to install LSA at consecutive structures to be effective at addressing direct strike or shielding failure flashovers.

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.

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 lighting 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 60071-2:1996, Figure 7 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; 1996, Figure 8). 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.

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. [15][16][80][81][83][84][85].

6.2.5 Substation insulation coordination: Arrester application practices

6.2.5.1 General

Substation performance can be affected by both substation 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 substation equipment and the bus work. This is achieved by providing substation shielding. As an additional safety in case of shielding failure, surge arresters applied near important substation equipment will provide additional protection.
- Protection of substation equipment from incoming surges caused within the network. This is based on the line design, substation 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 the substation 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 substation shielding. It is usually feasible to provide shielding for the substation even though the associated lines are unshielded. Substation shielding reduces the probability of high voltages and steep wave fronts within the substation 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 substation. If the lines are shielded, the surges entering the substation 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 Substation 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 substation, 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 substation 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 substations, whereas masts are in normal use for low voltage, small-area substations. Shield wires usually provide better protection.

6.2.5.2.3 AIS substations; Incoming surges from lightning strikes on lines

Since substations are usually shielded from direct strikes to substation equipment, substation lightning performance depends primarily on the incoming surges from the lines [7]. The overall procedure is outlined as follows:

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 substation.
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 Um, highest voltage for equipment.
4) Evaluate Normal and Contingency Conditions: For substations 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 substation 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 substation is based on:

- the distance between the substation and the strike-terminating point,
- the magnitude of the strike current
- the initiating event – shielding failure or back flash.

In turn, the number of surges that arrive at the substation is a function of this distance and the back flashover 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 substation that just exceed the insulation strength, the mean time between failures of the equipment (MTBF) is 400 years.

For multi-line substations, the situation is more complex, since each line may bring a different number of surges into the substation. For substation 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 as all subsequent strikes will have a high probability off flashover. 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 between overhead line-cable terminal to apparatus, surge arrester protection may be required at both ends. This is more of an issue for lower voltage systems.

For short cable lengths between apparatus, the arresters that protect the apparatus is also protecting the cable.

The arresters are to be placed directly next to the cable ends. The connecting leads should be as short as possible. If the cable sheath is earthed the earth connection of the arrester has to be connected with as short lead as possible to the cable sheath.

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

If detailed insulation coordination studies are not available, it is recommended to put arresters at both ends for shorter cable lengths and at the overhead line-cable terminal for longer cables.

6.2.5.2.6 Arrester protection of gas insulated switchgear (GIS) substations

6.2.5.2.6.1 General

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 SF_6 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

SF_6 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 economical 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 substation arrangement and equipment design are possible means to reduce such risks [82].

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]:

- substation 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
- substation insulation strengths are described by LIWV for apparatus (transformers) or CFO for air clearances (bus)
- design value of the SSFOR for the substation 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 worst case conditions associated with the lightning or switching protection levels and the surge arrester energy handling capability [28].

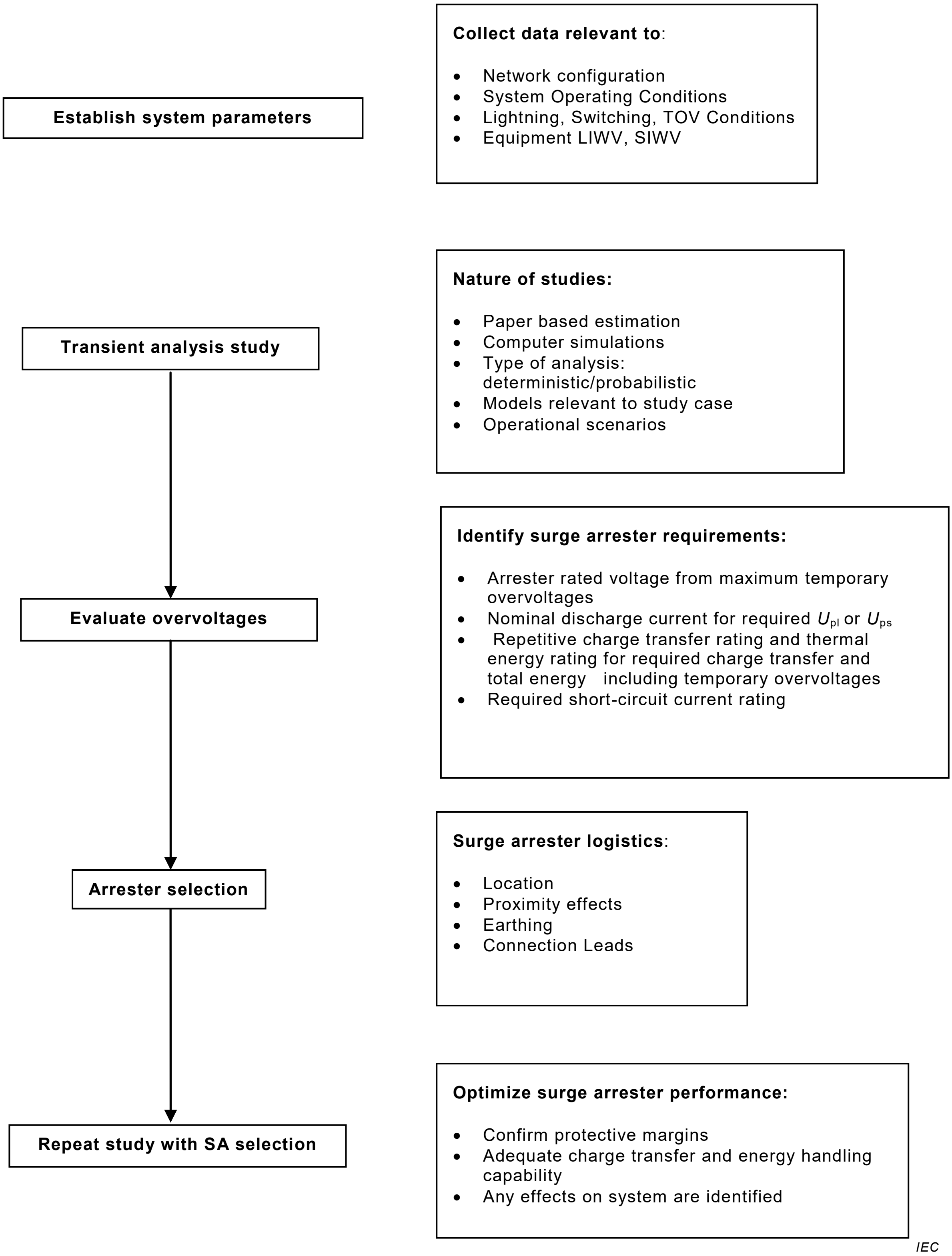


Figure 18 – Typical procedure for a surge arrester insulation coordination study

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 charge transfer and 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.

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 diagrams of Figure 19a and Figure 19b, 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 repetitive charge transfer rating and the thermal energy rating 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 repetitive charge transfer rating or thermal energy rating, 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.

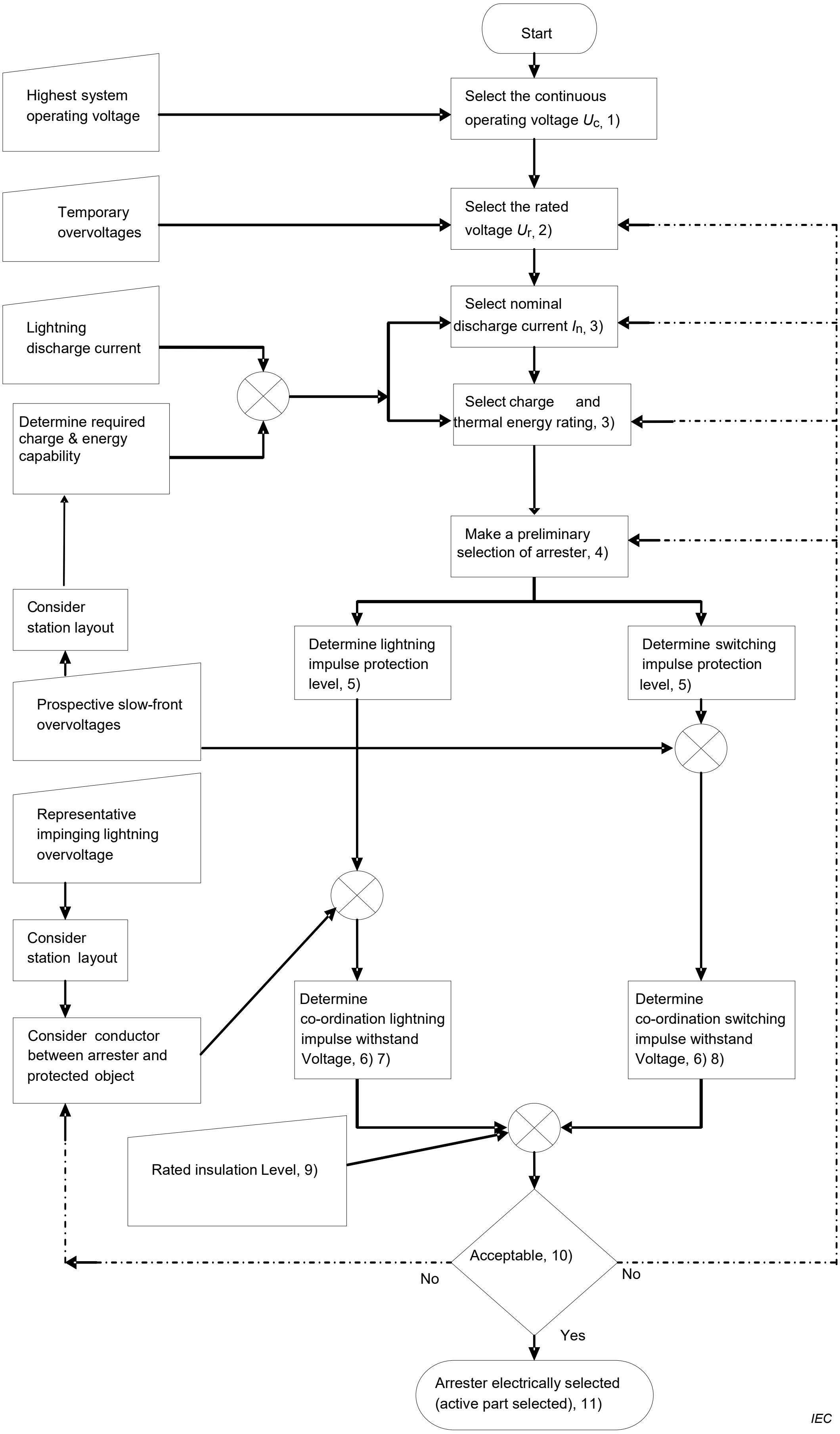


Figure 19a – Selection with respect to electrical data

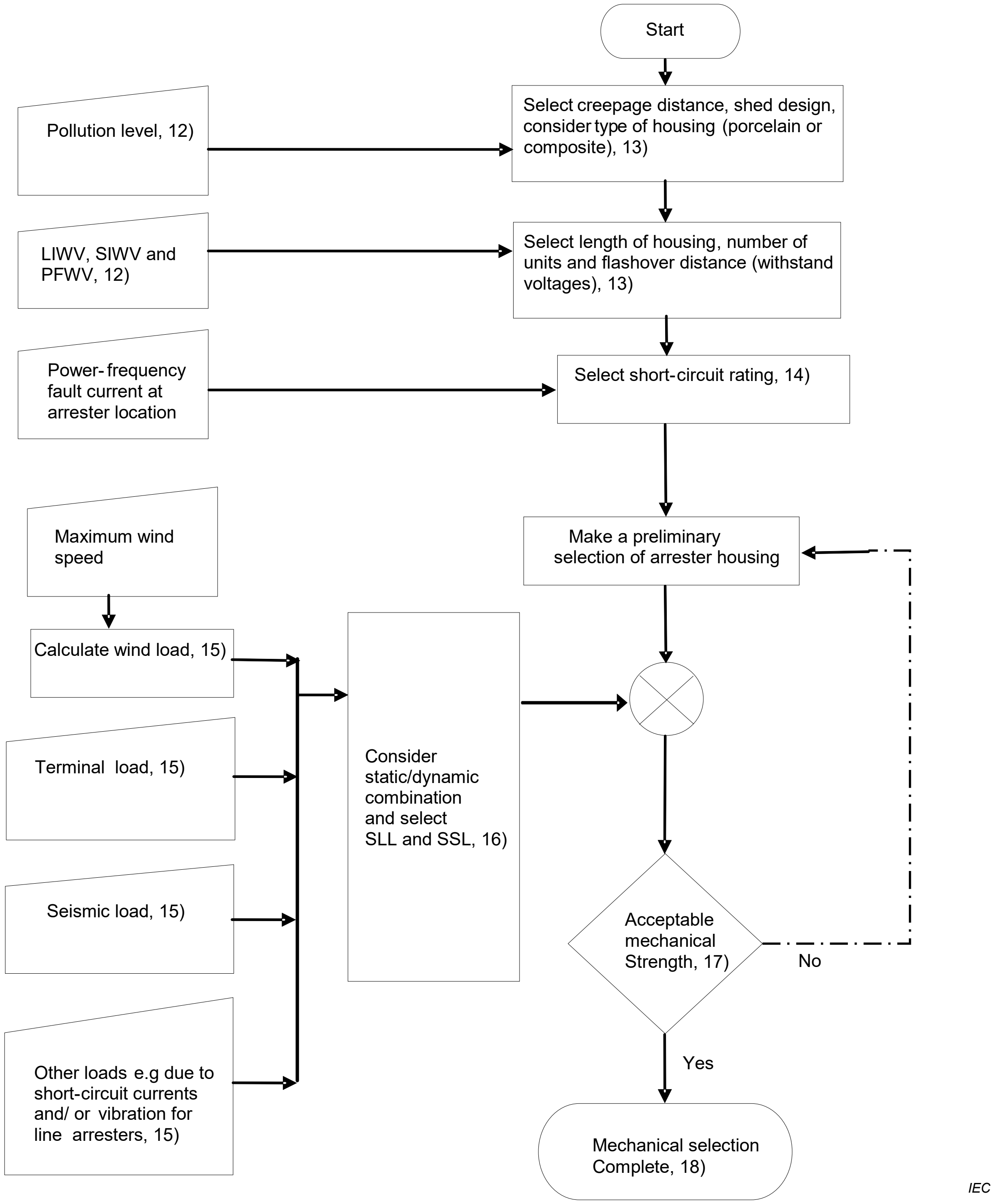


Figure 19b – Selection with respect to mechanical data

Figure 19 – Flow diagrams for standard selection of surge arrester

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

The continuous operating voltage U_c of the arrester 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 1,05 x $U_s/\sqrt{3}$.

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 continuous voltage U_c.

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. Therefore, manufacturers give curves for the TOV capability with and without prior duty.

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 Figure 20a and Figure 20b respectively. Note that the examples in this case are for the same arrester with a U_c equal to 0,8 × U_r.

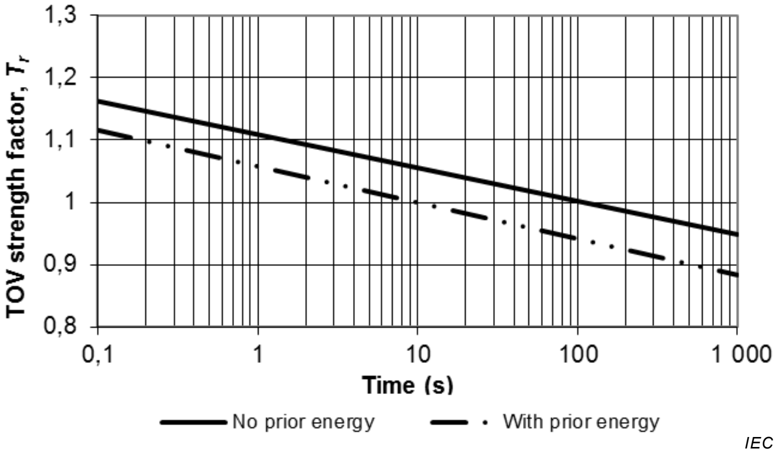


Figure 20a –Given as a factor of rated voltage, $T_r = U/U_r$

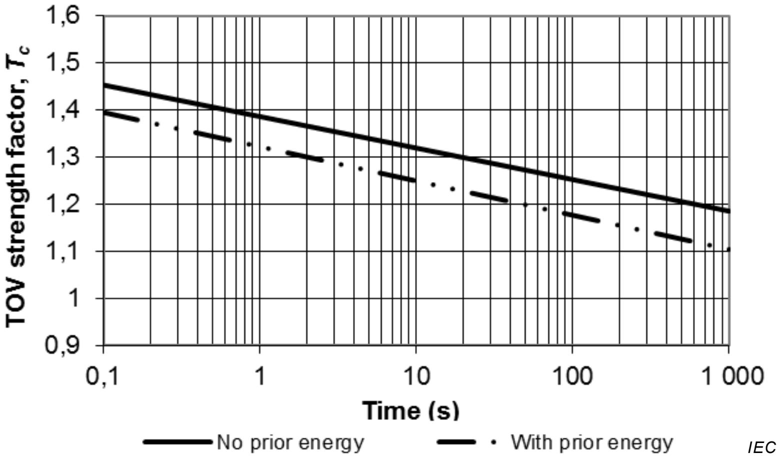


Figure 20b –Given as a factor of continuous operating voltage, $T_c = U/U_c$

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 × U_r.

Figure 20 – Examples of arrester TOV capability

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 $T_{\mathrm{c}} \times U_{\mathrm{c}}$ 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 charge transfer rating or thermal energy rating

The nominal discharge current has two different (though not independent of each other) purposes: It is a co-ordination current necessary for insulation co-ordination, and it is an arrester classifying current, to which a couple of other arrester characteristics are referring.

For insulation co-ordination, the nominal discharge current is an important parameter, because the lightning impulse protection level, U_{pl}, of an arrester is referring to I_{n} rather than to a certain current value. Using U_{pl} in the insulation co-ordination process is, therefore, based on the assumption of typically occurring lightning currents in the system. I_{s}, for instance, a value of 5 kA chosen as I_{n}, then U_{pl} is the arrester's residual voltage related to this current. But if the lightning currents are typically higher, e.g. 10 kA, U_{pl} is being assumed too low, because the arrester's residual voltage at these currents is higher than U_{pl}, and the insulation co-ordination procedure will be performed under too optimistic assumptions. Another example: If two arresters having the same U_{pl}, but one is of I_{n} = 5 kA and the other one of I_{n} = 10 kA, both arresters will have different UI-characteristics, and the arrester with the higher I_{n} value (i.e. a lower U_{I}-characteristic) will be energetically stressed more severely than its neighbor of the lower I_{n} value.

It should also be noted that arresters normally can withstand currents significantly higher than I_{n}. For instance, an arrester of I_{n} = 10 kA can be stressed with an 8/20 current impulse of 20 kA or even more without any risk of damage. It will just develop a residual voltage $U_{\mathrm{res}} > U_{\mathrm{pl}}$ under this condition.

Arresters in an electrical power system will be stressed by lightning currents originating from backflashovers and direct strikes to the line in front of the substation where the arrester is located. The current, which the arrester will discharge, depends on several parameters, e.g.:

- Degree of shielding of the line
- Line geometry
- Number and location of shield wires
- Insulation strength of the line
- Tower grounding
- Number of lines to the substation
- Arrester location at open line end or at a transformer

Assuming that the arrester is installed at an open line end the arrester current due to reflections of traveling waves will increase to a value that can be roughly estimated as follows:

$$I_{\mathrm{arrester}} = (2 \times U_{\mathrm{incoming}} - U_{\mathrm{pl}})/Z_{\mathrm{line}}. \tag{4}$$

where

U_{incoming} due to backflashovers is estimated to 1,2 × $U_{\mathrm{50positive}}$ and for shielding failure related overvoltages 1,2 × $U_{\mathrm{50negative}}$ of the line insulators [7]. These values of incoming surge amplitudes should in most cases be on the safe side but for a more accurate calculation of the amplitude of incoming waves the methods in [7] are recommended. Furthermore, the $U_{\mathrm{50\ negative}}$ is assumed to be 1.08 times the $U_{\mathrm{50\ positive}}$ [7].

Example for U_{s} = 420 kV (assumptions: insulator flashover distance = 3 m, U_{50} = 1.6 MV, Z_{line} = 350 Ω, U_{pl} = 800 kV):

$$I_{\text{arrester}} = (2 \times U_{\text{incoming}} - U_{\text{pl}})/Z_{\text{line}} = (3{,}84\ \text{MV} - 800\ \text{kV})/350\ \Omega = 8{,}7\ \text{kA}.$$

Example for U_s = 145 kV (assumptions: insulator flashover distance = 1,5 m, U_{50} = 800 kV, Z_{line} = 450 Ω, U_{pl} = 250 kV):

$$I_{\text{arrester}} = (2 \times U_{\text{incoming}} - U_{\text{pl}})/Z_{\text{line}} = (1.92\ \text{MV} - 250\ \text{kV})/450\ \Omega = 3{,}7\ \text{kA}.$$

The current through the arrester can exceed these values due to two reasons:

1) The arrester is installed in front of a transformer, and the capacitance of the transformer will increase the arrester current with approximately a factor of 1,6 [7] as per formula (4) below.

$$I_{\text{arrester}} = 1{,}6 \times (2 \times U_{\text{incoming}} - U_{\text{pl}})/Z_{\text{line}} \tag{5}$$

   This will give 13,9 and 5,9 kA for the 420 kV and 145 kV examples above.

2) If the shielding failure causes a flashover at the struck point or by a backflashover the arrester current will be increased due to reflections from the struck point [7].

Considering a shielding failure causing a flashover or a backflashover in front of the substation according to (4) above reflections from the struck point will result in an arrester current according to formula (5):

$$I_{\text{arrester}} = 2 \times (N+1) \times U_{\text{incoming}}/Z_{\text{line}} \times (1-N \times T_s/\tau)-2 \times N \cdot U_{\text{incoming}}/Z_{\text{line}} \tag{6}$$

Where

T_s = travel time between the arrester and struck point in μs

τ = tail time constant of the incoming surge in μs, assumed: 10 μs … 20 μs

N = number of reflections from the struck point (N = 0, 1, 2, 3, etc.)

Maximum current is obtained for $N = N_m = 0{,}5 \times (\tau/T_s \times (1-U_{\text{pl}}/U_{\text{incoming}})-1)$ [7].

Note that in this case the power frequency voltage is neglected and only one line is considered in the substation.

Assuming that the struck point is 600 m from the substation T_s will become 2 μs, and for the 420 kV example above the arrester current will be 14,9 kA and for the 145 kV example 8,1 kA.

Therefore, in the 420 kV example I_n = 10 kA or I_n = 20 kA would be a reasonable choice, and in the 145 kV example I_n = 10 kA would be sufficient.

From these considerations it is obvious that the appropriate nominal discharge current of the arresters in a system depends on the performance of the line and on the fact if it is shielded or not, as well as if flashover occurs or not, and on the location of the arrester, at an open line end or at a transformer.

Distribution lines are typically not shielded, and so nearly any current amplitude in case of a lightning strike to the conductors is possible (up to 200 kA). It depends now on the design of the line which flashover voltages are reached. In case of perfectly earthed cross arms the flashover voltage of the insulators is relevant. For instance, in a 24 kV (isolated neutral) system the insulators (assumed flashover distance 230 mm) might flashover at a voltage of U_{50} = 135 kV. The resulting current through the arrester in a substation will be according to equation (1) (Z = 450 Ω, U_{pl} = 80 kV):

$I_{\text{arrester}} = (2 \times U_{\text{incoming}} - U_{\text{pl}})/Z_{\text{line}} = (324\ \text{kV} - 80\ \text{kV})/450\ \Omega \approx 0{,}54\ \text{kA}$ (open ended line)

$I_{\text{arrester}} = 1{,}6 \times (2 \times U_{\text{incoming}} - U_{\text{pl}})/Z_{\text{line}}$ = (324 kV – 80 kV)/450 Ω ≈ 0,87 kA (transformer connected to the line end)

Mostly a direct strike to a distribution line will result in flashovers between all three phases, and therefore the arresters of all three phases will share the duty. On the other hand, the surge impedance will be lower, in the order of 250 Ω, due to a 3-phase travelling surge and thus the total current will be higher than given above. A nominal discharge current of I_n = 2,5 kA is definitely an appropriate choice in this case, resulting in a "DL" arrester.

In the case of wooden poles, where the cross arms are not earthed, a flashover from conductor to ground will develop. For a typical clearance of 5 m to ground this results in a flashover voltage in the range of 2 MV to 3 MV. Assuming a value of 3 MV, the current through the arrester in a substation will then be, according to equation (1) and (2) and further assuming a 3-phase travelling surge with surge impedance of 250 Ω:

$I_{\text{arrester}} \approx$ 28 kA (open ended line)

$I_{\text{arrester}} \approx$ 46 kA (transformer connected to the line end)

But again, as all three phases will be involved, the arresters of each phase will be stressed by only about one third of this value (if exactly matched). Therefore, the current will typically be in the range of 10 kA in the first case, and I_n = 10 kA (a "DH" arrester) would be the choice in this case. In the second case, where currents between 10 kA and 20 kA through the individual arresters may be expected, a "DH" arrester with I_n = 10 kA or a "SL" arrester with I_n = 10 kA could be chosen, depending on further information that is available for the system.

Once a reasonable value of the nominal discharge current has been determined for given system configurations, this current value is then used for the further selection of surge arresters. It will there have the function of an arrester classifying parameter, and other arrester characteristics are chosen based on its nominal discharge current, I_n.

If it is known that the charge to be transferred is typically higher than related to the so determined I_n (Table 1 of IEC 60099-4:2014) and takes a value that would be related to the next higher I_n value, this I_n value should be chosen. For charge transfer ratings of $Q_{\text{rs}} \geq 1{,}1$ C, generally I_n = 10 kA shall be chosen.

However, the user may still use another coordination current than the nominal discharge current for determining the LIPL of the arrester, such as 0,5 or 2 times I_n. Correlations of the nominal discharge current I_n with other specific ratings are given in Table 2.

For surge arresters protecting high-voltage substation equipment typically arresters with designation SL, SM or SH are used. In medium voltage systems, mainly arresters with designation DL, DM or DH are used. For specific applications as protection of cables, rotating machines or capacitor banks arresters with higher repetitive charge transfer ratings may also be needed for medium voltage systems.

Table 2 – Arrester classification

Arrester class	Station			Distribution		
Designation	**SH**	**SM**	**SL**	**DH**	**DM**	**DL**
Nominal discharge current[a]	20 kA	10 kA	10 kA	10 kA	5 kA	2,5 kA
Switching impulse discharge current[a]	2 kA	1 kA	0,5 kA	–	–	–
Q_{rs} (C)	≥ 2,4	≥ 1,6	≥ 1,0	≥ 0,4	≥ 0,2	≥ 0,1
W_{th} (kJ/kV)	≥10	≥ 7	≥ 4	–	–	–
Q_{th} (C)	–	–	–	≥ 1,1	≥ 0,7	≥ 0,45

NOTE The letters "H", "M" and "L" in the designation stand for "high", "medium" and "low" duty, respectively.

[a] Other currents may be specified upon agreement between manufacturer and user.

6.3.2.4 Surge arrester charge transfer and energy dissipation during lightning current discharges

A rough estimation of the charge from lightning strikes for substation arresters can be estimated from Formula (7) [3][4]:

$$Q=\left[2\times U_{\mathrm{f}}-N\times U_{\mathrm{res}}\left(1+\ln\left(2\times\frac{U_{\mathrm{f}}}{N\times U_{\mathrm{res}}}\right)\right)\right]\frac{T_{\mathrm{l}}}{Z} \qquad (7)$$

where

Q	is the charge. If the distances between substations in distribution systems are small, the charge can be divided because of current sharing.
ln	is the natural logarithm;
U_{res}	is the residual voltage at the actual lightning current through the arrester, as a first approach U_{pl} of the arrester can be used;
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 (N = 1 or N = 2), (as explained in IEC 60071-2);
T_{l}	is the equivalent duration of the current of a lightning flash including first and subsequent strikes. Typical value 3×10^{-4} s.

The energy is obtained by multiplying the charge with the actual residual voltage of the arrester U_{res}.

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 cumulative charge transfer and energy during line switching

The arrester switching cumulative charge transfer and energy are 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 charge and energy rating capacity greater than the accumulated charges transferred and energy during the severest operating duty. The required surge arrester charge transfer and 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 evaluating arrester line discharge energy classes and capabilities, (see Formula H.1 of Annex H).

The simplified arrester cumulative charge (8a) and corresponding energy (8b) are 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]. Therefore, accuracy is dependent on identifying the appropriate arrester residual voltage and current which matches the prospective switching voltage magnitude and the line surge impedance.

Using the line discharge concept establishes an interesting relationship between arrester charge and energy because during the relevant line discharge period, both the arrester currents and voltages are practically constant. Consequently, for the line discharge cases, the simplified formulas can provide similar accuracy as those obtained from detailed computer simulations as illustrated in Annex I. This annex also contains useful formulas for estimating arrester discharge voltages and currents by linearizing the arrester voltage-current characteristic in the switching region.

$$Q_{\mathrm{s}} = \frac{U_{\mathrm{rp}} - U_{\mathrm{res}}}{Z} \times 2 \times \frac{l}{c} \tag{8a}$$

$$W_{\mathrm{s}} = U_{\mathrm{res}} \times Q_{\mathrm{s}} \tag{8b}$$

where

U_{rp} is the representative maximum switching voltage;

U_{res} is the arrester residual voltage during the line discharge;

l is the line length with surge travel time at speed of light, c;

Q_{s} is the cumulative charge transferred during one single line switching;

W_{s} is the cumulative energy absorbed by arrester during one single line switching;

Z is the line surge impedance;

c is the speed of light.

NOTE The required thermal energy rating of the arrester, W_{th}, is two times W_{s}.

Major characteristic differences between line re-energization/switching event and line discharge operations are that arrester voltage and current waveforms are neither constant nor similar over each of the several discharges. Consequently, some caution is necessary since possibility of unrealistic line surge impedances, line length and prospective switching overvoltages can occur when they are based on arrester ratings as prescribed by the IEC 60099-4:2009 to establish arrester line discharge classes. For completeness, some examples of arrester charges and energies generated during practical line energization using computer simulations are compared with those obtained from simplified line discharge formulas.

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 are not generally suitable for limiting the typically lower magnitude overvoltages resulting from earth faults and fault clearing.

The influence of 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 that are most frequently equal to each other. If lower phase-to-phase protective levels are required, additional arresters phase-to-phase are needed.

The problems with switching overvoltages are:

a) the ability of the MO resistors to withstand the imposed thermal-mechanical stresses

b) the ability of surge arresters to recover from MO resistors temperature rise resulting from absorption of energies.

These problems can only be addressed by adequate identification of likely sources of overvoltages and appropriate specification of a surge arrester with a suitable thermal energy and repetitive charge transfer 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 systems with nominal voltages greater than 245 kV (Range II).

In Range I, except for rotating machines, installed equipment typically has such a high insulation level that protection from slow-front overvoltages is not generally necessary. 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, except for 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 (9), (10), (11) and (12) [68]:

$$\frac{U_{\mathrm{ps}}}{U_{\mathrm{e2}}} \leq 0{,}7\,; \quad K_{\mathrm{cd}} = 1{,}1 \tag{9}$$

$$0{,}7 < \frac{U_{\mathrm{ps}}}{U_{\mathrm{e2}}} \leq 1{,}2\,; \quad K_{\mathrm{cd}} = 1{,}24 - 0{,}2 \times \frac{U_{\mathrm{ps}}}{U_{\mathrm{e2}}} \tag{10}$$

$$1{,}2 < \frac{U_{\mathrm{ps}}}{U_{\mathrm{e2}}}\,; \quad K_{\mathrm{cd}} = 1{,}0 \tag{11}$$

and the coordination switching impulse withstand voltage as

$$U_{cw} = K_{cd} \times U_{ps} \tag{12}$$

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} the protection by arresters does not have to be considered.

6.3.2.7 Protection from fast-front overvoltages

6.3.2.7.1 General

In general, surge arresters cannot adequately protect equipment with large separation distances between line entrances and the equipment to be protected. The height of up to several meters especially of high voltage arresters in substations may significantly reduce the protection distance and by this affect the protection margin, as far as fast-front transients are concerned. This is due to the fact that the arrester height is contained in the overall maximum protection distance. Consequently, arresters are typically installed as close as possible to critical equipment. Additional arresters may need to be installed at the line entrances to limit the magnitude of overvoltages entering the substation.

The presence of a sizable surge capacitance at the line terminal or substation entrance could reduce the steepness of the incoming surge. The withstand voltage for fast-front overvoltage coordination (coordination withstand voltage, U_{CW}) can then be determined from a “modified” empirical formula, which considers the fundamental characteristics of lightning overvoltage behaviour in substations (see IEC 60071-2). A steepness reduction factor, f_s, is introduced to take into account the effects of capacitances at the line entrance. As shown in Annex G, this factor is:

$$f_s = \frac{S_s}{S_0} = \frac{C_0}{(C_0 + C_s)} = \frac{1}{(1 + C_s/C_0)} \tag{13}$$

where

S_0 is steepness due to corona alone, see Formula G.4;

S_s is steepness with added capacitance;

C_s is the effective surge capacitance at line terminal in μF;

C_o is the equivalent surge capacitance of the incoming surge related to corona, see Formula G.5.

The resulting coordination withstand voltage considering the line entrance capacitances is:

$$U_{cw} = U_{pl} + \frac{A \times f_s}{N} \times \frac{L_t}{L_{sp} + L_f} \tag{14}$$

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 substation;

f_s steepness reduction factor with surge capacitance at line terminal;

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

L_t is the total length $L + L_1 + L_2 + L_{A,}$ (see Figure 8 and Figure 9);

L_{sp} is the span length;

$L_f = R_a/r$ is the length of the overhead line in front of the substation, 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 Formula (14) 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 substation. 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 (14) is small and can be neglected. Formula (14) is then simplified to:

$$U_{cw} = U_{pl} + \frac{A \times f_s}{N} \times \frac{L_t}{L_{sp}} \tag{15}$$

Table 3 – Definition of factor A in formulas (14 and 15) 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 case of 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.	

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 4 – Examples for protective zones calculated by formula (16) for open-air substations

System voltage	Protec-tion level	Withstand voltage		Span	Axfs	Protective zone L_p					
		Rated	Co-ordina-tion			r = 0,1[a)]	r = 0,5[a)]		r = 2[a)]		r = 6[a)]
						N = 2	N = 1	N = 2	N = 1	N = 2	N = 2
kV	kV	kV	kV	m	kV	m	m	m	m	m	m
24	80	125	109	100	2 700	–	–	–	2,4	4,8	3,0
				200	900	–	–	–	10,4	20,8	15,5
123	350	550	478	300	fs=1,0, 4 500	160	23	46	12,0	24	–
					fs=0,5, 2 250	320	46	92	24,0	48	–
245	450	950	827	300	fs=1,0, 7 000	300	43	86	23	46	–
					fs=0,5, 3 500	600	86	172	46	92	–
420	800	1 425	1240	400	fs=1, 11 000	116	36	72	21	42	–
					fs=0,5, 5 500	232	72	144	42	84	–
550	900	1 550	1352	400	fs=1, 11 000	236	37	74	22	43	–
					fs=0,5, 5 500	472	74	148	44	86	–
765	1474	2100	1828	400	fs=1, 11 000	186	29	57	17	28	–
					fs=0,5, 5 500	372	58	114	34	56	–

r line design outage rate (per 100 km and year) corresponding to the first kilometre in front of the station.

[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)

The protective zones of surge arresters in case of fast-front overvoltages 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.

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 (16):

$$L_{\mathrm{p}} = \frac{N}{\left(A \times f_{\mathrm{s}}\right)}\left[\left(\frac{U_{\mathrm{rw}}}{1,15}\right) - U_{\mathrm{pl}}\right]\left(L_{\mathrm{sp}} + L_{\mathrm{f}}\right) \qquad (16)$$

where

L_p is the protective zone;

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

Formula (16) indicates that for a given substation, the protective zone increases with:

- increasing difference between rated withstand voltage and protective level;
- incoming surge steepness reduction by increasing surge capacitance at line terminal;
- decreasing outage rate of the overhead line in front of the substation, 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) and 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 CIGRÈ TB 440 [78].

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 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 thermal charge transfer rating or thermal energy rating, the high current value of the arrester considering an acceptable arrester failure rate

NOTE Lightning discharge currents and related discharge energy may be significantly higher than for substation 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 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 U_c.

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.

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 rating 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 charge and energy requirements

NGLAs 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 H of IEC 60099-4:2014. NGLAs on shielded lines typically have a nominal discharge current of 5 kA or 10 kA according to IEC with charge transfer ratings of Q_{rs} from 0,5 C to 1,6 C , depending on their application.

For NGLAs installed for lightning protection on unshielded lines a nominal discharge current of 10 kA or 20 kA according to IEC with charge transfer ratings of 1,0 C to 2,4 C may be used depending on the isokeraunic levels (thunder days/year, T_D) and acceptable outage rate. There is special software available on the market which will give guidance for the dissipated charge/energy from lightning strokes.

NGLAs for protection from switching overvoltages are selected to have the same or in most cases one IEC charge transfer rating lower than what the substation arresters have, due to that for longer lines the NGLAs are installed around the midpoint reducing the line length and thereby also the charge and energy for the involved NGLA. Typically a nominal discharge current of 10 kA or 20 kA according to IEC with charge transfer ratings of Q_{rs} from 1,6 C to 3,6 C may be used. These charge values basically correspond to previous LD classes 3 to 5 (see Table H.3 of Annex H) [16][83]

6.3.3.2.4 Fault clearing and disconnectors

Disconnectors are used to facilitate fast reclosing as NGLAs 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 on 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 charge transfer 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 so that fast reclosing is facilitated.

Therefore a coordination of the disconnectors’ opening times versus short circuit currents compared to the actual operating times of reclosing system is necessary especially for not directly earthed systems with very low short circuit currents.

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 disconnector 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

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

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.

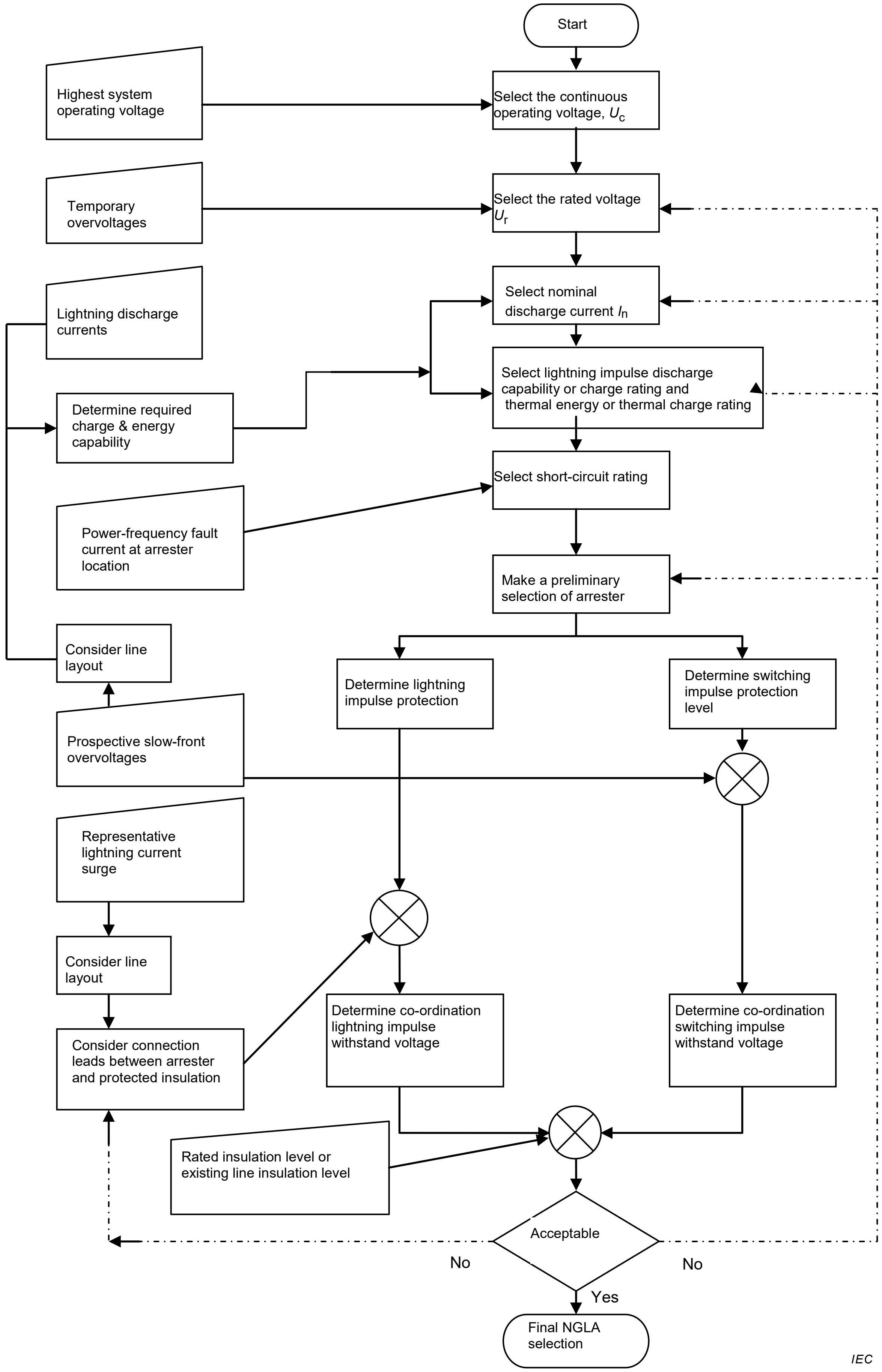


Figure 21 – Flow diagram for the selection of NGLA

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 substation 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 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 60099-8:2011.

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 on 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 charge transfer 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 H of IEC 60099-4:2014. 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 µs), or 5, 10, or 20 kA for classes X1-X4 (wave shape 8/20 µs) according to Table 1 of 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 µs. In this case, the high current impulse of 25 kA (2/20 µs) in class Y2 corresponds nearly to the direct lightning strike of 30 kA (2/70 µs) 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		2/70 µs
	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

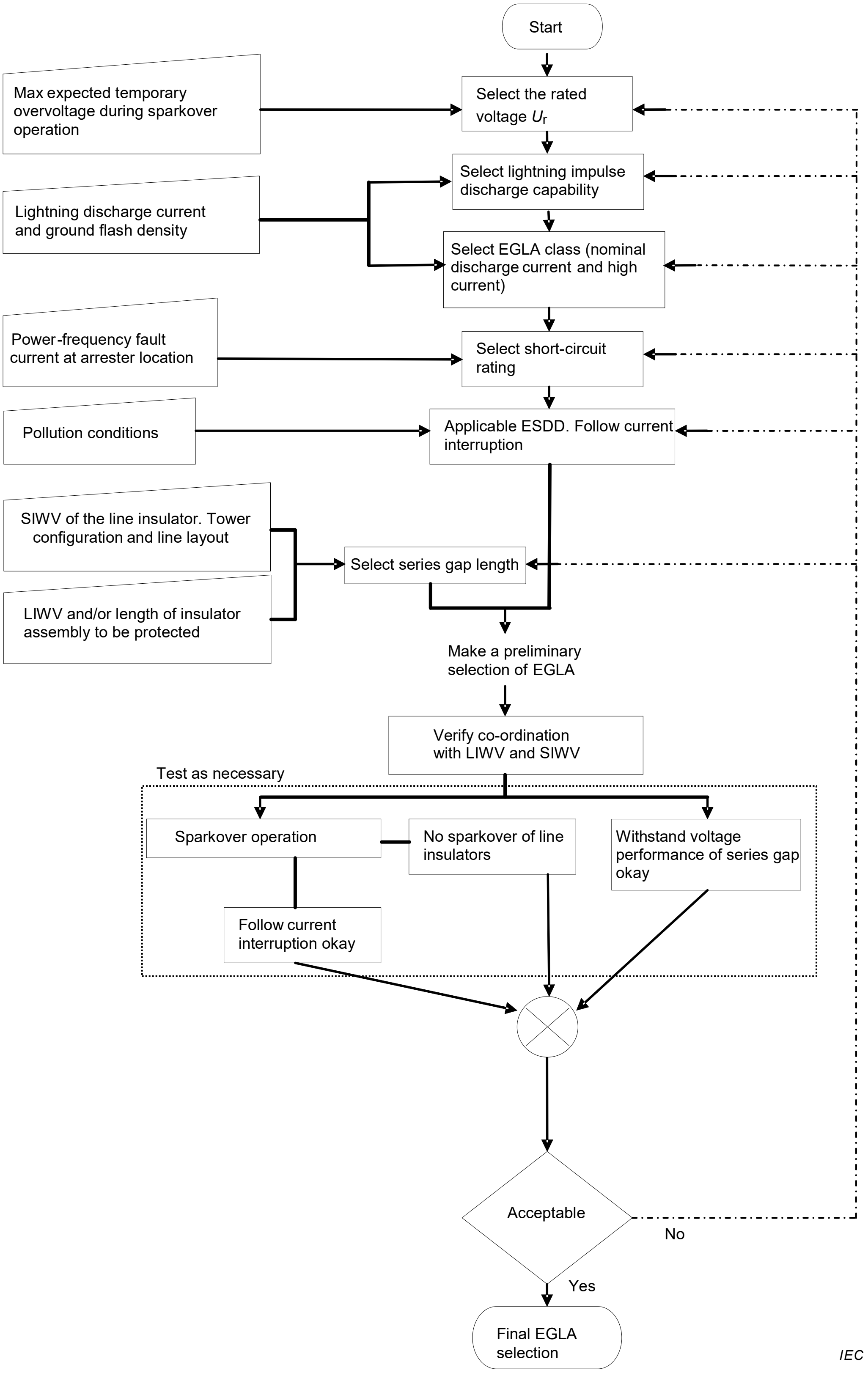


Figure 22 – Flow diagram for the selection of EGLA

6.3.3.3.3.2 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 60099-8:2011). 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 60099-8:2011 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:

$$U_{\mathrm{50EGLA}} + X \times \sigma < U_{\mathrm{50LI}} - X \times \sigma \tag{17}$$

where

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

U_{50EGLA} is the 50 % probability spark over voltage for EGLA at the standard lightning impulse. Furthermore U_{50EGLA} 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 (17) 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

$$U_{\mathrm{50EGLA}} + X \times \sigma = U_{\mathrm{50LI}} - X \times \sigma \quad (\sigma = 3\ \%) \tag{18}$$

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.

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.

Table 6 – Probability of insulator flashover in Formula (18)

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

6.3.4 Selection of arresters for cable protection

6.3.4.1 Overvoltage protection of cables connected to overhead lines

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 60Ω. 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 there is 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, if the cable is connected to an overhead line, or if one cable end “sees” an open end. 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.

For cables, the reflection of the transient wave at the end of the cable represents a high risk and may cause flashovers with subsequent damages to the cable insulation as well. This risk can only be reduced by the application of surge arresters at this cable end. Cable ends should therefore be treated like substation equipment with respect to insulation coordination

The protection of the cable ends against overvoltages can be improved by applying shield wires along the last approximately 3 to 4 spans. For a better protection of the overhead line 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 directly to the cable sheath.

Longer cables between overhead lines 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. If detailed insulation coordination studies are not available, it is recommended to install arresters at both the overhead line-cable terminals.

As cables can store a relatively high energy it is advisable to choose arresters with a higher charge transfer rating than used for the protection of distribution substations. This offers 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 due to circulating currents) cable sheaths of power cables in high voltage systems are earthed at one end only. Circulating currents in cable sheaths can be avoided or at least reduced by cross bonding the sheaths along the cable line or by disconnecting the cable sheath from ground at specific locations in order to increase the current rating of the cable line. The open ends as well as the cross bonding points should be protected against slow- and fast-front overvoltages by suitable surge arresters.

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, single or three phase (triangular or single plane, spacing between cables)

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 critical for the selection of the arrester. Considering the TOV curve of the arrester the induced voltage, which is applied to the arrester for the time until the fault is cleared, needs to remain below the curve specified for “no prior energy.

With an approximation the U_c for cable sheath arresters can be calculated from Formula (19).

$$U_c \geq \frac{U_i \times I_k \times L_k}{T_c} \tag{19}$$

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

$T_c = U_{TOV} / U_c$

NOTE 1 U_i reaches in maximum 0,3 kV per kA of fault current and km of cable length.

NOTE 2 Manufacturers may state actual arrester TOV capability as $T_r = U_{TOV} / U_r$ instead of $T_c = U_{TOV} / U_c$. The ratio between T_r and T_c is the same ratio as between U_r and U_c.

The charge transfer rating has to be determined case by case. 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. For transmission cables detailed calculations may have to be performed.

NOTE 3 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 rarely 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 of an issue than fast-front overvoltages and are therefore not considered.[1]

A similar procedure to that shown in Figure 19a, and Figure 19b for substation arresters is used for distribution arresters.

6.3.5.2 Energy handling capability

The most significant electrical stress distribution arresters must handle is associated with a lightning discharge. During this charge transfer event heat is generated in the arrester as a function of the arresters residual voltage and discharge current. For lightning discharges, the current is not influenced by the arrester's residual voltage, and therefore the higher the residual voltage the more energy is dissipated.

All distribution arresters are designed to withstand high current impulses 4/10 μs of 25 kA, 65 kA or 100 kA amplitude for preconditioning and verification of internal dielectric strength. In the operating duty test current impulses with a wave shape of 8/20 μs are applied to prove the thermal stability. These test currents must not be confused with real lightning currents of the same amplitude. Distribution arresters only have charge transfer ratings that in combination with the arrester's residual voltage under the applied current provide a means of assessing energy handling capability.

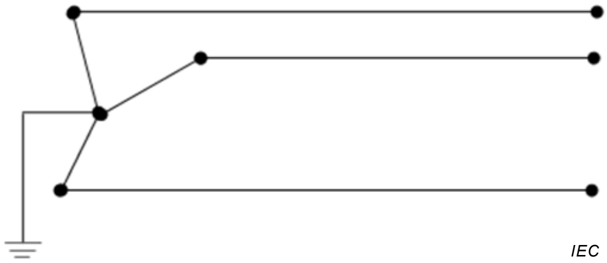
6.3.5.3 TOV considerations

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. The worst case voltage rise depends on the system neutral grounding configuration and this will impact on the selection of U_c of the arrester. Figure 23a, Figure 23b, Figure 23c and Figure 23d indicate the appropriate U_c for different grounding configurations.

For each of the below 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 is then selected with help of manufacturers' TOV-data (see Figure 20a, and Figure 20b).

6.3.5.4 Failure modes

Distribution arresters shall be tested per short-circuit procedures of IEC 60099-4:2014, Table 7 to withstand fault currents claimed by the manufacturer.



Uc ≥ 1,4 times Us/√3

Figure 23a – Three-wire single earthed systems (earthed at source only) Earth Fault Factor 1,4

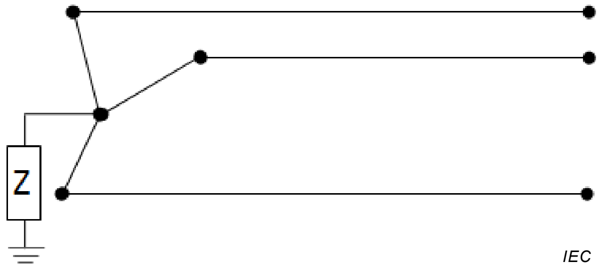


Figure 23b – Three-wire impedance earthed systems. Earth Fault Factor 1,73

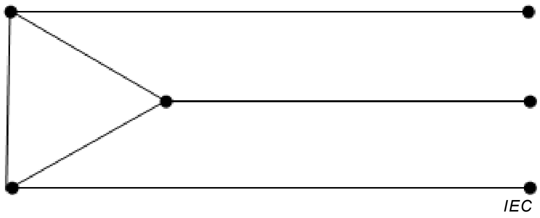


Figure 23c – Delta systems. Earth Fault factor 1,73

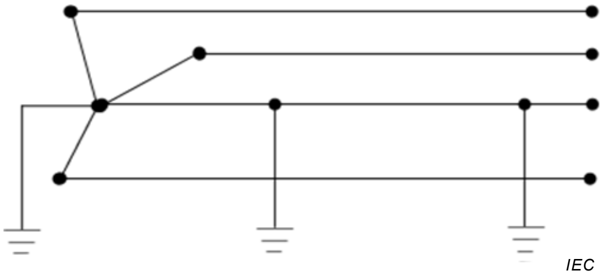


Figure 23d – Four-wire multi-earthed -wye systems. Earth Fault Factor 1,25

Figure 23 – Common neutral configurations

6.3.6 Application and coordination of disconnectors

6.3.6.1 General

Disconnectors are mainly used in two applications, for distribution type arresters and for gapless line arresters, NGLA. For both applications, the arresters are at a higher risk to be exposed to lightning strokes with a charge exceeding their capability than for other applications. As a consequence of this the risk of these arresters causing a permanent short-circuit due to an overload is also higher. Disconnectors are applied to mitigate that risk.

Disconnectors serve a dual purpose, firstly to separate the overloaded arrester from the system in order to facilitate fast reclosing of the system. Secondly to visually indicate when an arrester has been overloaded.

6.3.6.2 Disconnector characteristics and operation

Disconnectors are simple devices set to operate for power frequency currents but not for fast impulse currents. Its characteristics is measured as current in amperes versus time to disconnect. The higher the short-circuit current the quicker it disconnects. Many of these arrester applications may be far out from the generating substation or on not directly grounded systems so the short-circuit currents may be rather low just tens or hundreds of amperes.

Once the arrester is shorted to earth, the short-circuit current of the system is passing through the disconnector triggering it to operate. It operates in such a way that the disconnector separates into two pieces and the earth wire attached to the lower part falls down. At the same time the protection relays will react, triggering the circuit breaker to operate. Depending how quick the reclosing scheme is set, the circuit breaker will then reclose the line back. During this time slot – relay reacting time, circuit breaker operating time, reclosing time interval, and circuit breaker closing time – the disconnector should have fulfilled its duty. The separated earth wire must have enough clearance when the reclosing occurs even though it may be exposed to high wind guts. So the actual clearing time is somewhat dependent on environmental conditions. Properly selected disconnectors shall allow the first reclosing to be successful. One important feature of a disconnector is that once triggered it must continue its operation even if the circuit breaker has opened the circuit. If not, there is a high risk that the disconnector may not work as intended.

6.3.6.3 Coordination of arrester and disconnector characteristics

The disconnector shall only operate if the arrester is overloaded, so for all other duties that the arrester can withstand, the disconnector shall not operate. This is shown by testing the disconnectors with the same duties as the actual arresters it is used together with. These duties may include the highest energies and charges from IEC 60099-4:2014.

One important coordination is the TOV capability of the arrester versus the disconnector characteristics as the disconnector cannot differentiate between the origins of currents. TOV curves show withstand voltages versus time. However, arrester manufacturers should have recordings of the actual currents which shall then be compared to the currents from the disconnector characteristics. The TOV current for the actual overvoltage time shall always be lower than the triggering current for the disconnectors.

This means that the actual overvoltages of the system and also the protection scheme for reclosing should be known. The TOV capability used should be the one with no prior duty as healthy phases may see these overvoltages if there is an earth fault on the other phase. The critical case is if the arrester can withstand the actual TOV currents but the disconnector cannot handle the current without disconnecting.

6.3.6.4 NGLA applications

Selecting a higher rated voltage for NGLA than for the substation arrester has several advantages. Proper disconnector operations can be assured and also NGLA classes can be selected for protection against lightning strokes only. With lower rated voltage substation arresters they will take care of any slow front overvoltages like switching events, so these will not stress the NGLA.

Today there is a tendency to have faster reclosing schemes as outage times shall be limited. Updated coordination of the disconnector characteristics and reclosing schemes need to be considered if this scheme is changed on already installed NGLA.

If the TOV currents are higher than the operating currents for the disconnectors in NGLA applications, the solution is just to select a higher rated voltage of the arresters. In these applications, there is always ample margins for the needed protection levels of the arresters.

6.3.6.5 Distribution applications

The coordination here is more complicated if there are fuses connected in series with the arresters. The operating times of the fuse will then also have to be considered in the total coordination. The most common installation is that the arresters are installed between the fuse and transformer.

A critical case may occur if the arrester fails (in short-circuit) but the disconnector did not operate before the nearby fuse clears the fault. In such a case, when the fuse is replaced, the already short-circuited arrester will be re-energised, resulting in a potentially hazardous situation for the worker replacing the fuse. It is therefore very important that the disconnector and fuse characteristics are coordinated so that the disconnector starts its operation before the fuse has cleared, and that it continues its disconnection after the fuse operation.

6.3.7 Selection of UHV arresters

6.3.7.1 General

Basically the same selection procedure is applicable for UHV arresters as for all other arresters. IEC 60099-4:2014 takes into account what in particular characterizes UHV arresters as:

- Very high charge and energy requirements. IEC 60099-4:2014 gives charge transfer ratings and thermal energy ratings without any upper limit.
- External insulation. The switching surge protection levels will determine the necessary clearances – a complete arrester must be tested to verify a suitable margin if arcing distances do not fulfil requirements according to formulas given in IEC 60099-4:2014.
- The use of multiple-column arresters to meet demanding requirements on protection levels and charge and energy withstand capability. This requires tests to establish the starting temperature in the operating duty test as well as determining a correct thermal prorated section. Such tests are specified in IEC 60099-4:2014.

6.3.7.2 Insulation co-ordination

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. In order to achieve proper LIPL multi-column arresters are in general necessary. To effectively suppress lightning overvoltages, in addition 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.

IEC 60071-2, Ed.4[2], *Insulation co-ordination – Part 2: Application guide*, also presents the coordination of Very Fast Transients in UHV substations.

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 economic reasons a SIWV of around 1,6 to 1,7 p.u. is desirable. There are different possible solutions:

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[2] Under preparation. Stage at the time of publication: IEC/PRVC 60071-2:2016.

- 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 SF_6 and hence a higher U_c/U_r ratio [11];
- controlled switching algorithms;
- circuit breakers with opening or closing/opening resistors;
- single phase reclose;
- any combination(s) of the above.

These possibilities can greatly contribute to optimize the economical design and size of UHV equipment and power transmission lines [8][9][10][11][12][13][83].

6.3.7.3 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 may better cope with severe seismic stresses. Porcelain-housed arresters may 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.

6.4 Standard and special service conditions

6.4.1 Standard service conditions

Standard service conditions for the arresters are specified in IEC 60099-4:2014 where they are named normal service conditions [59].

a) ambient air temperature within the range of –40 °C to +40 °C;
b) solar radiation

NOTE The effects of maximum solar radiation (1,1 kW/m^2) have been taken into account by preheating the test specimen in the type tests. Other heat sources that may affect the application of the arrester are not considered under normal service condition,

c) altitude not exceeding 1 000 m;
d) frequency of the AC power supply not less than 48 Hz and not exceeding 62 Hz;
e) power-frequency voltage applied continuously between the terminals of the arrester not exceeding its continuous operating voltage;
f) wind speeds ≤ 34 m/s;
g) vertical erection, not suspended.

6.4.2 Special service conditions

6.4.2.1 General

A list of possible special service conditions is given in Annex A of IEC 60099-4:2014 referred to as abnormal service conditions in that Annex. A short guidance on the topics is given as follows:

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

For higher ambient temperature, it may be necessary to increase the temperature for pre-heating in the operating duty test.

Further on a correction of the continuous operating voltage Uc may be necessary to compensate the higher power losses due to increased ambient temperature.

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. Polymer material may become brittle at such low temperatures. 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 length of the housing, design and positioning of grading rings must be considered regarding the decreased insulation strength of the air. Guidance is found in IEC 60071-2.

Regarding potential need for creepage correction, as stated in IEC TS 60815-1:2008 current knowledge is limited and practices too diverse to give recommendations. The matter is discussed e.g. in CIGRE TB 361 [79].

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 C of IEC 60099-4:2014. In this case the pollution performance could be improved by following measures:

   - Selecting a 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. This is for polymer-housed arresters to some extent checked in the salt fog test as given in 10.8.17.2 of IEC 60099-4:2014. For porcelain-housed arresters no relevant test exists in IEC 60099-4.

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 is in general not recommended. High pressurized water may give damage to the polymer insulators. The manufacturer should be consulted if live washing is requested.

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 charge transfer rating, energy withstand 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 Operation at frequencies below 48 Hz or 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 16,7 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. When measuring the leakage current of MO arresters during commissioning it should be considered that the leakage current is almost pure capacitive, which leads to a linear increase of the capacitive current with increasing 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 charge transfer or energy withstand 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 Wind speed > 34 m/s

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

6.4.2.14 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).

6.4.2.15 Torsional loading of the arrester

The manufacturer shall be consulted.

6.4.2.16 Tensile loading of the arrester

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

6.4.2.17 Use of the arrester as mechanical support

This may be possible depending on the design of the arrester and the required mechanical loads. However, careful consideration of the potential risks associated with the installation is recommended. Surge arresters are not generally inherently designed to be used as a station post insulator and standardized type tests do not explicitly consider the consequences of all potential HV connection methods. Additional evaluation and special testing could be needed to verify that the surge arrester, HV line terminal and insulated base (when applicable) are capable of properly and safely withstanding the specifics of the installation. Important matters to consider when intending to use an arrester as mechanical support include:

- Arresters may deflect considerably during applied large terminal force
- An arrester line terminal may not be rated for permanently carrying high current
- Possible mechanical effects on the arrester after overload, in which case mechanical integrity may be entirely lost (housing shattered) or seriously compromised by system fed power frequency short circuit current
- An arrester after overloading may constitute a high-ohmic or low-ohmic short circuit
- A prolonged outage will likely be needed to remove the surge arrester from service and reinstate power

6.4.2.18 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 charge transfer rating or the energy handling capability of neutral arresters should be at least the same as required for the phase-to-earth arresters. In extended resonance-earthed systems, neutral arresters may be subjected to very high charges and energies possibly higher than the phase-ground arresters. System studies are recommended to specify necessary requirements on the arresters in such cases.

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 special environmental 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 higher rated 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

7.2.1 General

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 to take account of possible voltage harmonics. 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.

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.

7.2.2 6-arrester arrangement

In special cases, such as in arc furnace installations, switching overvoltages occur, which are insufficiently limited by arresters between phases and earth. In such cases it is necessary to install additional arresters between the phases. The arresters between the phases should have a continuous operating voltage of $U_c \geq 1,05\ U_s$. The continuous operating voltage U_c of the phase to earth arresters depends on the earthing of the transformer neutral. A typical arrangement of a 6-arrester design is given in Figure 24a.

7.2.3 4-arrester (Neptune) arrangement

A variation of the 6-arrester arrangement is the so called “Neptune” design, because of its arrangement of the arresters. It consists of four similar arresters. Two arresters in series are fitted between the phases and the earth and also between the phases, see Figure 24b. This arrangement permits an overvoltage protection both between the phases and between the phases and earth.

This kind of arrangement has a fundamental disadvantage in comparison to the 6-arrester arrangement. Since the arresters behave in a capacitive manner at continuous operating voltage, all 4 arresters together form in case of an earth fault an asymmetrical capacitive system. In the case where each arrester has identical capacitance (means the arresters have identical ratings), the arresters A1 to A3 would be stressed with $0,661 \times U_s$ and A4 with $0,433 \times U_s$. However, to achieve reasonably low protection levels, a different rating for the arrester at A4 may want to be chosen compared to A1 to A3. Since the arrester capacitance is inversely proportional to arrester U_c, the final steady state voltages need to be calculated individually for each specific case.

A simple solution would be to use four arresters of the same type and rating, although this would lead to a much higher residual voltage compared to the 6-arrester-arrangement. All four arresters would then typically have an $U_r \geq 0,661 \times U_s$. As always, the arresters must also consider the necessary rating required to withstand the TOV that unfaulted phases will see during a phase-to-ground earth fault. In particular, when the earthing is not solidly grounded and fault clearing times are long, a significantly high U_r would need to be chosen.

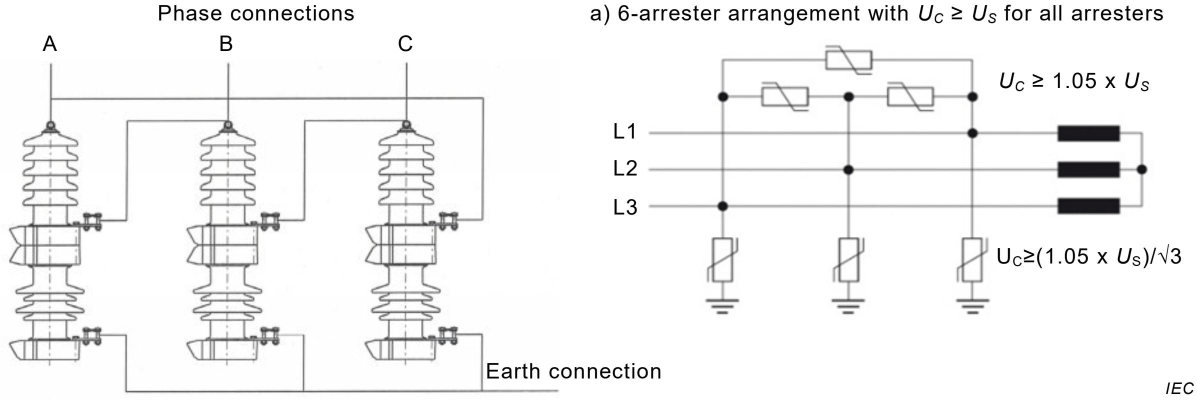


Figure 24a – Six arrester connection

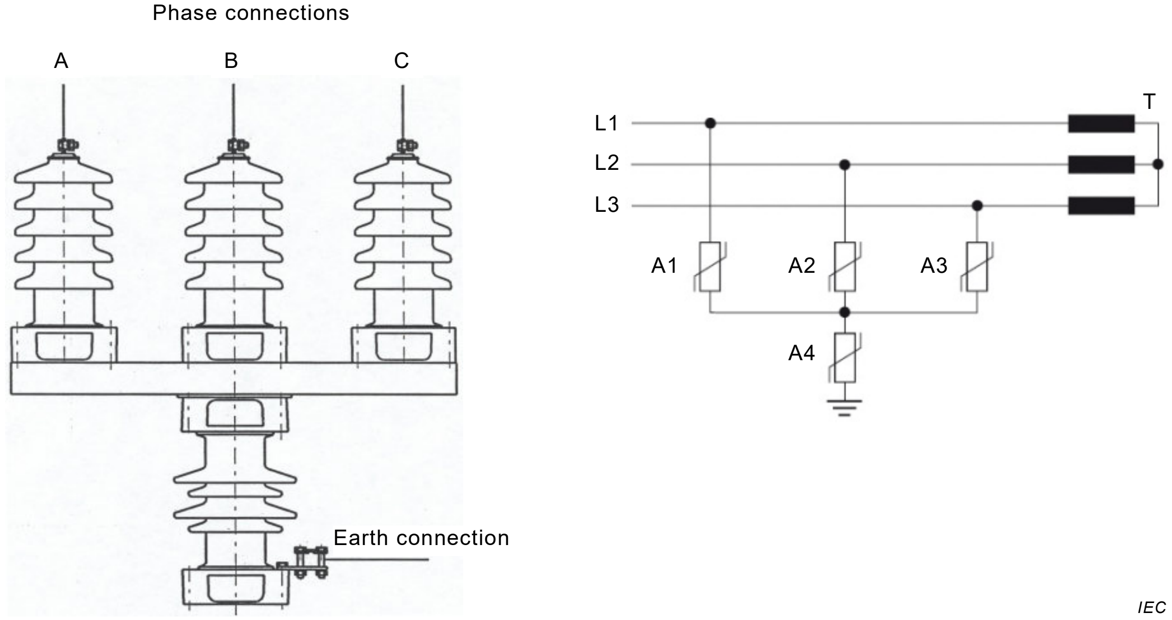


Figure 24b – Four arrester (Neptune) connection

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

If a lower U_r is to be chosen for the arrester A4 compared to A1 to A3, then another capacitive ratio has to be considered, and a detailed calculation has to be made. As always, the arresters must also consider the rating required to withstand the TOV that unfaulted phases will see during a phase-to-ground earth fault [86].

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 substation 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 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 substation, 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 substation, which may not be possible with only one set of arresters due to distance effects and/or operation of the substation.
- A single arrester may not be able to handle the charge in the decisive case.
- Rebuilding and extension of the substation 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 substation 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 diverted 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 will result in a lower protection level at the transformer.

7.4.1.3 Charge transfer and energy considerations

It cannot be assumed that the total charge or 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 the charge more evenly (for example, where it is known that the charge from the system event would exceed the charge transfer or 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 substation should be sized to individually withstand the decisive case charge or energy. Alternatively, only one arrester sized to withstand the decisive case charge or energy would be necessary provided that all other arresters in the substation have at least 10 % higher residual voltage.

The charge or 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 “knee-point” 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 “knee-point” of the characteristic has a negative temperature coefficient, in contrast to the case for higher currents where the temperature coefficient is positive. For these reasons, each arrester in the substation should be selected so that it can individually withstand the expected worst case TOV. Therefore, MO surge arresters cannot limit or protect against TOV, but they have to withstand possible TOV.

7.4.2 Combining different designs of arresters

In a substation with both gapped and gapless arresters, the gapless arrester will most often have a much lower SIPL and thus will take most of the charge from a switching surge (and will effectively protect the gapped arrester in that circuit). Thus, the charge transfer capability for a new metal-oxide arrester to be installed in parallel with SiC arresters shall be calculated ignoring any 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 capacitor 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 charge transfer capability and resulting 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) [68][75].

As a rough estimation the arrester energy W will be:

$$W = \tfrac{1}{2} \times C \times \left[(3 \times U_0)^2 - \left(\sqrt{2} \times U_r\right)^2 \right] \tag{20}$$

where

C is the single-phase capacitance of the bank

U_o 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.

The most severe case for the stress of an arrester is the sequence of a three phase break of capacitive load followed by multiple restrikes in two phases [68].

The required charge transfer capability is approximately obtained by dividing the energy by the arrester protection level at the switching impulse discharge current.

It should be considered that up to three restrikes can occur without sufficient cooling in between, resulting in increased charge transfer and thermal energy absorption by the arrester. The arrester charge transfer 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.

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 charge transfer capability and consequently energy handling capability is important because, in the event of a capacitor discharge into an earth fault the energy absorbed by the arrester may be very large. The energy to be considered is approximately:

$$W = \tfrac{1}{2} \times C \times U_{sw}^{2} \tag{21}$$

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 required charge transfer capability is approximately obtained by dividing the energy by the arrester protection level at the nominal discharge current.

The duration and magnitude of the discharge may be different from those used in arrester testing according to IEC 60099-4:2014. 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 charge transfer capability than would normally be used. The manufacturer should be consulted in such cases.

It should be considered that up to three restrikes can occur without sufficient cooling in between, resulting in increased charge transfer and energy absorption by the arrester. The arrester charge transfer 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 arresters used in series capacitors are often called “varistors” or “MO varistors” (MOV) and testing is not covered by IEC 60099-4.

Because the capacitors are placed in series with the line, the voltage across the capacitor is proportional to the line current. In the event of a fault on the transmission system, a high fault current could result in capacitor voltage increasing to well beyond the capacitor withstand level. An arrester can be connected across the capacitor to limit this voltage, thereby preventing damage to the capacitors. However, in so doing, the arrester will conduct the full fault current for a portion of each cycle, resulting in very high levels of arrester absorbed energy. A single arrester typically will not have the energy handling capability for such an event, and it is usual that a MOV will have many parallel-connected arresters to limit the amount of fault current within each arrester to a manageable level (typically not more than a few hundred amperes per arrester). In some cases, it may be necessary to use several tens of parallel arresters.

To protect the MOV from overloading, a triggered spark gap may be used in parallel to the MOV. If the rated short-term energy is exceeded or the temperature of the MOV has become too high due to repeated energy injections the spark gap is triggered to divert fault current from the MOV through a by-pass path. The spark gap can also be used for fast by-passing of the MOV for some faults; for example faults on the same line as the series capacitor (known as internal faults), when normally there is no need to keep the series capacitor in service during the fault. In some cases the by-pass breaker is the only overload protection for the MOV. Recently the spark gap, in some applications, has been replaced by a so called Fast Protective Device (FPD) utilizing a combination of a spark gap and an extremely fast switch.

The MOV are tested according to IEEE Std. 824-2004 (IEEE Standard for Series Capacitor Banks in Power Systems) and/or IEC 60143-2: 2012, *Series capacitors for power systems – Part 2: Protective equipment for series capacitor banks*.

Because of the highly non-linear behaviour of MO resistors, the individual arresters that make up the MOV must be very carefully matched to each other in terms of their voltage-current characteristics. The above referenced standards address this particular aspect, but it is ultimately the manufacturer’s responsibility to ensure a sufficient degree of matching for each particular MOV application. It is typical that control systems implemented for series compensation systems contain some means of monitoring the division of current through parallel sections of the MOV during system fault events, generating an alarm if the division is out of pre-set limits, indicating the possibility of a degraded arrester that is conducting more than its proper share of the current. The user can then conduct an investigation to find the degraded arrester, using, for example, one of the diagnostic techniques given in Annex D.

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 to 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 LSA and distribution arresters. Regular inspections will be necessary to spot any open disconnectors. There is no possibility to check the correct operation of disconnector 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 SF_6, 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 SF_6 should be handled with care in case any tracking or arcing may have occurred which could generate contaminants in particular associated with SF_6 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 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 $R_1 << X_1$ 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, Figure A.2 to Figure 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.

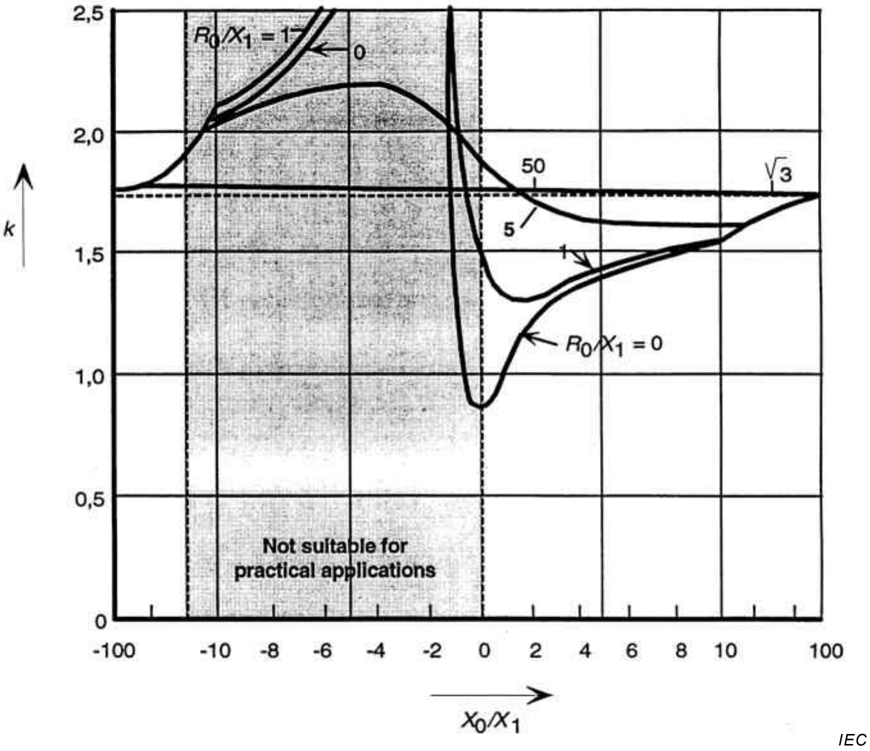


Figure A.1 – Earth fault factor k on a base of X_0/X_1, for $R_1/X_1 = R_1 = 0$

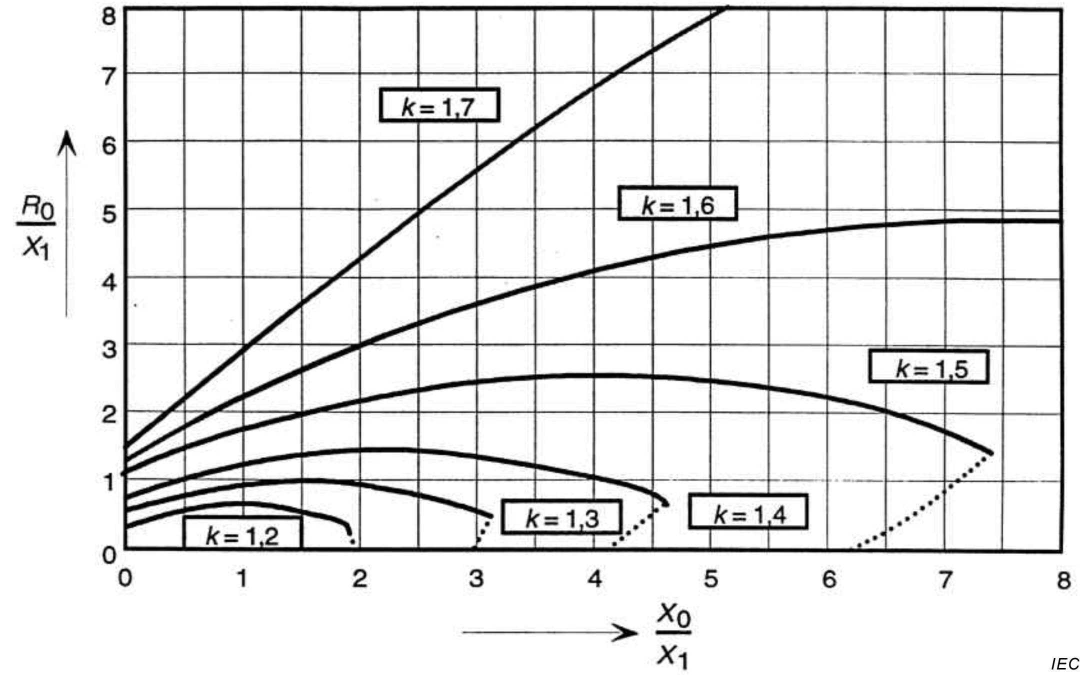


Figure A.2 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth fault factor k where R_1 = 0

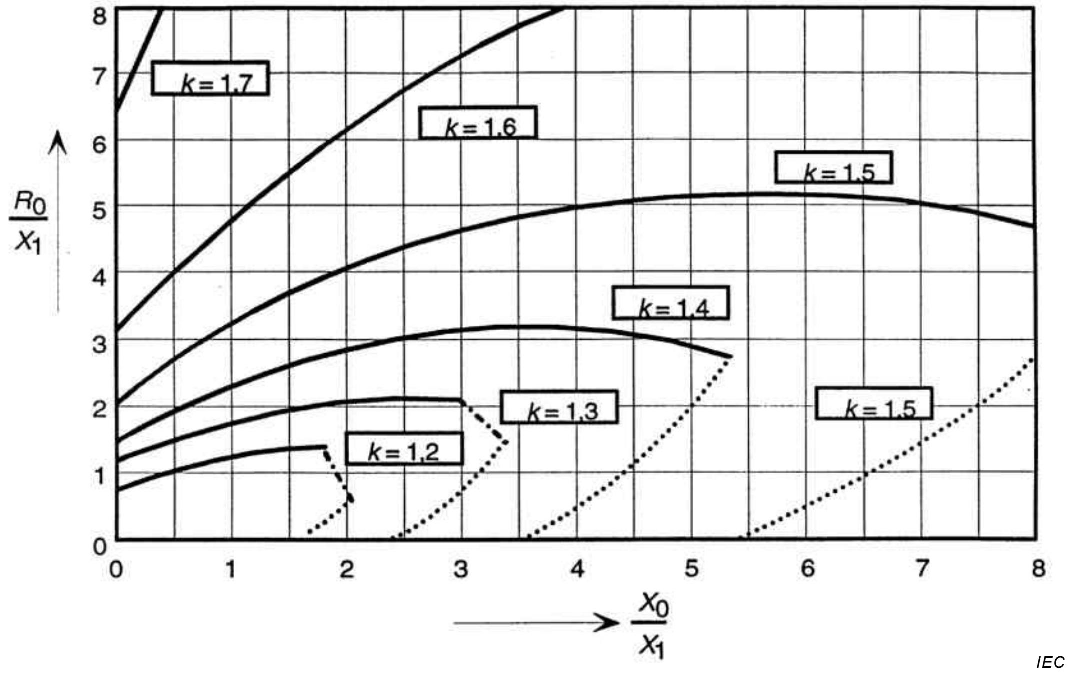


Figure A.3 – Relationship between R0/X1 and X0/X1 for constant values of earth fault factor k where R_1 = 0,5 X_1

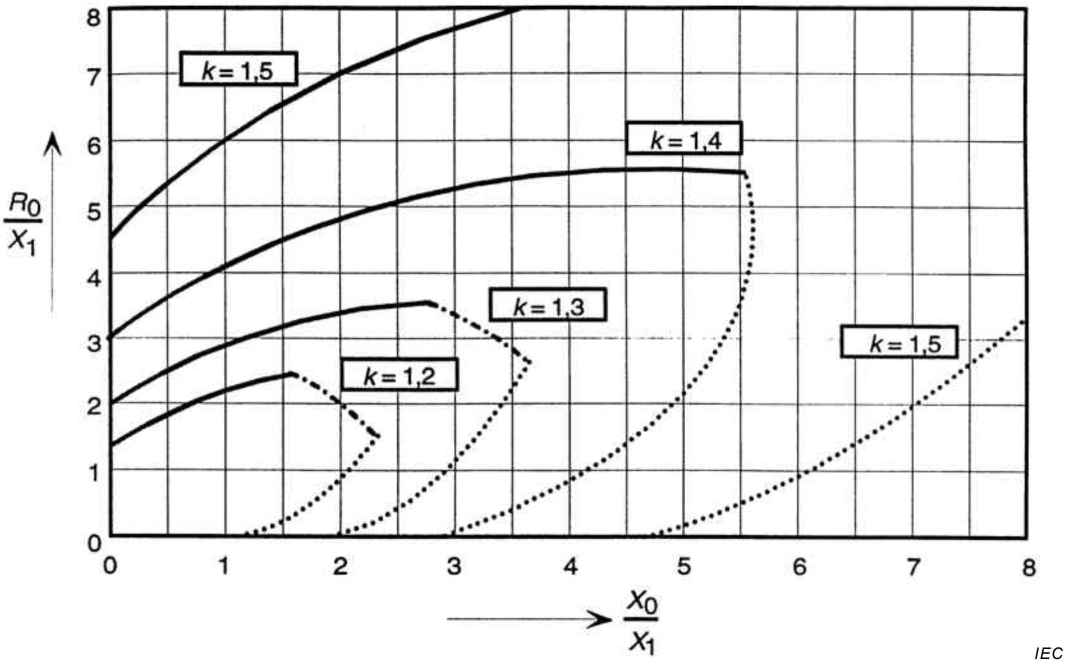


Figure A.4 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth fault factor k where $R_1 = X_1$

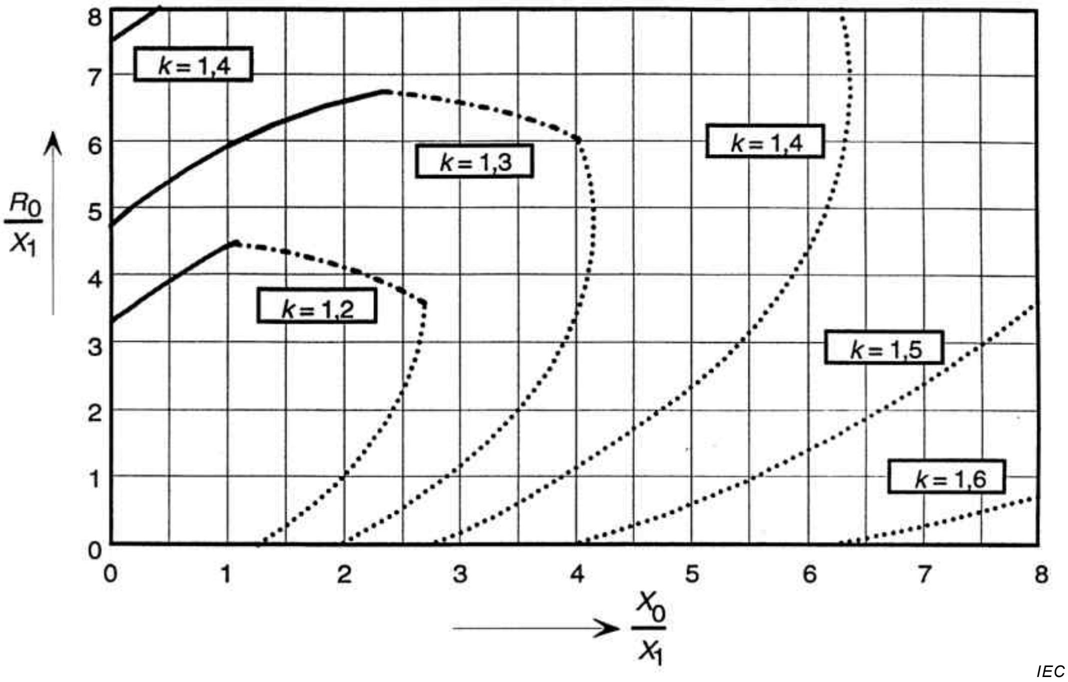


Figure A.5 – Relationship between R_0/X_1 and X_0/X_1 for constant values of earth fault factor k where $R_1 = 2X_1$

In Figure A.2 to Figure 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

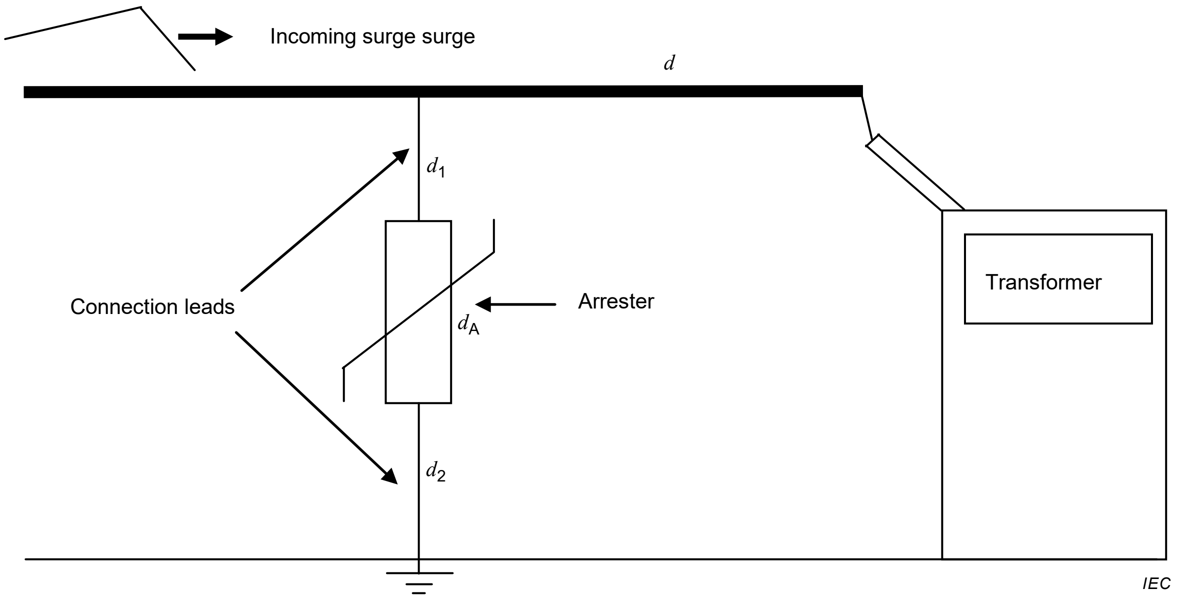
For the power supply systems within some countries, the application of this part of IEC 60099 may result in tables of consistently used surge arrester characteristics. For the use of this part of IEC 60099 within such countries, tables containing these characteristics may be added to this Annex, without deviating from this part of IEC 60099.

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 Figure 8 and Figure 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 μH/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 μH/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.

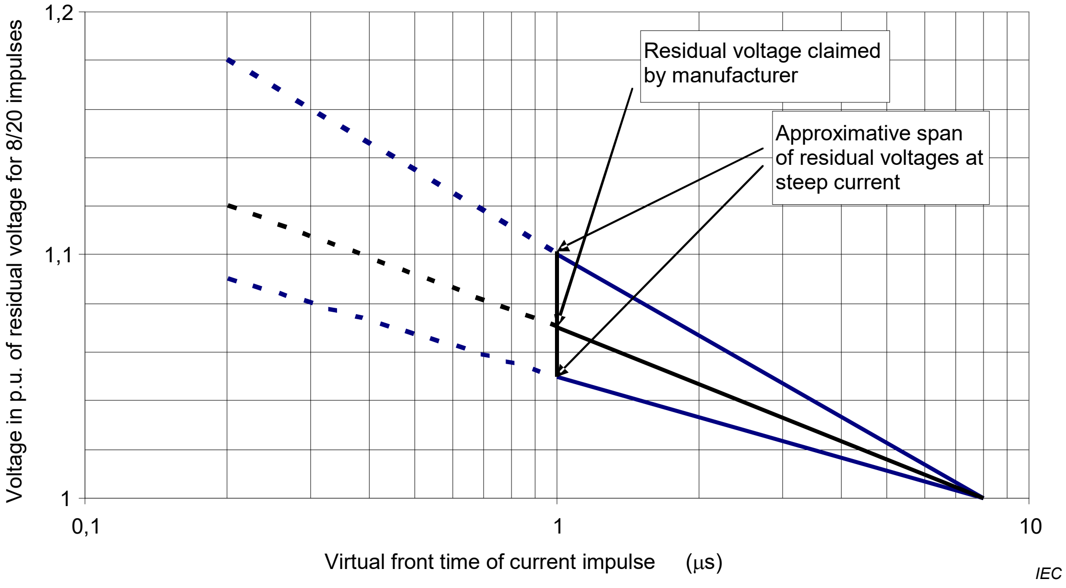


Key

d	length of conductor between transformer bushing 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 1μH/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 µs only indicate the estimated trend. When more accurate values are needed, the manufacture should be consulted.

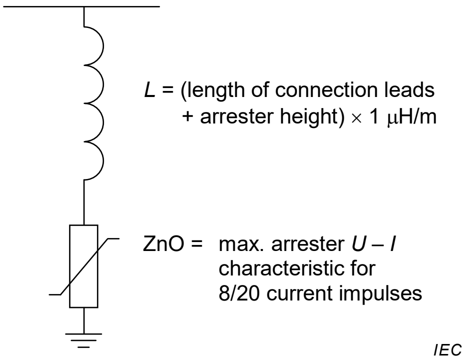
Figure C.2 – Increase in residual voltage as function of virtual current front time

C.2 Application to insulation coordination studies

Normally, decisive cases involve virtual current front times through the arrester of approximately 1 µs. 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

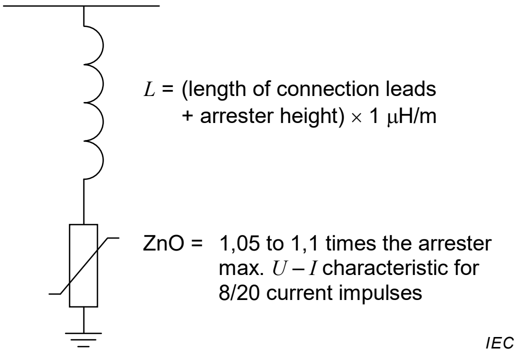
To summarise, the following models as shown in Figure C.3 to Figure C.5 are proposed for use under impulse conditions.



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 μH/m.

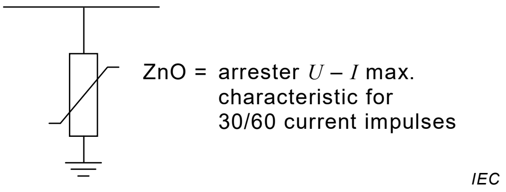
Figure C.3 – Arrester model for insulation coordination studies – fast- front overvoltages and preliminary calculation (Option 1)



The steepness of current surge (virtual front time of wave) is determined from the preliminary calculation. The U-I characteristics are then adjusted accordingly, and the calculations repeated.

NOTE For GIS arresters the inductance is set to 0,3 μH/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 Overview

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 especially suited for the purpose, e.g. mobile AC or DC 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.

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 AC 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.

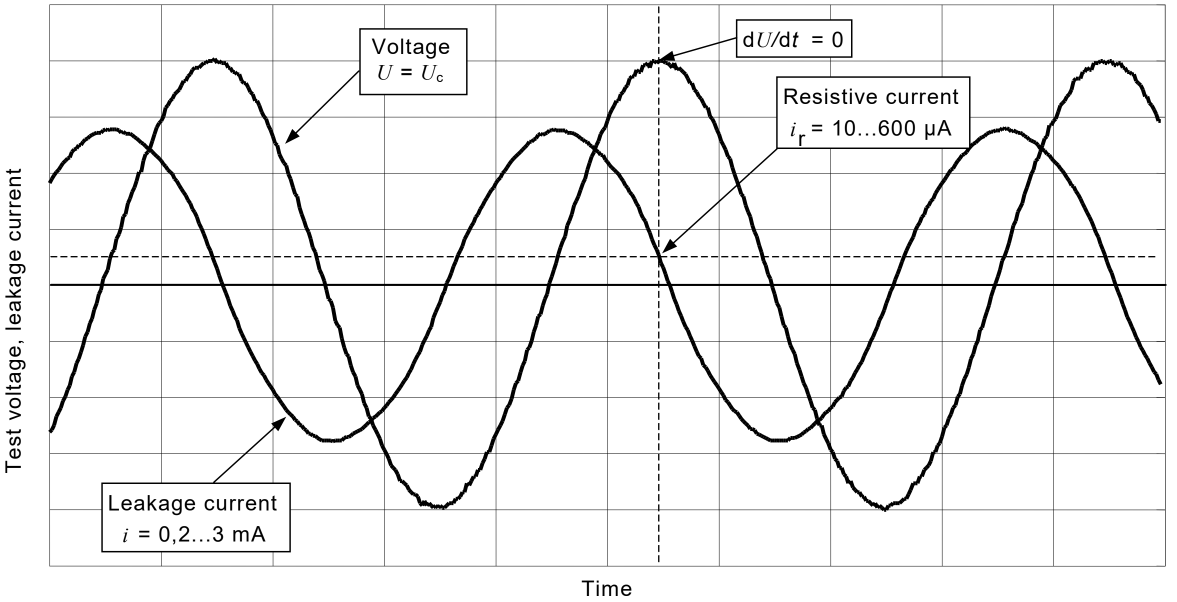


Figure D.1 – Typical leakage current of a non-linear metal-oxide resistor in laboratory conditions

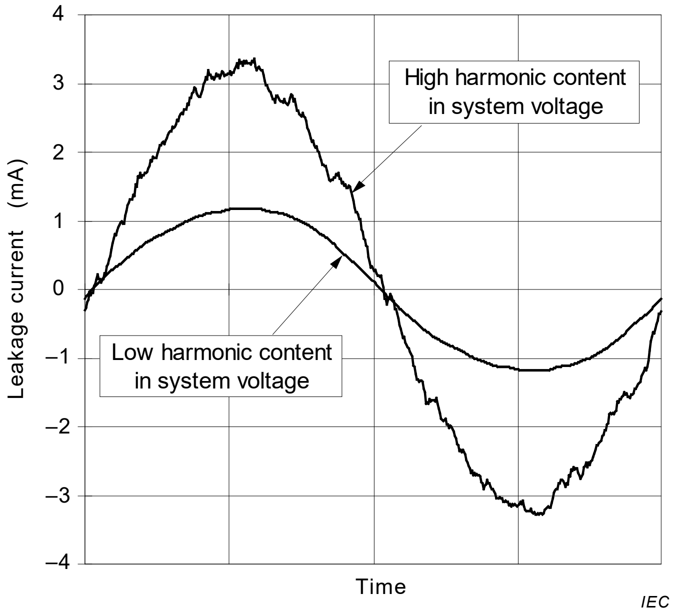


Figure D.2 – Typical leakage currents of arresters in service conditions

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 AC voltages are shown in Figure D.3. For comparison, typical characteristics for DC voltages are also shown in Figure D.3.

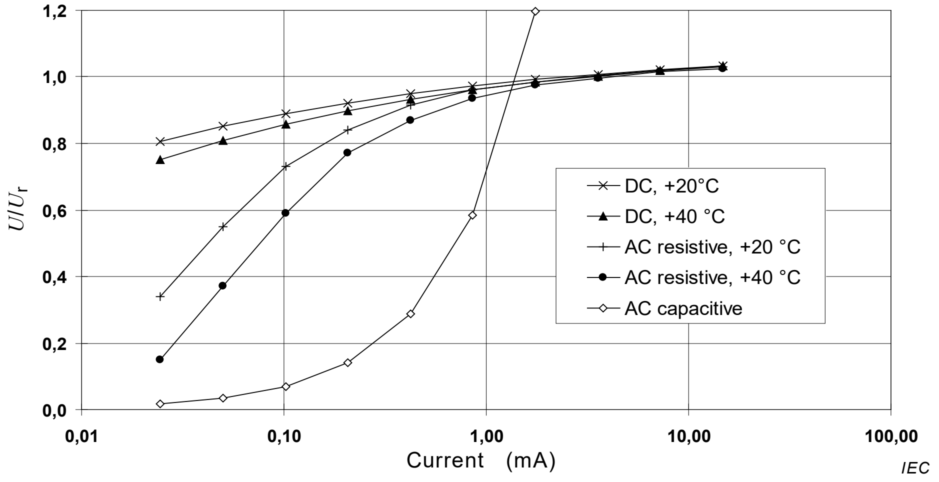


Figure D.3 – Typical voltage-current characteristics for non-linear metal-oxide resistors

The resistive component under AC 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 μA to 600 μA 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 AC voltage are indicated in Figure D.4 and Figure D.5, normalized to U_c and at +20 °C, respectively.

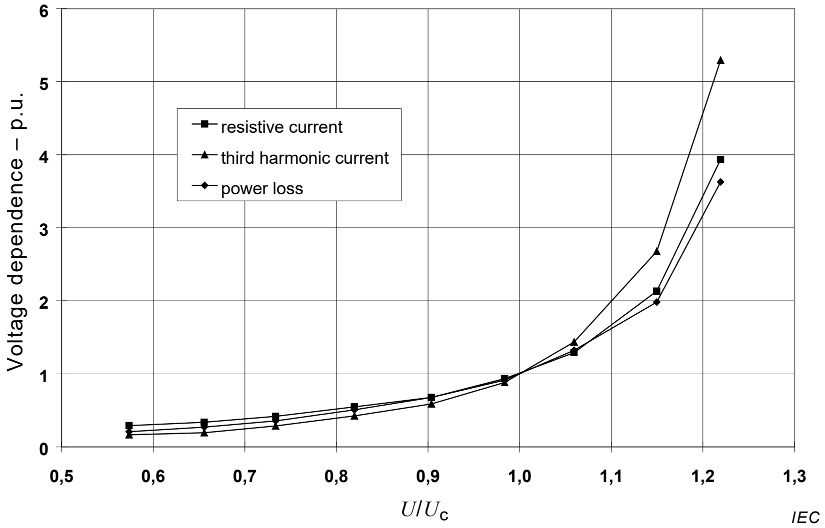


Figure D.4 – Typical normalized voltage dependence at +20 °C

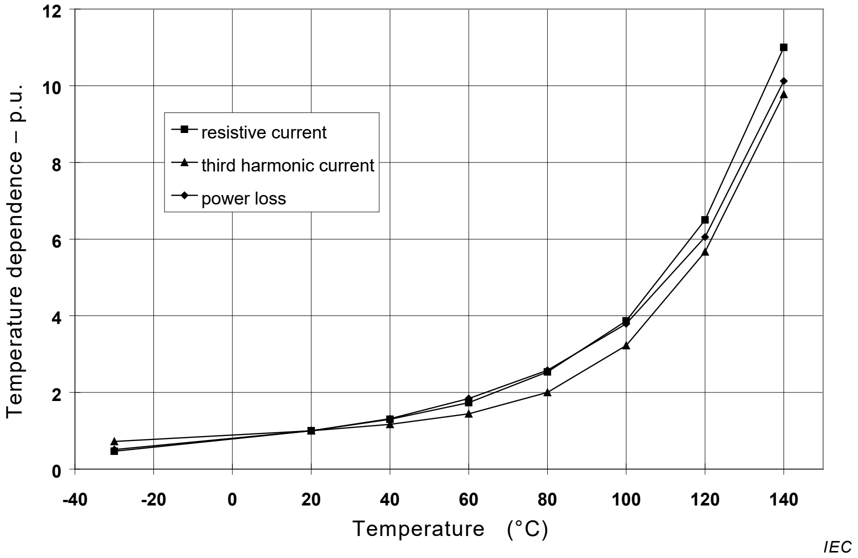


Figure D.5 – Typical normalized temperature dependence at U_c

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 AC voltage are indicated in Figure D.4 and Figure 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 Figure D.4 and Figure 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.

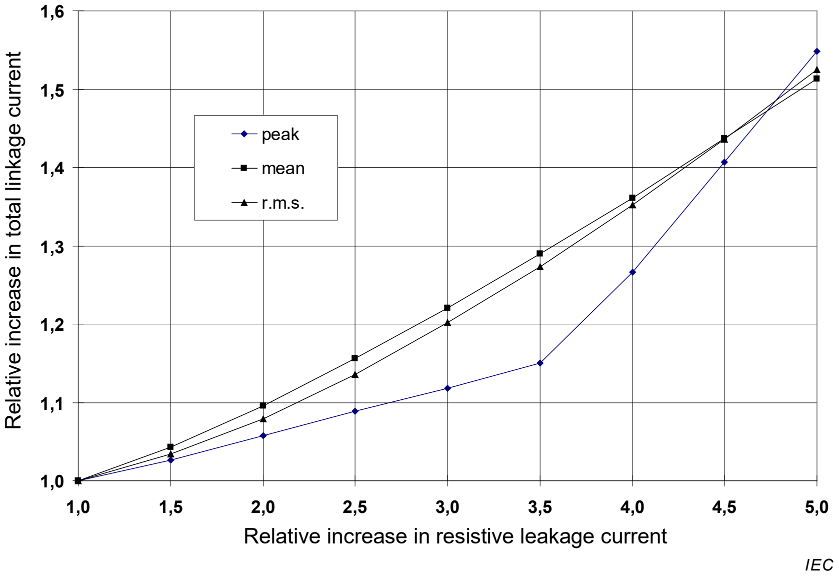


Figure D.6 – Influence on total leakage current by increase in resistive leakage current

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 ($\mathrm{d}U/\mathrm{d}t = 0$). 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

$$I_t(t) = I_c(t) + I_r(t) = C\,\frac{dU(t)}{dt} + I_r(t) \tag{D.1}$$

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

$$I_r(t_1) = I_r(t_2) = \left(\frac{1}{2}(\,I_t(t_1) + I_t(t_2)\,)\right) - \left(\frac{1}{2}(\,I_t(t_1) - I_t(t_2)\,)\right)\left(\frac{\frac{dU(t_1)}{dt} + \frac{dU(t_2)}{dt}}{\frac{dU(t_1)}{dt} - \frac{dU(t_2)}{dt}}\right) \tag{D.2}$$

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:

$$I_r(t_1) = I_r(t_2) = \frac{1}{2}\left(I_t(t_1) + I_t(t_2)\right) \tag{D.3}$$

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.

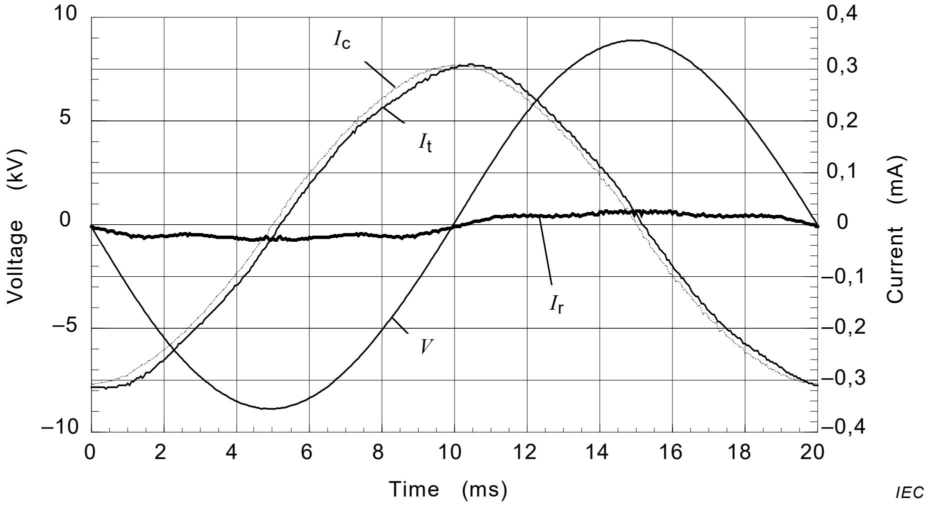


Figure D.7 – Measured voltage and leakage current and calculated resistive and capacitive currents (V = 6,3 kV r.m.s)

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.

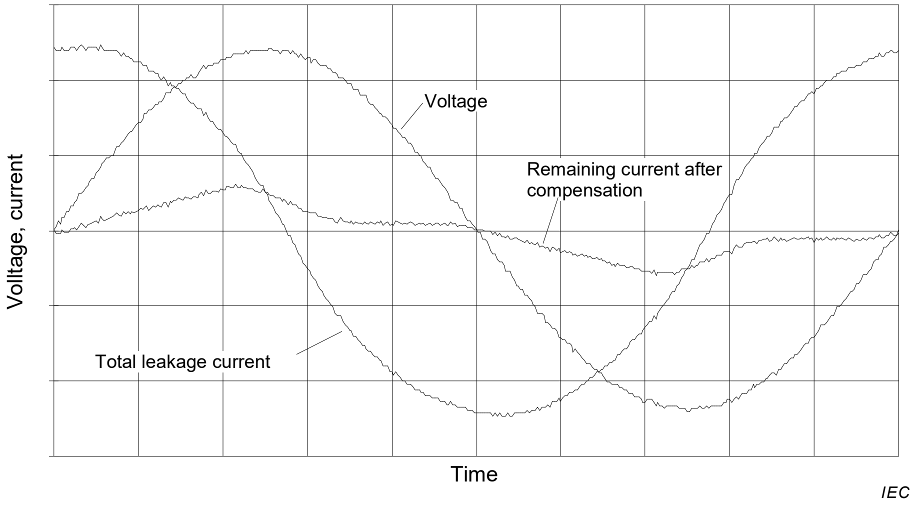


Figure D.8 – Remaining current after compensation by capacitive current at U_c

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 Figure D.4 and Figure 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.

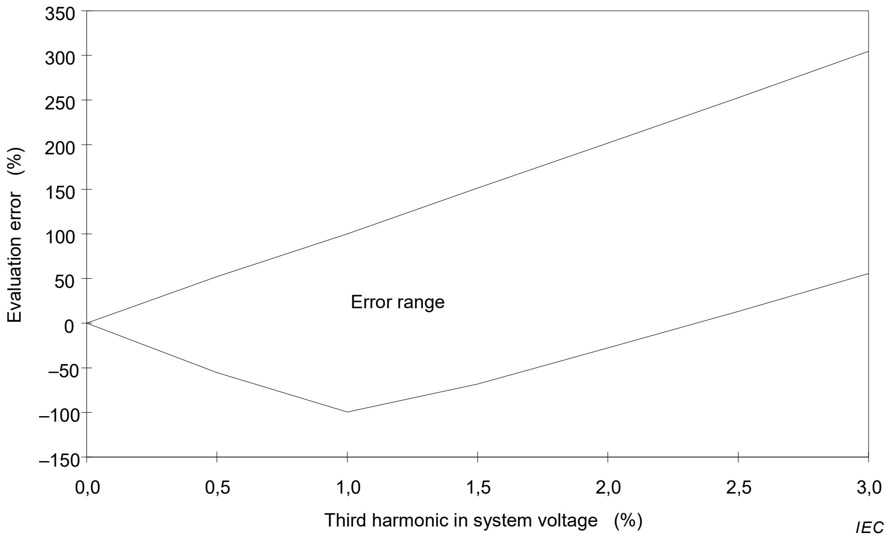


Figure D.9 – Error in the evaluation of the leakage current third harmonic for different phase angles of system voltage third harmonic, considering various capacitances and voltage-current characteristics of non-linear metal-oxide resistors

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 °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 °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 Figure D.10 and Figure D.11.

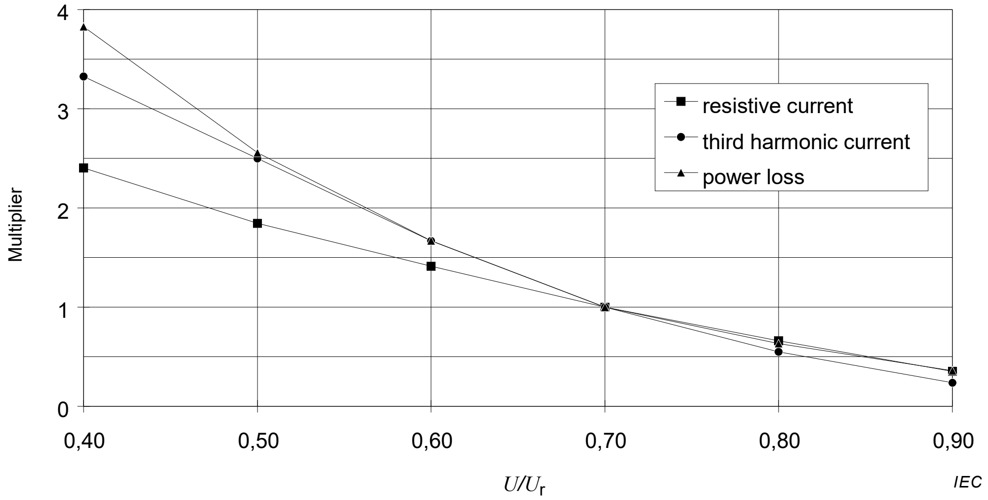


Figure D.10 – Typical information for conversion to "standard" operating voltage conditions

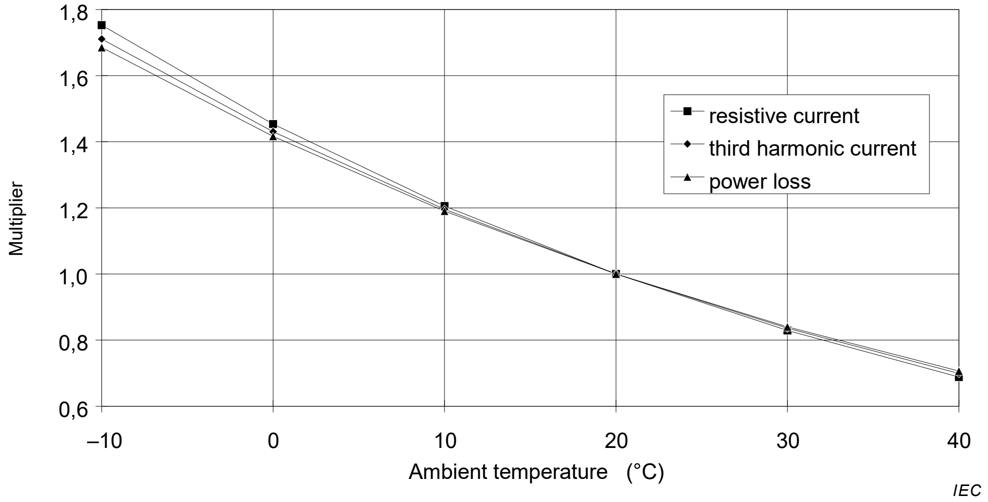


Figure D.11 – Typical information for conversion to "standard" ambient temperature conditions

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
Leakage current measurement 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 DC voltage source		n.a.	n.a.	high	high	high	limited
Service voltage or separate AC 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.a.
– using capacitive current cancellation	A4	high	high	high	low	low	limited
Harmonic analysis of leakage – 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(r.m.s. value)
Continuous operating voltage, U_c	kV(r.m.s. value)
Nominal discharge current, I_n	kA
Designation	DL, DM, DH, SL, SM, SH
Q_{rs}	C
W_{th} Substation Arresters	kJ/kV
Q_{th} Distribution & Line Arresters	C
Lightning impulse protective level, LIPL	kV(crest value)
Switching impulse protective level, SIPL[a)]	kV(crest value)
Rated short-circuit current, I_s	kA(r.m.s. 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

Table F.1 and Table 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 to 29				2,6 to 4,0	2,3 to 3,6	2,0 to 2,9
30 to 132	2,6 to 3,1	2,3 to 2,8	2,0 to 2,3	2,6 to 3,7	2,3 to 3,3	2,0 to 2,6
144 to 342	2,6 to 3,1	2,3 to 2,8	2,0 to 2,3	2,6 to 3,7	2,3 to 3,3	2,0 to 2,6
360 to 756	2,6 to 3,1	2,3 to 2,8	2,0 to 2,3	2,6 to 3,1	2,3 to 2,8	2,0 to 2,3
780 to 900	2,1 to 2,8	1,9 to 2,4	1,6 to 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, and 2 500 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	
kV r.m.s.	**Steep**	**Lightning**	**Steep**	**Lightning**
0,175 to 2,9	2,7 to 4,0	2,4 to 3,6	3,7 to 5,0	3,3 to 4,5
3 to 29	2,7 to 4,0	2,4 to 3,6	4,0	3,6
30 to 132	2,7 to 3,7	2,4 to 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 substation 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 substation 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 Steepness reduction factor

The voltage across a capacitor, when it is being charged through a line surge impedance, is given by G.1:

$$u(t) = 2{,}0\ \times U_{\text{Surge}} \times \left(1 - e^{-\frac{t}{Z \times C}}\right) \tag{G.1}$$

where

Z Line surge impedance (real value; i.e. lossless)

C Total capacitance

U_{surge} Incoming surge magnitude, in V, based on attenuation and corona distortion

NOTE An estimate of U_{surge} is $U_{\text{surge}} \approx 1{,}2 \text{ x } U_{50}$, where U_{50} is the line insulation critical flashover (CFO) voltage

The steepness of this voltage is:

$$S_0 = \frac{du(t)}{dt} = \frac{2{,}0 \times U_{\text{Surge}} \times e^{-\frac{t}{Z \times C}}}{Z \times C} \tag{G.2}$$

For steepness affected by corona alone,

$$S_0(t) = \frac{2{,}0\ \times\ U_{\text{surge}}\ \times\ e^{-\frac{t}{Z \times C_0}}}{Z \times C_0}$$

where

C_0 equivalent surge capacitance of the incoming surge related to corona

In the case of additional line terminal capacitance, the steepness becomes

$$S_s(t) = \frac{2{,}0 \times U_{\text{surge}} \times e^{-\frac{t}{Z\times(C_0+C_s)}}}{Z \times (C_0 + C_s)}$$

where

C_s additional surge capacitance at line terminal

The ratio of steepnesses (steepness reduction factor) is then given by

$$f_s(t) = \frac{S_s(t)}{S_0(t)} = \frac{C_0}{C_0 + C_s} \times \frac{e^{-\frac{t}{Z\times(C_0+C_s)}}}{e^{-\frac{t}{Z\times C_0}}}$$

For the surge front, near t = 0, this simplifies to

$$f_s \approx \frac{C_0}{C_0+C_s} \qquad \text{(G.3)}$$

The steepness of the original incoming surge S_0 associated with line corona and accepted equipment failure rate distance from substation is given in formula G.4:

$$S_0 = \frac{A \times \frac{c}{2}}{L_{\text{sp}} + L_{\text{f}}} \quad \text{in kV/µV} \qquad \text{(G.4)}$$

where

A From Table 3 in 6.3.2.7, in kV

c 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.

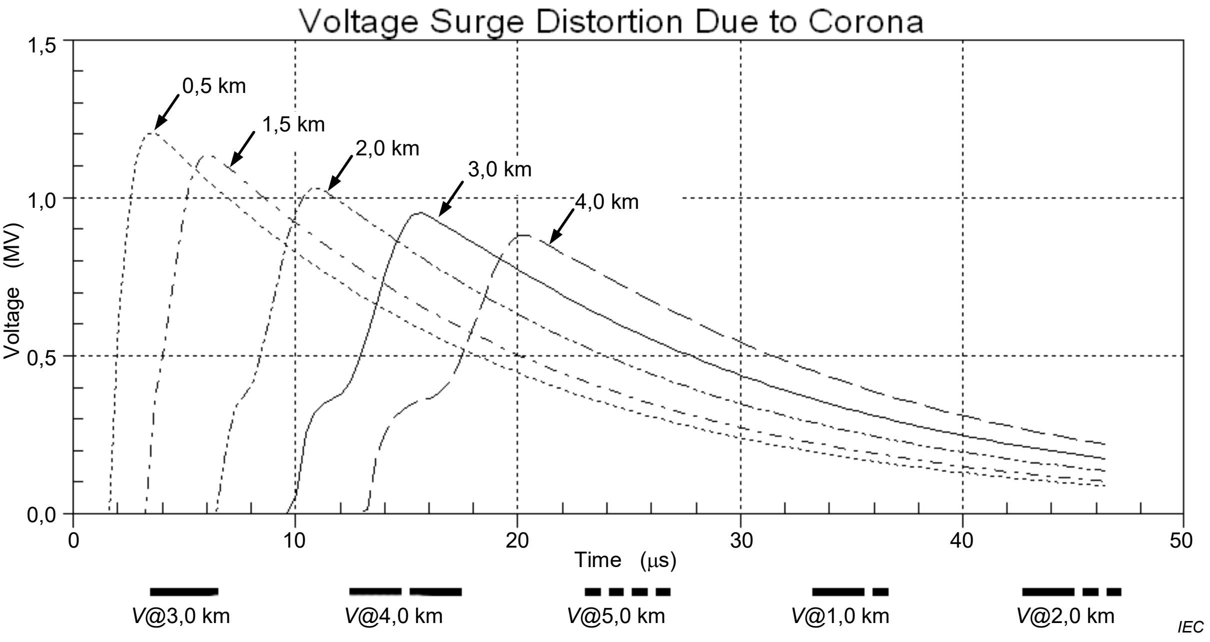


Figure G.1 – Surge voltage waveforms at various distances from strike location (0,0 km) due to corona

G.3 Equivalent capacitance associated with incoming surge fronts

G.3.1 General

If $t_0/(Z \times C_0)$ is taken to be a fixed value,the equivalent capacitance C_0, associated with the original incoming surge with steepness S_0, can be estimated by equating two values of t_0 as follows:

1) if $t_0/(Z \times C_0)$ is assumed constant at 0,5 then:

$$\frac{t_0}{Z \times C_0} = 0{,}5 \quad \text{or} \quad t_0 = 0{,}5 \times Z \times C_0$$

2) but also, t_0, the time taken by the incoming surge with steepness S_0 to attain voltage $U_{\text{cap}}(t_0)$, is given by:

$$t_0 = \frac{U_{cap}(t_0)}{S_0}$$

$$U_{cap}(t_0) = 2 \times U_{\text{Surge}} \times (1 - e^{-0{,}5}) = 0{,}8 \times U_{\text{Surge}}$$

$$t_0 = \frac{0{,}8 \times U_{\text{Surge}}}{S_0}$$

Solve for equivalent capacitance C_0 by equating the above two formulas for t_0:

$$t_0 = 0{,}5 \times Z \times C_0 = \frac{0{,}8 \times U_{\text{Surge}}}{S_0}$$

and thereby obtain equivalent capacitance:

$$C_0 = \frac{1{,}6 \times U_{\text{Surge}}}{Z \times S_0} \qquad \text{(G.5)}$$

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:

$$f_{\text{s}} = \frac{S_{\text{s}}}{S_0} = \frac{C_0}{C_0 + C_{\text{s}}} = \frac{1}{1 + \frac{C_{\text{s}}}{C_0}}$$

Therefore, modified steepness S_{s} is related to f_{s} and S_0 as follows in formula G.6:

$$S_{\text{s}} = f_{\text{s}} \times S_0 \qquad \text{(G.6)}$$

Table G.1 shows the influence of the effective surge capacitance at line terminal on the steepness reduction.

Table G.1 – C_s impact on steepness ratio f_s and steepness S_n

CFO = 1900	U_{surge} ~ 1,2 × CFO		S_0(kV/us) = K_c/L		C_0(nF) = (10^3 × 1,6 × U_{cap})/(Z × S_0)			$S_S = f_s \times S_0$ $f_s = C_0/(C_0 + C_s)$	
U_{class}	U_{surge} [kV]	Z typical	K_c (kV-km/us)	D [km]	S_0 [kV/us]	C_0 [nF]	C_s [nF]	$f_s(S_n/S_0)$	S_c [kV/us]
500	2 280	320	1 700	0,50	3 400	3,4	0,0	1,00	3 400
							1,0	0,77	2 619
							2,0	0,63	2 130
							3,0	0,53	1 794
500	2 280	320	1 700	1,00	1 700	6,7	0,0	1,00	1 700
							1,0	0,87	1 479
							2,0	0,77	1 309
							3,0	0,69	1 175
CFO = 1200	U_{surge}~ 1,2 × CFO		S_0(kV/us) = K_c/L		C_0(nF) = (10^3 × 1,6 × U_{cap})/(Z × S_0)			$S_S = f_s \times S_0$ $f_s = C_0/(C_0 + C_s)$	
U_{class}	U_{surge} [kV]	Z typical	K_c (kV-km/us)	D [km]	S_0 [kV/us]	C_0 [nF]	C_s [nF]	$f_s(S_n/S_0)$	S_c [kV/us]
245	1 440	450	1 000	0,5	2 000	2,6	0,0	1,00	2 000
							1,0	0,72	1 438
							2,0	0,56	1 123
							3,0	0,48	921
245	1 440	450	1 000	1,0	1 000	5,1	0,0	1,00	1 000
							1,0	0,84	837
							2,0	0,72	719
							3,0	0,63	631

G.3.2 Examples of incoming surge steepness change, f_s, using typical 550 kV & 245 kV circuit parameters

$$U(t) = 2{,}0 \times U\text{surge} \times \left(1 - e^{-[\frac{t}{Z \times C}]}\right)$$

$$A(t) \times \frac{t_0}{Z \times C_0} = 0{,}5 ; \quad e^{-0{,}5} = 0{,}6 ; \quad 1 - e^{-0{,}5} = 0{,}4$$

When

$$u(t_0) = 0{,}8 \times U_{surge} ; \qquad t_0 = \frac{0{,}8 \times U_{surge}}{S_0} = 0{,}5 \times Z \times C_0$$

$S_0 = \frac{K_c}{L}$; $K_c = A \times \frac{c}{2}$; $c = 0{,}3$ km/μs; L(km) = strike distance from substation

Therefore

$$\frac{0{,}8 \times U_{\text{surge}}}{S_0} = 0{,}5 \times Z \times C_0 \quad \text{or} \quad C_0 = \frac{1{,}6 \times U_{\text{surge}}}{Z \times S_0}$$

G.3.3 Change in coordination withstand voltage, U_{cw}, with steepness reduction, f_{s}:

$$U_{\text{cw}} = U_{\text{pl}} + \frac{A \times f_{\text{s}}}{N} \times \frac{L_{\text{t}}}{L_{\text{sp}} + L_{\text{f}}}$$

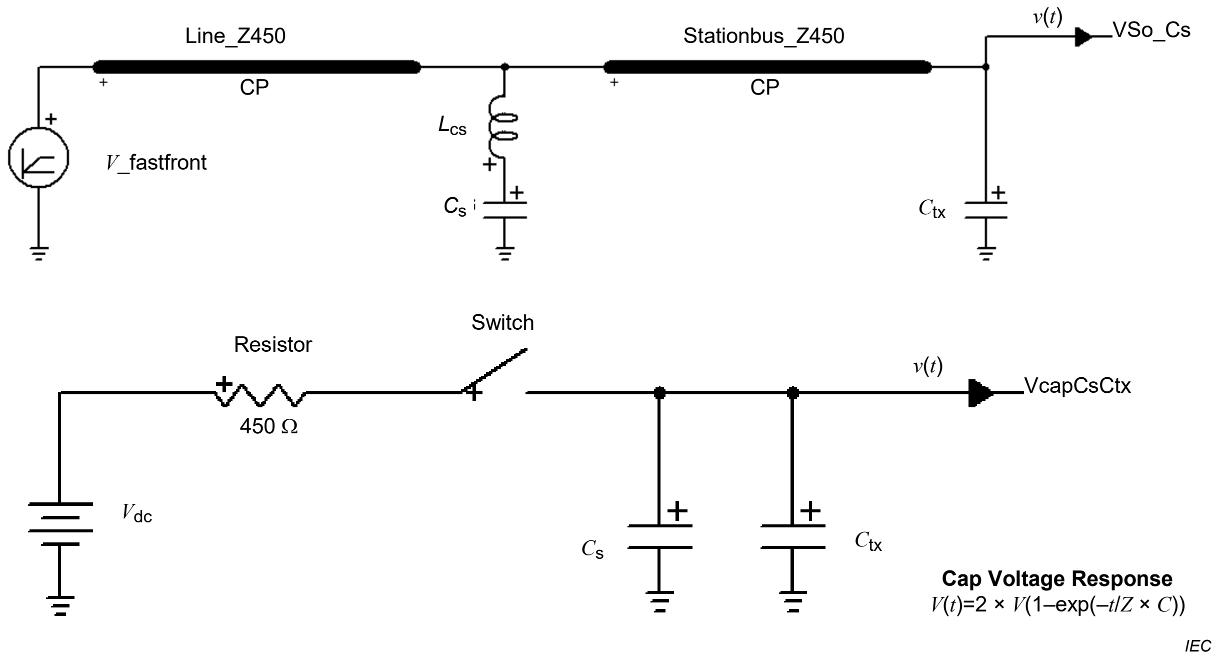
Table G.2 shows how U_{cw} changes for different surge steepness S_0 and steepness reduction f_{s}.

Table G.2 – Change in coordination withstand voltage, U_{cw}

N = 1 U_{sa} = 192 kV U_{pl} = 450 kV						
A(kV)	$L_{\text{sp}} + L_{\text{f}}$ (km)	L_{t}(km)	U_{pl}(kV)	S_0(kV/us)	f_{s}	U_{cw}(kV)
7000	0,3	0,02	450	3500	1	912
7000	0,3	0,02	450	3500	0,5	683
7000	0,6	0,02	450	1750	1	683
7000	0,6	0,02	450	1750	0,5	567

G.4 EMTP & capacitor charging models for steepness change comparisons at line open terminal

Two cases are shown in Figure G.2 and Figure G.3.



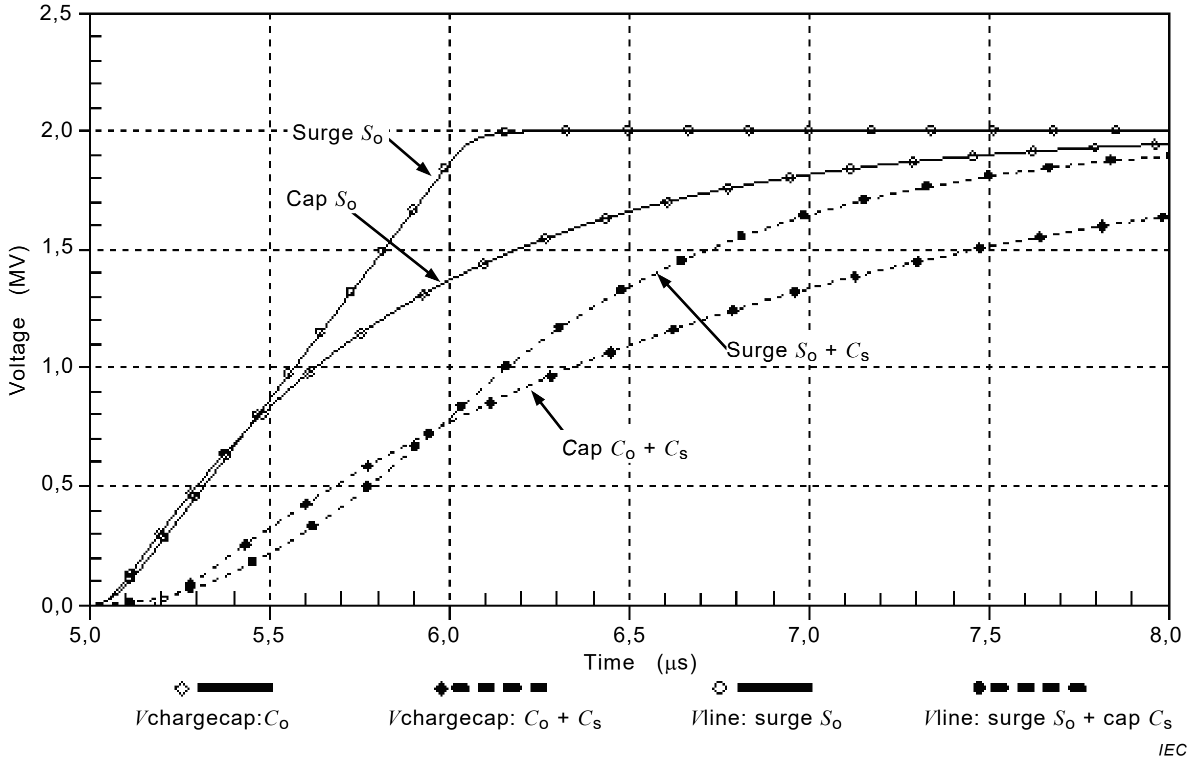
Example: U_{surge} = 1 000 kV, Z_{c} = 450 Ω, S_0 = 2 000 kV/µs

C_0 (corona equivalent) = 1,6 × $U_{\text{surge}}/(Z \times S_0)$ = 1,78 nF, C_{tx} = 0,1 nF

C_0 = 1,78 nF, C_{s} (in addition) = 1,78 nF, C_{total} = 3,76 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) & substation bus (Z,c) & Cap(C_{s})

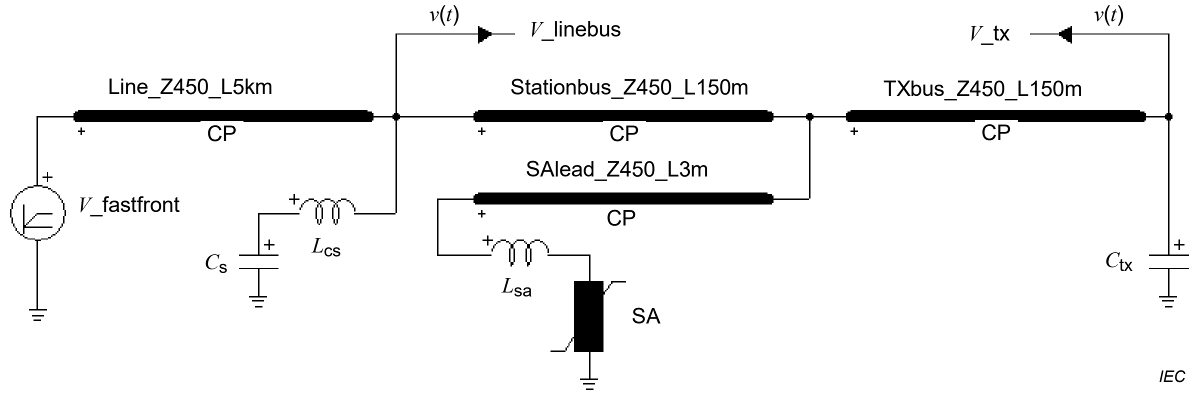


- Surge S_0 (no C_s): Surge with U_{cap} = 1 000 kV, S_0 = 2 000 kV/µs
- Surge $S_0 + C_s$ (with C_s): Surge with U_{cap} = 1 000 kV, S_0 = 2 000 kV/us and $C_s = C_0$ = 1,8 nF,
- Cap C_0: Capacitor C_0 = 1,8 nF charged through Z = 450 Ω,
- Cap $C_0 + C_s$: Capacitors C_0 = 1,8 nF and $C_s = C_0$ charged through Z = 450 Ω

Figure G.3 – Case 2: Capacitor Voltage charge via line Z: $u(t) = 2 \times U_{surge} \times (1 - \exp[-t/(Z \times C)])$

G.5 Typical steepness (S_0= 1000 kV/µs), change comparisons with C_0 & C_s

Figure G.4 shows the EMTP model used for a faster steepness example, while Figure G.5 and Figure G.6 show the results of the simulated surge analysis.



Distances; Surge arrester – Transformer = 20 m, Surge arrester – Line bus = 150 m

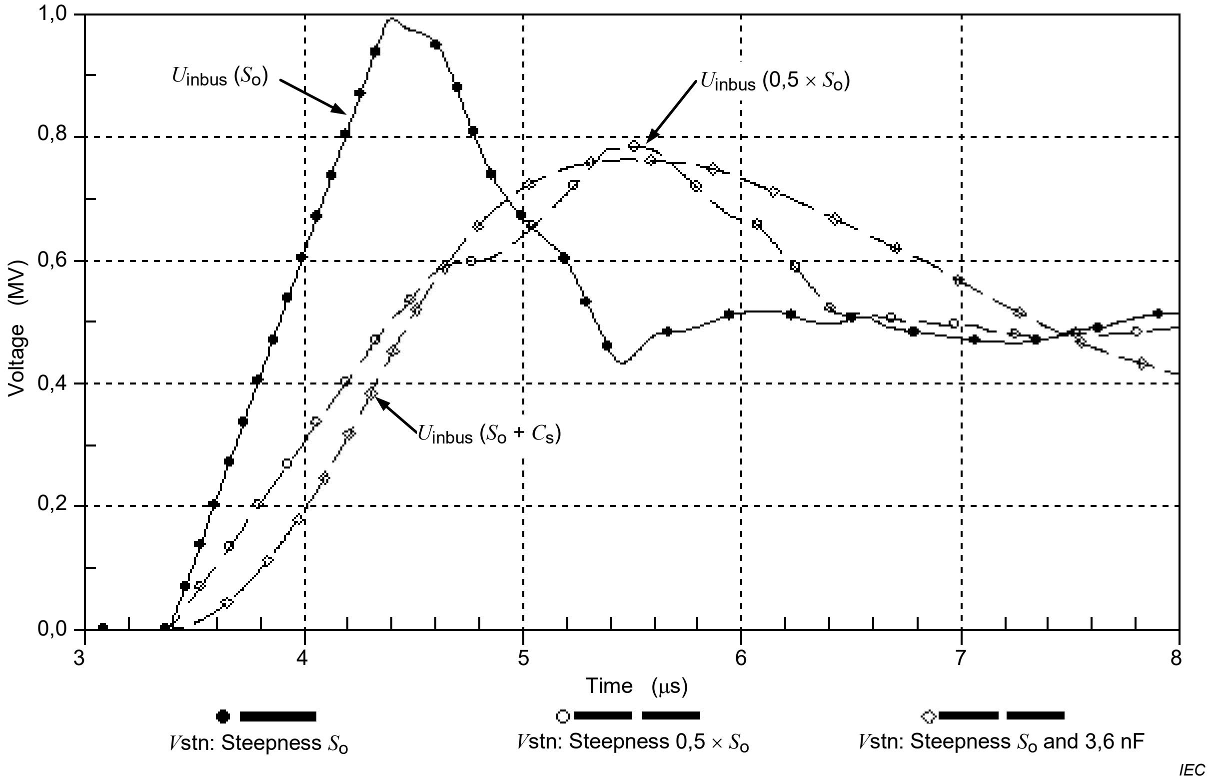
1st: S_0 = 1 000 kV/µs, U_{surge} = 1 000 kV, Z = 450 Ω, $C_0 = 1{,}6 \times U_{cap}/(Z \times S)$ = 3,6 nF

2nd: $S = S_0/2$ = 500 kV/µs U_{surge} = 1 000 kV

3rd: S_0 = 1 000 kV/µs and additional $C_s = C_0$ = 3,6 nF at line terminal

NOTE In the above figure V is used for the voltage instead of U.

Figure G.4 – EMTP model



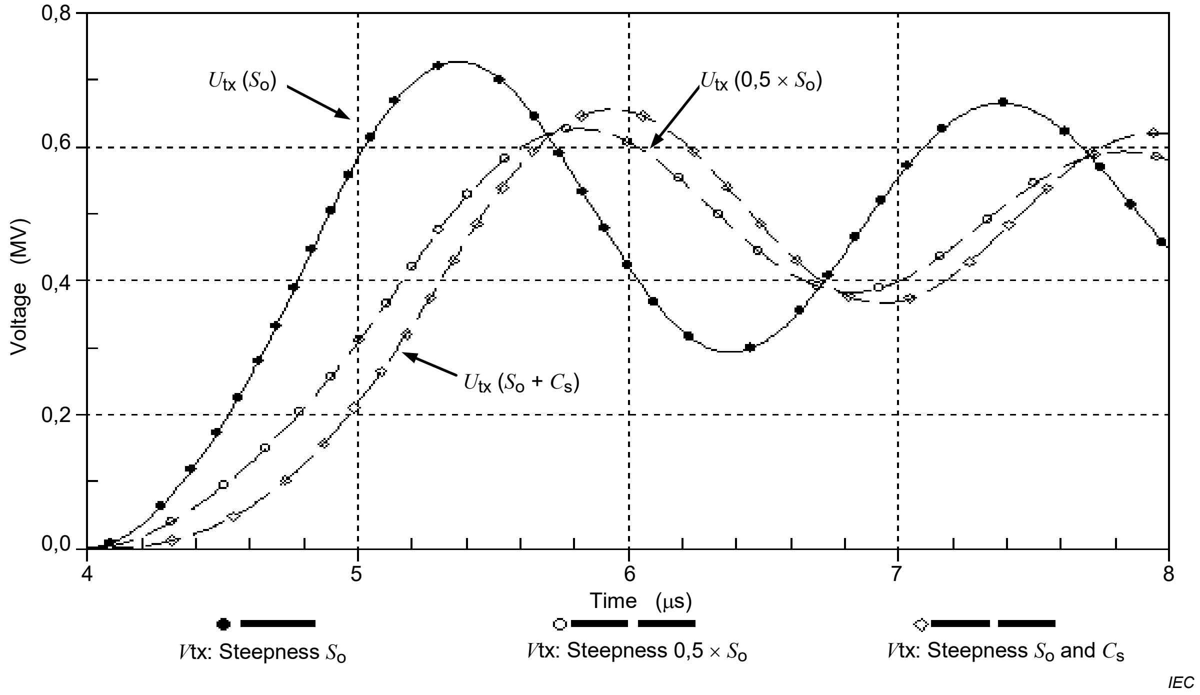
Distance: Surge arrester – Line substation bus interface = 150 m

Graph 1: S_0 = 1 000 kV/μs

Graph 2: $S_0/2 = 0,5 \times S_0$ = 500 kV/μs

Graph 3: $S_0 + C_s = S_0 + C_s$(3,6nF)

Figure G.5 – Simulated surge voltages at the line-substation bus interface



Distance: Surge arrester – Transformer = 20 m

Graph 1: S_0 = 1 000 kV/µs

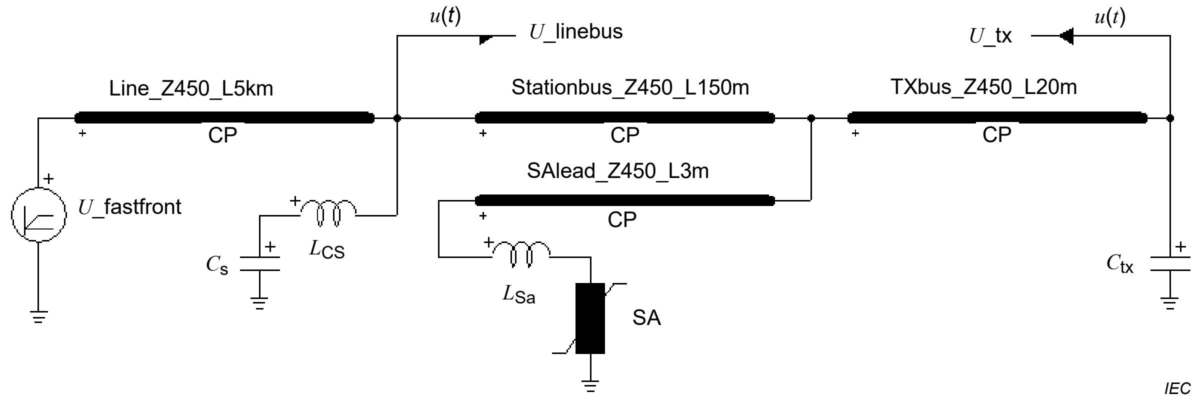
Graph 2: $S = S_0/2 = 0{,}5 \times S_0$ = 500 kV/µs

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_o & C_s

Figure G.7 shows the EMTP model used for a faster steepness example, while Figure G.8 and Figure G.9 show the results of the simulated surge analysis.



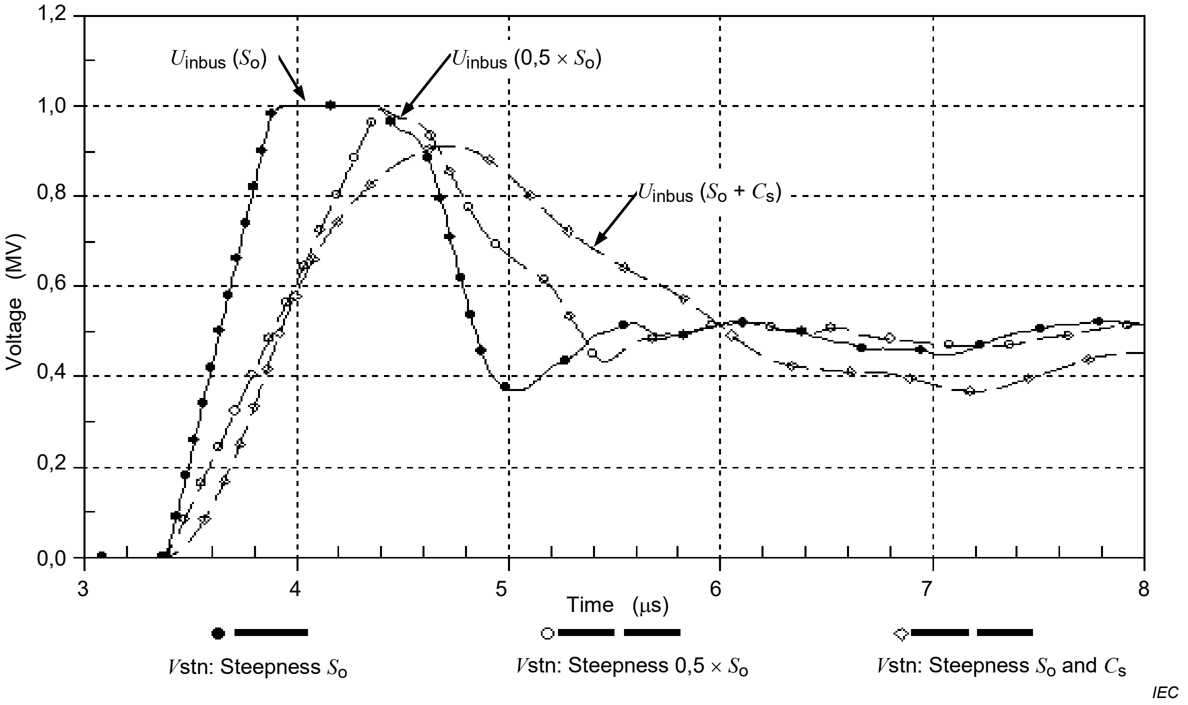
Distances: Surge arrester – Transformer = 20 m, Surge arrester – Linebus = 150 m

1st: S_0 = 2 000 kV/µs, U_{surge} = 1 000 kV, Z = 450 Ω, $C_0 = 1{,}6 \times U_{cap}/(Z \times S)$ = 1,8 nF, C_{tx} = 1nF

2nd: $S = S_0/2$ = 1 000 kV/µs U_{surge} = 1 000 kV

3rd: S_0 = 2000 kV/µs and additional $C_s = C_0$ = 1,8 nF at line terminal

Figure G.7 – EMTP model



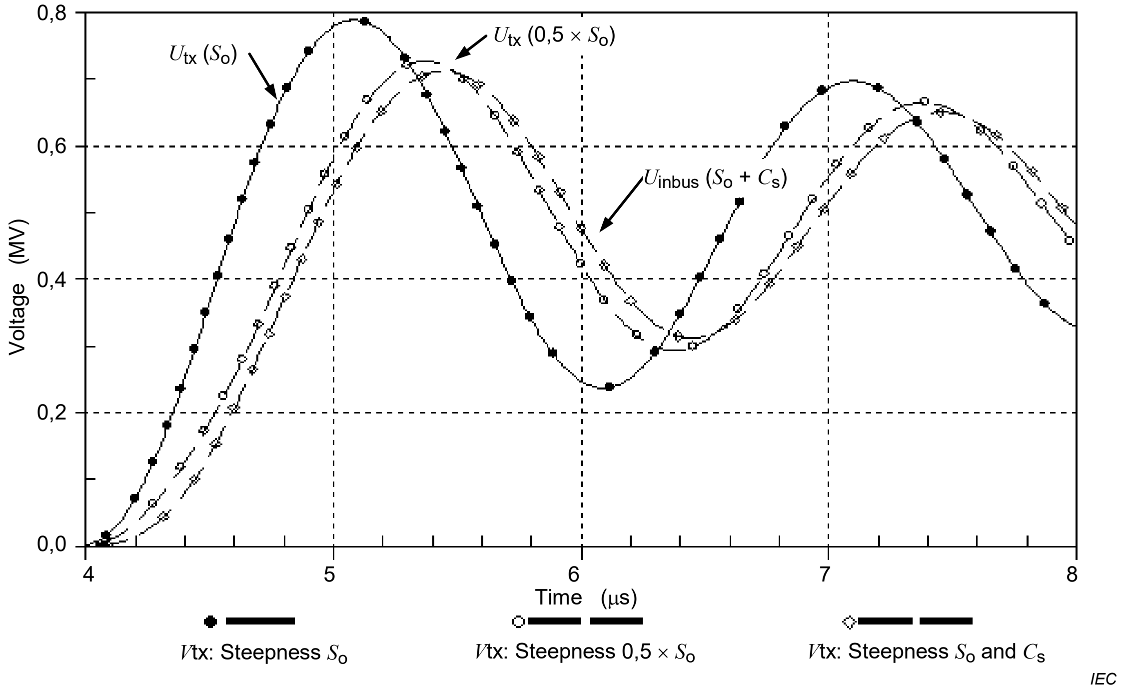
Distance: Surge arrester – Line substation bus interface = 150 m

Graph 1: S_0 = 2 000 kV/µs

Graph 2: $S = S_0/2 = 0,5 \times S_0$ = 1 000 kV/µs

Graph 3: $S_0\ C_s = S_0 + C_s$ (1,8 nF)

Figure G.8 – Simulated surge voltages at the line-substation bus interface



Distance: Surge arrester – Transformer = 20 m

Graph 1: S_0 = 2 000 kV/µs

Graph 2: $S = S_0/2 = 0,5 \times S_0$ = 1 000 kV/µs

Graph 3: $S_0C_s = S_0 + C_s$ (1,8 nF)

Figure G.9 – Simulated surge voltages at the transformer

Annex H
(informative)

Comparison of the former energy classification system based on line discharge classes and the present classification system based on thermal energy ratings for operating duty tests and repetitive charge transfer ratings for repetitive single event energies

H.1 General

To demonstrate energy handling capability of surge arresters “Long duration current impulse withstand tests” and “Switching impulse operating duty tests” had to be carried out according to IEC 60099-4:2009. The “Long duration current impulse withstand test” had to be performed on single metal oxide resistors and, therefore, was a MO resistor related test. The “Switching impulse operating duty test” had to be performed on prorated sections – representing electrical and thermal behaviour of the complete arrester – in order to verify thermal recovery after energy dissipation according to the particular line discharge class. It was, therefore, related to the MO resistor characteristic and the overall design of the complete arrester.

The parameters for the former line discharge test had been specified with the intention to obtain increasing energies with increasing discharge class for arresters having a given ratio of switching impulse residual voltage to rated voltage. However, the energy dissipated in the test samples during test was strongly dependent on the actual residual voltage of the tested MO resistors and in particular for the higher line discharge classes 3 to 5 as shown by Figure H.1. For estimating the discharge energy thus the minimum residual voltage of the arrester was important and not the maximum specified. By increasing the protection level of an arrester by e.g. adding more MO resistors in series the discharge test energy could be decreased and a higher line discharge class could be claimed for the same type of resistors. It was thus difficult to compare actual energy handling capability of an arrester by only the line discharge rating if the actual test energy was not also published.

For reference, Table 4, Table 5 and Figure E.1 from IEC 60099-4:2009, which provide relevant information for this discussion, are reproduced here as Table H.1, Table H.2 and Figure H.1, respectively.

Table H.1 – Peak currents for switching impulse residual voltage test

Arrester classification	Peak currents A
20 000 A, line discharge Classes 4 and 5	500 and 2 000
10 000 A, line discharge Class 3	250 and 1 000
10 000 A, line discharge Classes 1 and 2	125 and 500

Table H.2 – Parameters for the line discharge test on 20 000 A and 10 000 A arresters

Arrester classification	Line discharge class	Surge impedance of the line Z Ω	Virtual duration of peak T µs	Charging voltage U_L kV DC
10 000 A	1	4,9 U_r	2 000	3,2 U_r
10 000 A	2	2,4 U_r	2 000	3,2 U_r
10 000 A	3	1,3 U_r	2 400	2,8 U_r
20 000 A	4	0,8 U_r	2 800	2,6 U_r
20 000 A	5	0,5 U_r	3 200	2,4 U_r
U_r is the rated voltage of the test sample in kilovolts r.m.s.				
NOTE Classes 1 to 5 correspond to increasing discharge requirements. The selection of the appropriate discharge class is based on system requirements and is dealt with in Annex E.				

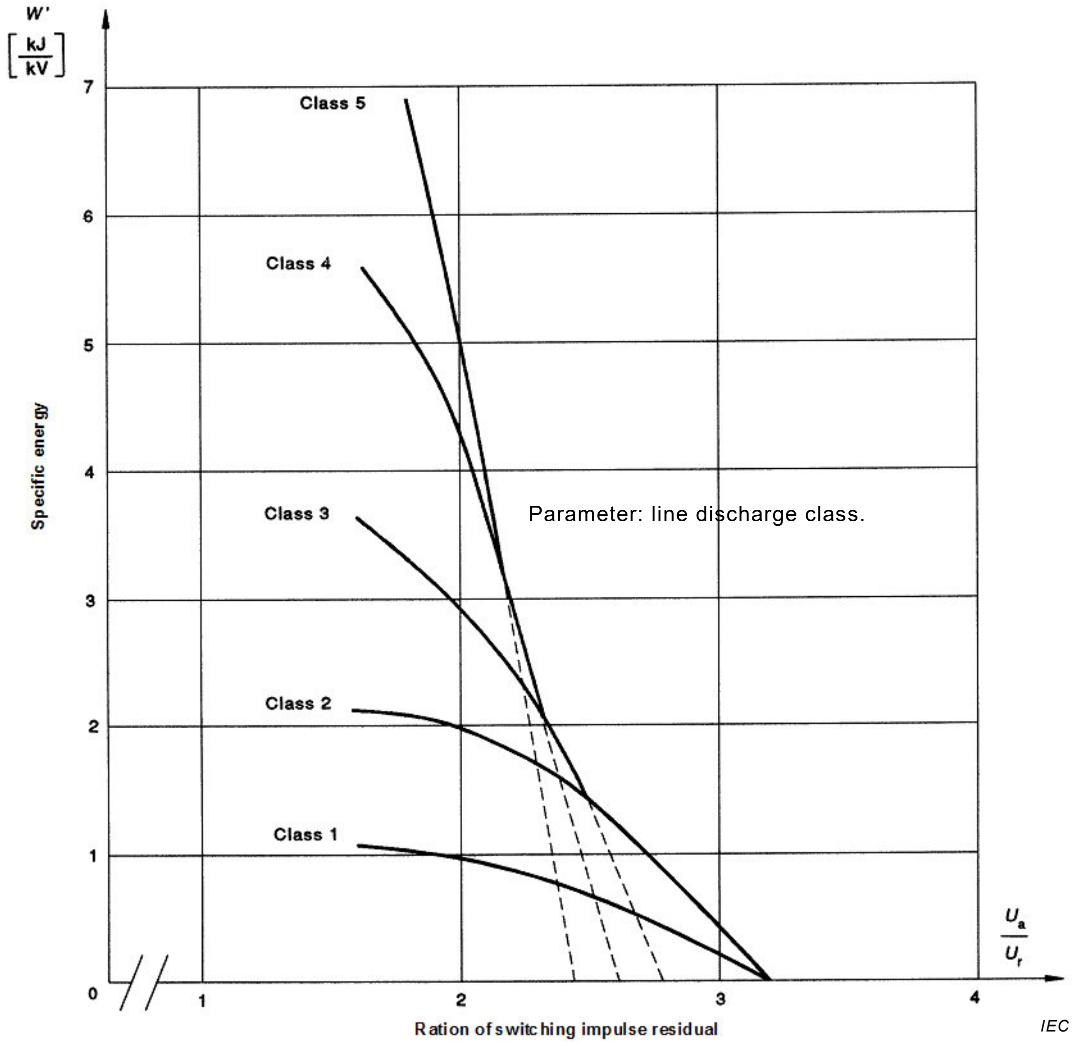


Figure H.1 – Specific energy in kJ per kV rating dependant on the ratio of switching impulse residual voltage (U_a) to the r.m.s. value of the rated voltage U_r of the arrester

The curves of Figure H.1 are derived from the formula

$$W' = \frac{U_{res}}{U_r}\left[\frac{U_L}{U_r} - \frac{U_{res}}{U_r}\right] \times \frac{U_r}{Z} \times T \tag{H.1}$$

where

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

U_L is the charging voltage of the generator;

W' is the specific energy equal to the energy divided by the rated voltage;

U_{res} is the residual voltage at switching impulse current (see Table H.1);

Z is the surge impedance of the line;

T is the virtual duration of the current peak.

In the present system, the line discharge classes are replaced by charge ratings to test the repetitive single event energy handling of a MO resistor and by energy ratings to test the thermal recovery of an arrester after energy dissipation.

In general, the following designations are used in this Annex:

U_r	rated voltage
LDC	line discharge class
U_{pl}	lightning impulse protection level
W	energy = $U_{res} \cdot (U_L - U_{res}) \cdot 1/Z \cdot T$ (required minimum test energy)
$U_{resmax}(I)$	maximum residual voltage at a given switching impulse current as per Table H.1
$U_{resmin}(I)$	minimum residual voltage at a given switching impulse current I as per Table H.1
U_L; Z; T	test parameters according to Table H.2

Table H.3 provides a comparison of the former (IEC 60099-4:2009) and the present (IEC 60099-4:2014) systems for typical system configurations.

Table H.3 – Comparison of the classification system according to IEC 60099-4:2009 and to IEC 6099-4 2014

For mer LDC	**Required minimum test energy**[a] kJ/kV	**Corresponding thermal energy rating as per Annex A W_{th}** kJ/kV	**Estimated current at former LD test** [b] A	**Charge calculated with the same current and duration as for former LDC to give the required minimum energy** C	**Corresponding repetitive charge transfer rating as per Annex A Q_{rs}** C	**Repetitive charge transfer test value (= 1,1 × Q_{rs})** C
1	1,0	2	277	0,56	0,5	0,55
2	2,1	4	538	1,10	1	1,10
3	3,3	7	721	1,78	1,6	1,76
4	5,0	10	962	2,75	2,4	2,64
5	6,9	14	1118	3,75	3,6	3,96

[a] Calculated with $U_{resmin}(I_{min}) = 1{,}8 \times U_r$ (see Figure L.1).

[b] Estimated from LD parameters and b) and c) above.

The discharge energies in the different line discharge classes are given under the following assumptions:

a) Maximum switching surge protection level $U_{resmax}(I_{max}) = 2{,}0 \times U_r$ at maximum currents in Table H.1.

b) Minimum switching surge protection level U_{resmin} (I_{max}) = 1,9 × U_{r} at maximum currents in Table H.1.

c) Minimum residual voltage U_{resmin} (I_{min}) = 1,8 × U_{r} at minimum currents in Table H.1.

MO resistors with the highest acceptable residual voltage in the design shall be tested. This may reduce the selected rated charge additionally.

H.2 Examples

The first of the following examples provides detailed steps in the calculation of current, energy and charge for an arrester with line discharge class 2. Subsequent examples are given for arresters with line discharge classes 3, 4 and 5. In these subsequent examples, the same approach as for the first example is used, but the details of the steps have been omitted. Arresters with different ratios of protective level to rated voltage are given to illustrate the impact of arrester protective level on current, energy and charge. In particular, two different cases are given for line discharge class 3 and two different cases are given for line discharge class 5.

Example 1 with detailed steps

This example, for line discharge class 2, uses line discharge parameters based on Table H.2 and minimum and maximum switching impulse currents given in Table H.1.

U_{r} = 120 kV (for system voltage, U_{s} = 145 kV)

LDC = 2

T = 2 000 µs

L = T / 2 × 3×10^8 m/s = 300 km (corresponding line length)

Z = 2,4 × U_{r} = 2,4 Ω/kV × 120 kV = 288 Ω

I_{n} = 10 kA

U_{pl} = 310 kV

U_{rp} = 3,2 × U_{r} = 3,2 x 120 kV = 384 kV (corresponding to 2,6 pu of U_{s})

$U_{\text{resmax (500 A)}}$ = 240 kV (2,00 x U_{r})

$U_{\text{resmin (500 A)}}$ = 228 kV (1,90 x U_{r})

$U_{\text{resmin (125 A)}}$ = 216 kV (1,80 x U_{r})

- The arrester current, I_{a}, during the line discharge corresponds to the intersection of the load line voltage, U_{L}, and the surge arrester characteristic for switching surges, U_{ps}, linearized between I_{min} and I_{max}.

  Load line voltage: $U_{\text{L}} = U_{\text{rp}} - Z \times I$

  Surge arrester characteristic linearized between I_{min} and I_{max}

  $$U_{\text{ps}} = U_{\text{resmin (125 A)}} + (I - I_{\text{min}}) \times (U_{\text{resmin (500 A)}} - U_{\text{resmin (125 A)}}) / (I_{\text{max}} - I_{\text{min}})$$

  Defining the arrester current, I_{a}, when $U_{\text{L}} = U_{\text{ps}}$ and solving for this current, we obtain:

  $$I_{\text{a}} = [U_{\text{rp}} - U_{\text{resmin (125 A)}} + I_{\text{min}} \times (U_{\text{resmin (500 A)}} - U_{\text{resmin (125 A)}}) / (I_{\text{max}} - I_{\text{min}})] / [(U_{\text{resmin (500 A)}} - U_{\text{resmin (125 A)}}) / (I_{\text{max}} - I_{\text{min}}) + Z]$$

  $$I_{\text{a}} = [384\text{ kV} - 216\text{ kV} + 0{,}125\text{ kA} \times (228\text{ kV} - 216\text{ kV}) / (0{,}5\text{ kA} - 0{,}125\text{ kA})] / [(228\text{ kV} - 216\text{ kV}) / (0{,}5\text{ kA} - 0{,}125\text{ kA}) + 288\ \Omega] = 0{,}538\text{ kA}$$

  Load line voltage : $U_{\text{ps}} = U_{\text{rp}} - Z \times I$

  Surge arrester characteristic linearized between I_{min} and I_{max}

  $U_{\text{ps}} = U_0 + R_{\text{a}} \times I_{\text{a}}$

  $R_{\text{a}} = (U_{\text{resmin (500 A)}} - U_{\text{resmin (125 A)}}) / (I_{\text{max}} - I_{\text{min}})$

$U_0 = U_{\text{resmin (125 A)}} - I_{\text{min}} \text{ x } R_{\text{a}}$

Defining the arrester current, I_{a} and solving for this current, we obtain:

$U_0 + R_{\text{a}} \text{ x } I_{\text{a}} = U_{\text{rp}} - Z \text{ x } I_{\text{a}}$

$I_{\text{a}} = (U_{\text{rp}} - U_0) / (\text{Z} + R_{\text{a}})$

$R_{\text{a}} = (228 \text{ kV} - 216 \text{ kV}) / (500 \text{ A} - 125 \text{ A}) = 32\ \Omega$

$U_0 = 216 \text{ kV} - 125 \text{ A x } 32\ \Omega = 212 \text{ kV}$

$I_{\text{a}} = (384 \text{ kV} - 212 \text{ kV}) / (\ 288\ \Omega + 32\ \Omega) = 0{,}538 \text{ kA}$

The calculated current is the same as in Table H.3 for LDC 2.

- Minimum test energy obtained using $U_{\text{resmin (125 A)}}$.

  $W = (U_{\text{rp}} - U_{\text{resmin (125 A)}}) / \text{Z} \times U_{\text{resmin (125 A)}} \times T$

  $W = (384 \text{ kV} - 216 \text{ kV}) / 288\ \Omega \times 216 \text{ kV} \times 2\ 000\ \mu\text{s} = 252 \text{ kJ}$

  $W / U_{\text{r}} = 252 \text{ kJ} / 120 \text{ kV} = 2{,}1 \text{ kJ/kV}$

  The calculated energy is the same as in Table H.3 for LDC 2.

  Applied two times in the switching impulse operating duty test ⇒ 2 x $W / U_{\text{r}} = 4{,}2$ kJ/kV

- (i.e. test value = 1,32 C)To calculate the charge, we must know the corresponding voltage at line discharge and adapt the virtual duration of current peak, T, to obtain the required minimum energy W:

  Voltage at LD: $U_{\text{a}} = U_{\text{rp}} - Z \text{ x } I_{\text{a}} = 384 \text{ kV} - (288\ \Omega \text{ x } 0{,}538 \text{ A}) = 229{,}1 \text{ kV}$

  Energy at LD: $W_{\text{a}} = U_{\text{a}} \text{ x } I_{\text{a}} \text{ x } T = 229{,}1 \text{ kV x } 0{,}538 \text{ kA x } 2\ 000\ \mu\text{s} = 246{,}5 \text{ kJ}$

  Virtual duration of current peak adjusted to obtain the required minimum test energy, W:

  $T_{\text{a}} = \text{W} / (U_{\text{a}} \text{ x } I_{\text{a}}) = 252 \text{ kJ} / (0{,}538 \text{ kA x } 229{,}1 \text{ kV}) = 2046\ \mu\text{s}$

  Charge calculated with the same current and duration as for LD to give the required minimum energy:

  $Q = I_{\text{a}} \text{ x } T_{\text{a}} = 0{,}538 \text{ kA x } 2046\ \mu\text{s} = 1{,}10 \text{ C}$

  Repetitive charge transfer rating, Q_{rs}, is then chosen from standard values defined in clause 8.5.4 of IEC 60099-4:2014. In this case,

  $Q_{\text{rs}} = 1{,}1$ C (i.e. test value = 1,21 C)

Example 2

$U_{\text{r}} = 120 \text{ kV}$

LDC = 3

$I_{\text{n}} = 10 \text{ kA}$

$U_{\text{pl}} = 360 \text{ kV}$

$U_{\text{resmax (1 000 A)}} = 289 \text{ kV } (2{,}41 \times U_{\text{r}})$

$U_{\text{resmin (1 000 A)}} = 0{,}95 \times U_{\text{resmax (1 000 A)}} = 274{,}6 \text{ kV}$

$U_{\text{resmax (250 A)}} = 270 \text{ kV}$

$U_{\text{resmin (250 A)}} = 0{,}95 \times U_{\text{resmax (250 A)}} = 256{,}5 \text{ kV}$

Calculated:

- Current at LD: $I = 475$ A
- Minimum test energy: $W = 313{,}7$ kJ ⇒ $W/U_{\text{r}} = 2{,}61$ kJ/kV

  to be applied two times in the switching impulse operating duty test ⇒ 5,22 kJ/kV

  Thermal energy rating: $W_{\text{th}} = 5$ kJ/kV
- Charge calculated with the same current and duration as for LD to give the required minimum energy: $Q = 1{,}2$ C

Repetitive charge transfer rating: Q_{rs} = 1,2 C (i.e. test value = 1,32 C)

Examples 1 and 2 show that arresters with different line discharge classes (2 and 3) will result in nearly the same repetitive charge transfer rating and nearly the same thermal energy rating when changing the switching impulse protection level accordingly. Also note that in Example 2 the protection level of the arrester is significantly higher than the typical value used in Table H.1, which reduces the discharge energy down to a typical value for LDC 2.

Example 3

U_r = 120 kV

LDC = 3

I_n = 10 kA

U_{pl} = 300 kV

$U_{resmax\ (1\ 000\ A)}$ = 241 kV (2,01·U_r)

$U_{resmin\ (1\ 000\ A)}$ = 0,95 × $U_{resmax\ (1\ 000\ A)}$ = 229,0 kV

$U_{resmax\ (250\ A)}$ = 225 kV

$U_{resmin\ (250\ A)}$ = 0,95 × $U_{resmax\ (250\ A)}$ = 213,8 kV

Calculated:

- Current at LD: I = 722 A
- Minimum test energy: W = 402,0 kJ ⇒ W/U_r = 3,35 kJ/kV

  to be applied two times in the switching impulse operating duty test ⇒ 6,7 kJ/kV

  Thermal energy rating: W_{th} = 7 kJ/kV
- Charge calculated with the same current and duration as for LD to give the required minimum energy: Q = 1,8 C

  Repetitive charge transfer rating: Q_{rs} = 1,6 C (i.e. test value = 1.76 C) or Q_{rs} = 2,0 C (i.e. test value = 2,2 C)

Example 3, in comparison to Example 2, shows that a lower protective level for the same line discharge class leads to higher requirements on repetitive charge transfer rating and thermal energy rating.

Example 4

U_r = 420 kV

LDC = 4

I_n = 20 kA

U_{pl} = 1051 kV

$U_{resmax\ (2\ 000\ A)}$ = 849 kV (2,02 × U_r)

$U_{resmin\ (2\ 000\ A)}$ = 0,95 × $U_{resmax\ (2\ 000A)}$ = 806.6 kV

$U_{resmax\ (500\ A)}$ = 803.3 kV

$U_{resmin\ (500\ A)}$ = 0,95 × $U_{resmax\ (500A)}$ = 763.1 kV

Calculated:

- Current at LD: I = 940 A
- Minimum test energy: W = 2092 kJ ⇒ W/U_r = 4,98 kJ/kV

  to be applied two times in the switching impulse operating duty test ⇒ 9,74 kJ/kV

  Thermal energy rating: W_{th} = 10 kJ/kV

- Charge calculated with the same current and duration as for LD to give the required minimum energy: Q = 2,69 C

  Repetitive charge transfer rating: Q_{rs} = 2,4 C (i.e. test value = 2,64 C) or Q_{rs} = 2,8 C (i.e. test value = 3,08 C)

Example 5

U_r = 420 kV
LDC = 5
I_n = 20 kA
U_{pl} = 1 100 kV
$U_{resmax\ (2\ 000\ A)}$ = 867 kV (2,06 × U_r)
$U_{resmin\ (2\ 000\ A)}$ = 0,95 × $U_{resmax\ (2\ 000A)}$ = 823,7 kV
$U_{resmax\ (500\ A)}$ = 810 kV
$U_{resmin\ (500\ A)}$ = 0,95 × $U_{resmax\ (500A)}$ = 769,5 kV

Calculated:

- Current at LD: I = 1042 A

  Minimum test energy: W = 2797 kJ ⇒ W/U_r = 6,66 kJ/kV

  to be applied two times in the switching impulse operating duty test ⇒ 13,32 kJ/kV

  Thermal energy rating: W_{th} = 13 kJ/kV
- Charge calculated with the same current and duration as for LD to give the required minimum energy: Q = 3,54 C

  Repetitive charge transfer rating: Q_{rs} = 3,2 C (i.e. test value = 3,52 C) or Q_{rs} = 3,6 C (i.e. test value = 3,96 C)

Example 6

U_r = 420 kV
LDC = 5
I_n = 20 kA
U_{pl} = 1 000 kV
$U_{resmax\ (2\ 000\ A)}$ = 788 kV (1,88 × U_r)
$U_{resmin\ (2\ 000\ A)}$ = 0,95·$U_{resmax\ (2\ 000\ A)}$ = 748,6 kV
$U_{resmax\ (500\ A)}$ = 750 kV
$U_{resmin\ (500\ A)}$ = 0,95 × $U_{resmax\ (500\ A)}$ = 712,5 kV

Calculated:

- Current (i.e. test value = 1,32 C) energy: W = 3208 kJ ⇒ W/U_r = 7,64 kJ/kV

  to be applied two times in the switching impulse operating duty test ⇒ 15,28 kJ/kV

  Thermal energy rating: W_{th} = 16 kJ/kV
- Charge calculated with the same current and duration as for LD to give the required minimum energy: Q = 4,38 C

  Repetitive charge transfer rating: Q_{rs} = 4,0C (i.e. test value = 4,4 C) or Q_{rs} = 4,4C (i.e. test value = 4,84 C)

As shown in Examples 5 and 6 the same line discharge class leads to different thermal energy ratings and repetitive charge transfer ratings depending on the switching impulse protection level. Also note that the protection level in Example 5 is relatively high for a normal class 5 arrester.

Annex I
(informative)

Estimation of arrester cumulative charges and energies during line switching

Switching transients are generated whenever switches with voltages across them are closed. During line energization and fast reclosing operations, switch voltages can exceed 1 and 2 p.u. respectively. Consequently, with random switching and no control, typical line switching overvoltages can exceed 2 p.u. and 3 p.u. To reduce switching overvoltages, line arresters with low protective level can be applied alone or in combination with other control means.

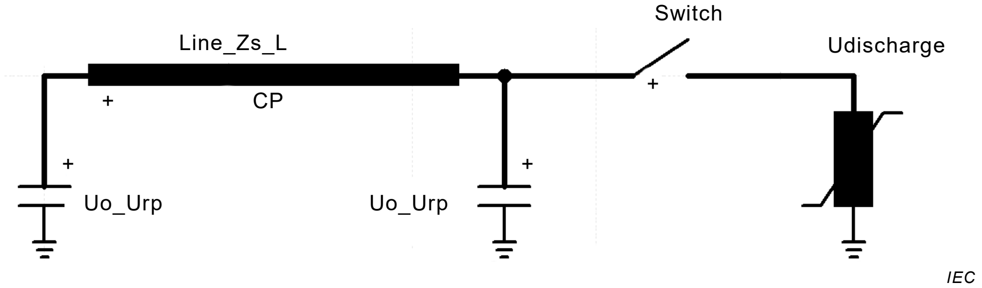
To estimate arrester charge and energy associated with line switching, computer simulations are typically performed using digital models of the system, including models of the highly non-linear arrester voltage-current characteristics, for various switching scenarios. For simple cases of switching single lines terminated by arresters, simplified formulas using piecewise linear representations of the arrester voltage-current characteristic and line parameters can be used to obtain a conservative estimate of arrester requirements [7].

Methods of estimating total charges transferred to the arrester and accumulated energies based on realistic line parameters and arrester discharges associated with system voltage classes are explained in the following three clauses of this annex. I.1 describes the simplified formula method [7] with the necessary line and arrester parameters. I.2 presents the IEC line discharge test method which employs the simplified method together with line parameter values which are defined by arrester ratings. I.3 compares results obtained using simplified formula and computer simulation methods for various system conditions and voltage classes

I.1 Simplified method of estimating arrester line switching energies

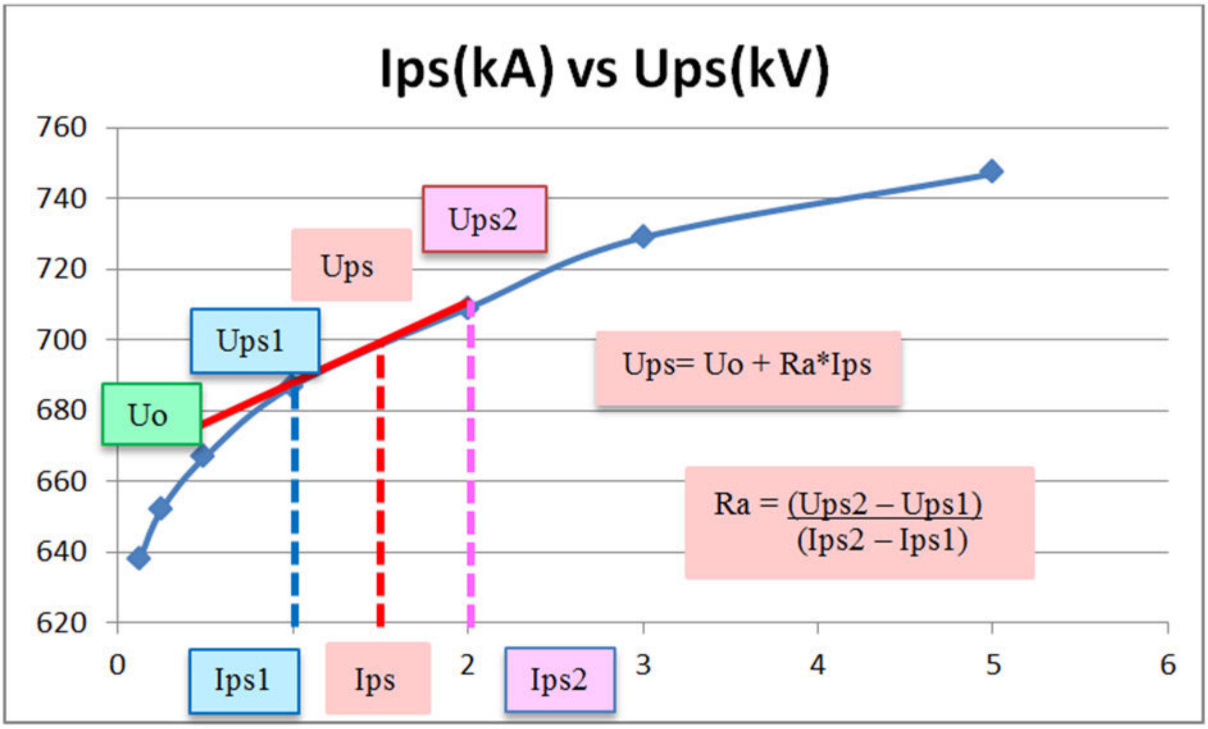
I.1.1 Introduction

Figure I.1 and the subsequent formulas can be used for estimating arrester line switching energies. The capacitances shown at the line terminals are considered negligibly small compared to actual line capacitances but included here only to illustrate the initial line charge condition prior to line discharge when the switch is closed. In the formulas, simplification is based on the linearization of the arrester characteristic in the switching current range as shown in Figure I.2. An approximate arrester discharge voltage-current relationship, based on per unitized arrester switching voltage at 0,5 kA current is tabulated in Table I.1 [7]. Actual arrester discharge currents and voltages are then solved together with the line parameters to estimate the energies.



NOTES Initial Line Voltage Condition (Switch Open): Line Charged to DC voltage equal to U_{rp} level
Switch Close Operation: Discharges Line DC trapped charges into surge arrester
U_{ps} & I_{ps}: surge arrester voltage and current during line discharge

Figure I.1 – Simple network used for Arrester Line Discharge Calculation and Testing according to IEC 60099-4:2009



U_{ps} is the arrester residual voltage at the switching impulse current;

I_{ps} is the arrester discharge current at residual voltage;

U_o is the voltage constant in the arrester linear voltage equation;

R_a is the arrester resistance in the linear voltage equation

Figure I.2 – Linearized arrester equation in the typical line switching current range (voltage values shown are for a 372 kV rated arrester used on a 420 kV system)

Table I.1 – Typical Arrester Switching (U_{ps} vs I_{ps}) Characteristics

I_{ps}(kA)	U_{ps}(pu)
0,5	1,00
1,0	1,03
2,0	1,07
5,0	1,14

I.1.2 Simplified method calculation steps

Steps in the calculation are as follows:

- Identify U_{ps1}/I_{ps1} below U_{ps2}/I_{ps2} from manufacturer's published arrester data or estimate from typical discharge voltage ratios for each of the arrester currents (Table I.1). The arrester residual voltages to be used should be the lowest given value or, if not known approximately 95% of the maximum U_{ps} as indicated by the manufacturer.
- Calculate approximate arrester resistance, R_a from two (U_{ps}, I_{ps}) arrester data points, Commonly U_{ps1} for I_{ps1} in the 0,25 -0,5 kA range is chosen

$$R_a = \frac{(U_{ps2} - U_{ps1})}{(I_{ps2} - I_{ps1})} \quad (I.1)$$

– Using U_{ps1} for I_{ps1} = 0,5 kA, calculate the arrester voltage constant, U_o

$$U_{\mathrm{o}} = U_{\mathrm{ps1}} - R_{\mathrm{a}} \times I_{\mathrm{ps1}} \tag{I.2}$$

– Estimate arrester discharge current, Ips by equating basic line-arrester discharge equation

$$U_{\mathrm{ps}} = U_{\mathrm{rp}} - Z_{s} \times I_{\mathrm{ps}} \tag{I.3}$$

where

Z_{s} is the line surge impedance

U_{rp} is the prospective overvoltage without arresters (see Figure I.3)

with linearized arrester equation (I.2), yielding.

$$I_{\mathrm{ps}} = \frac{(U_{\mathrm{rp}} - U_{\mathrm{o}})}{(Z_{s} + R_{\mathrm{a}})} \tag{I.4}$$

The simultaneous solution of the arrester equation (I.2) and line equation (I.3) is graphically illustrated in Figure I.3. The common line and arrester current (I_{ps}) solution is dependent on the prospective line switching condition (U_{rp}, Z_{s}) as well as the chosen protective voltage level of the arrester (U_{ps}).

- Calculate total charges, Q_{s}, transferred to arrester during line discharge time, T_{d}

$$Q_{\mathrm{s}} = I_{\mathrm{ps}} \times T_{\mathrm{d}} \tag{I.5}$$

where T_{d} is the line discharge time at twice the travel time of line

(T_{d} = 2 × L/c where L is the line length and c is the speed of light)

- Calculate arrester energy corresponding to total charges transferred to arrester,

$$W_{\mathrm{s}} = U_{\mathrm{ps}} \times Q_{\mathrm{s}} \tag{I.6}$$

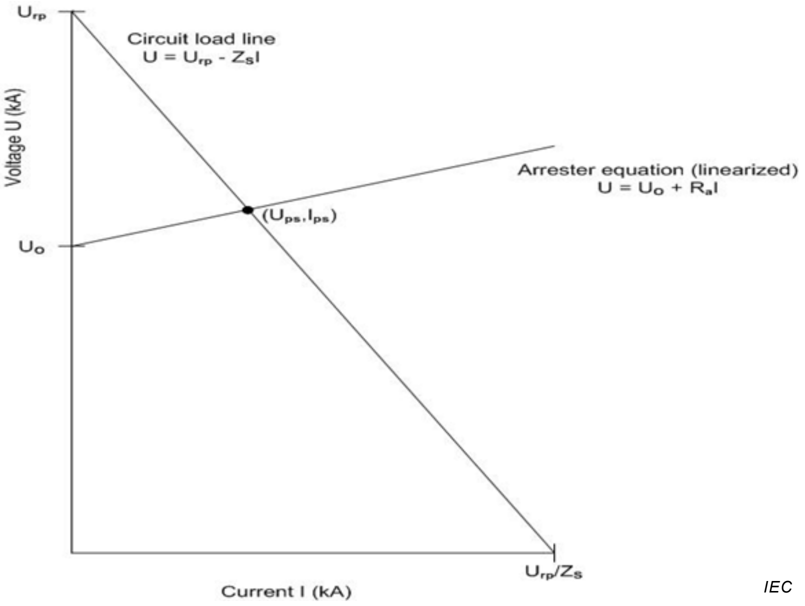


Figure I.3 – Graphical illustration of linearized line switching condition and arrester characteristic

I.1.3 Typical line surge impedances with bundled conductors

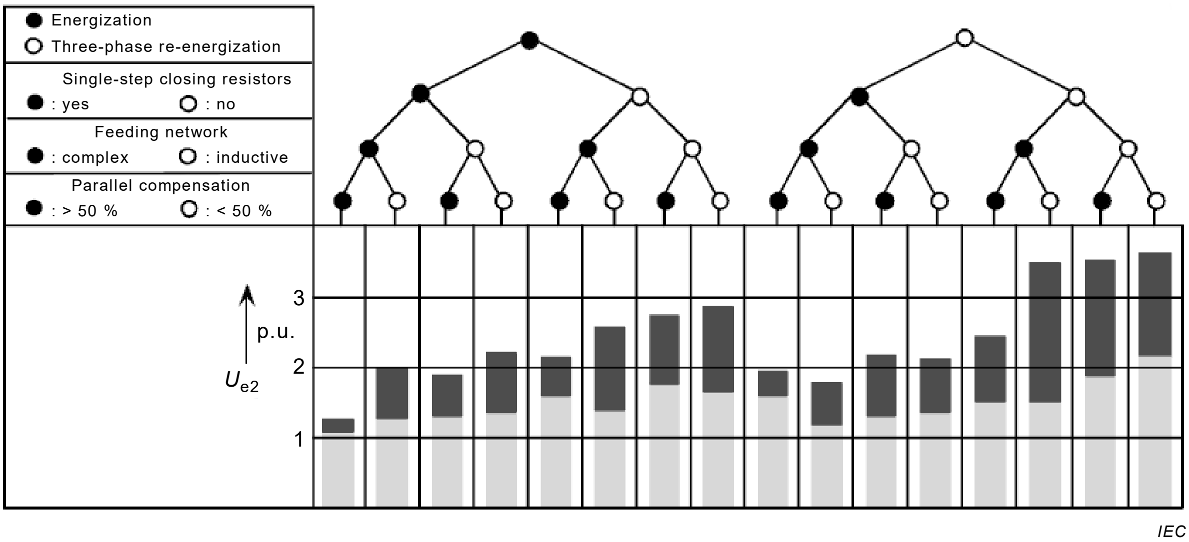
The surge impedance of a transmission line is dependent on the number of conductors in a bundle, type of conductor and the relative physical circuit configuration of the phases. Typical line surge impedances for bundled conductors for each phase are shown in Table I.2. It should be noted that single phase surge impedances are larger than those associated with aerial modes and smaller than those associated with ground modes of three-phase lines. Also, although realistic surge travel velocities will be typically lower than the speed of light, light velocity is considered adequate for the purposes of simplified line discharge calculations.

Table I.2 – Typical line surge impedances (Z_s) with single and bundled conductors

U_s-System(kV)	No. of Conductors in Bundle	Typical Z_s (ohms)
3-150	1	450
151-325	1	400
326-400	2	350
400-800	3 or 4	320
$>$ 800	6* or 8*	300
* IEC 60071-2 & Table 3 in 6.3.2.7		

I.1.4 Prospective switching surge overvoltages

Generally three-phase line switching produces overvoltages on all three phases of the line due to electrical and mechanical component interactions. The magnitudes of the prospective overvoltages (i.e. voltage without arresters present) depend on many factors: line characteristics such as number and size of conductors, phase configuration, line length; system voltage; type of switching devices and their controls; source network complexity (e.g. types of equipment, configuration of equipment and location of equipment in the power system). Properly selected and located arresters will limit the prospective overvoltages to acceptable performance levels. The statistical distribution of prospective switching overvoltage magnitudes can be obtained from computer simulations of appropriate network and line switching operations but typical values as illustrated in the chart of Figure I.4 (reproduced from IEC 60071-2 /ELECTRA 1973) might be considered when results from system studies are unavailable. The overvoltage ranges given in this chart consider basic elements of line switching such as energization or re-energization with residual line voltages from trapped charges, with or without switching control (breaker closing resistors in this case), complex or inductive source network and high or low level of line reactive compensation. All overvoltages shown are prospective overvoltages without arresters at the open receiving end of the line. Overvoltages along the line towards the sending end are generally substantially smaller.



Situation

Switching Operation:	Line Energization or Re-Energization with trapped charges
Circuit Breakers:	Closing Resistors or No control
Feeding Source Network:	Complex or Reactive
Line Shunt Compensation:	Greater than 50 % or Less than 50 %

Figure I.4 – Range of 2 % slow-front overvoltages at the receiving end due to line energization and re-energization

NOTE In some cases the actual maximum system voltages may be higher.

I.1.5 Use of IEC 60099-4:2009 to obtain values for surge impedance and prospective surge voltages

In the previous standards arresters were classified by their line discharge capability, proven by prescribed line discharge tests on pro-rated arrester sections. The transmission line parameters to be used for the line discharge tests are given in Table 5 of IEC 60099-4:2009, reproduced here as Table I.3.

Table I.3 – Line Parameters Prescribed by IEC 60099-4:2009 Line Discharge Class Tests

Arrester classification	Line discharge class	Surge impedance of the line Z_s Ω	Virtual duration of peak T_d µs	Charging voltage U_{rp} kV DC
10 000 A	1	4,9 U_r	2 000	3,2 U_r
10 000 A	2	2,4 U_r	2 000	3,2 U_r
10 000 A	3	1,3 U_r	2 400	2,8 U_r
20 000 A	4	0,8 U_r	2 800	2,6 U_r
20 000 A	5	0,5 U_r	3 200	2,4 U_r
U_r is the rated voltage of the test sample in kilovolts r.m.s.				

While these line parameters were provided for type tests on pro-rated sections to verify arrester line discharge capability, in principle they should also apply to full-size arresters. Using the factors from Table I.3, Table I.4 shows how the line discharge test parameters generate values for line surge impedances (Z_s) and prospective surge voltages (U_{rp}) that would be obtained for different system voltages and typical arresters that might be used for each of the listed system voltages.

Table I.4 – Line surge impedances and prospective surge voltages derived from line discharge tests parameters of IEC 60099-4:2009 for different system voltages and arrester ratings

			Surge Impedance				Prospective Surge Voltage	
Maximum system voltage	**Surge Arrester Rated Voltage** U_r	**Line discharge class**	**Multiplier** K_z	**Magnitude** $Z_s = K_z \times U_r$	**Line length** L	**Surge duration** T_d	**Multiplier** K_v	**Magnitude** $U_{rp} = K_v \times U_r$
kV	kVrms		p.u.	ohms	km	ms	p.u.	kV
145	120	2	2,4	288	300	2,0	3,2	384
	120	3	1,3	156	360	2,4	2,8	336
362	258	3	1,3	335	360	2,4	2,8	722
	258	4	0,8	206	420	2,8	2,6	671
550	420	4	0,8	336	420	2,8	2,6	1 092
	420	5	0,5	210	480	3,2	2,4	1 008
800	612	4	0,8	490	420	2,8	2,6	1 591
	612	5	0,5	306	480	3,2	2,4	1 469

When using values derived from the IEC 60099-4:2009 line discharge parameters for line switching arrester energy estimations, it is important to review the appropriateness of the prescribed line parameters, namely prospective switching voltages (U_{rp}), line surge impedance (Z_s), and line discharge time (T_d), since they should correspond to the applicable line switching conditions. T_d represents the time taken for the surge to travel twice the length of the line at the speed of light (3 × 108 ms^{-1}), and is therefore a measure of the line length for each of the cases shown (e.g. T_d = 2,0 ms corresponds to a line length of 300 km).

I.2 Example of charge and energy calculated using line discharge parameters

This example is for a 145 kV system using 120 kV rated arresters of former line discharge (LD) classes 2 and 3.

Table I.5 shows parameters derived for the two cases from the IEC 60099-4:2009 line discharge procedure (repeated from Table I.4).

Table I.6 shows the calculation parameters and subsequent calculation of arrester charge transfer, Q_{rs}, and absorbed energy, W_s, using the simplified method of I.1.2.

Table I.7 shows values calculated from Electromagnetic Transients Program (EMTP) simulations using the same base parameters as used for the simplified method.

NOTE W_s is the cumulative energy absorbed by arrester during one single line switching. The required thermal energy rating of the arrester, W_{th}, is two times W_s.

Close agreement can be observed between the simplified method and the EMTP simulations.

Table I.5 – Comparison of energy and charge calculated by simplified method with values calculated by EMTP simulation – Base parameters from Table I.4, used for simplified method and for EMTP simulation

U_{system} (kV)	U_{r} (kV)	LD Class	Z_{s} (ohms)	T_{d} (ms)	U_{rp} (kV)
145	120	2	288	2,0	384
145	120	3	156	2,4	336

Parameter: line discharge class.

Table I.6 – Comparison of energy and charge calculated by simplified method with values calculated by EMTP simulation – Calculations using simplified method

U_{system} (kV)	LD Class	I_{ps1} (kA)	U_{ps1} (kV)	I_{ps2} (kA)	U_{ps2} (kV)	I_{ps} (kA)	U_{ps} (kV)	U_{o} (kV)	Q_{rs} (C)	W_{s} (kJ/kV U_{r})
145	2	0,125	209	0,5	221	0,56	224	205	1,1	2,1
145	3	0,25	214	1,0	229	0,72	223	209	1,7	3,2

Table I.7 – Comparison of energy and charge calculated by simplified method with values calculated by EMTP simulation – I.5.(c) Results from EMTP studies

U_{system} (kV)	LD Class	I_{ps} (kA)	U_{ps} (kV)	Q_{rs} (C)	W_{s} (kJ/kV U_{r})
145	2	0,56	221	1,1	2,0
145	3	0,71	222	1,7	3,2

Figure I.5, Figure I.6, Figure I.7 and Figure I.8 graphically show the arrester voltage, current, transferred charge and absorbed energy, respectively, calculated by the EMTP simulations for the two arrester LD classes. The nearly constant arrester voltages and currents over the entire discharge period validate the assumptions made in the simplified method that arrester voltages can be used for calculation as the ratio between arrester charge and energy.

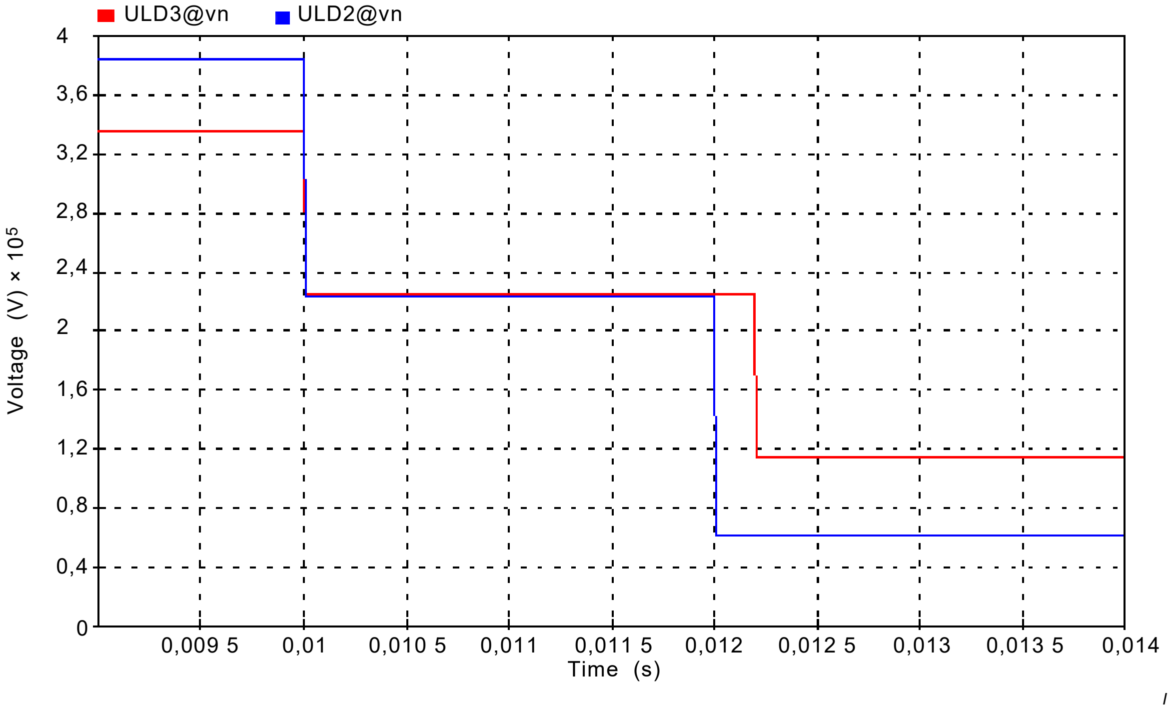


Figure I.5 – Arrester class 2 & 3 voltages calculated by EMTP calculations: U_{ps2} and U_{ps3} (V × 10^5)

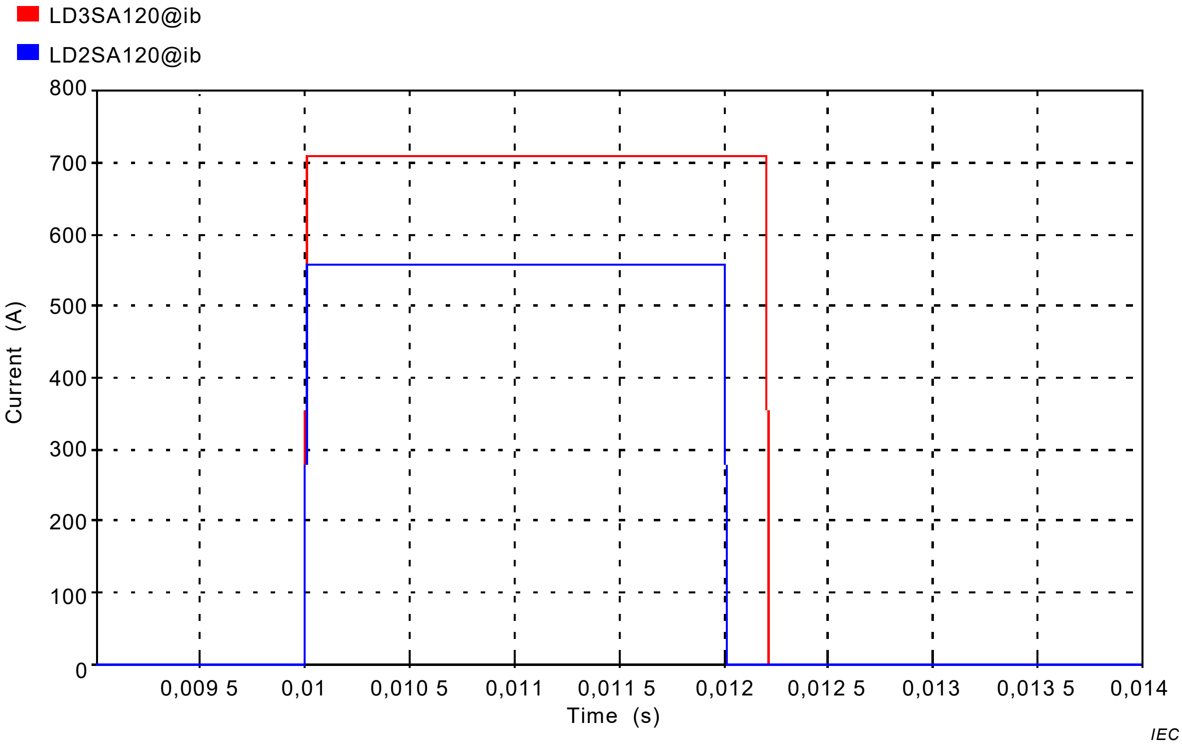


Figure I.6 – Class 2 & 3 arrester currents calculated by EMTP studies: I_{ps2} and I_{ps3} (A)

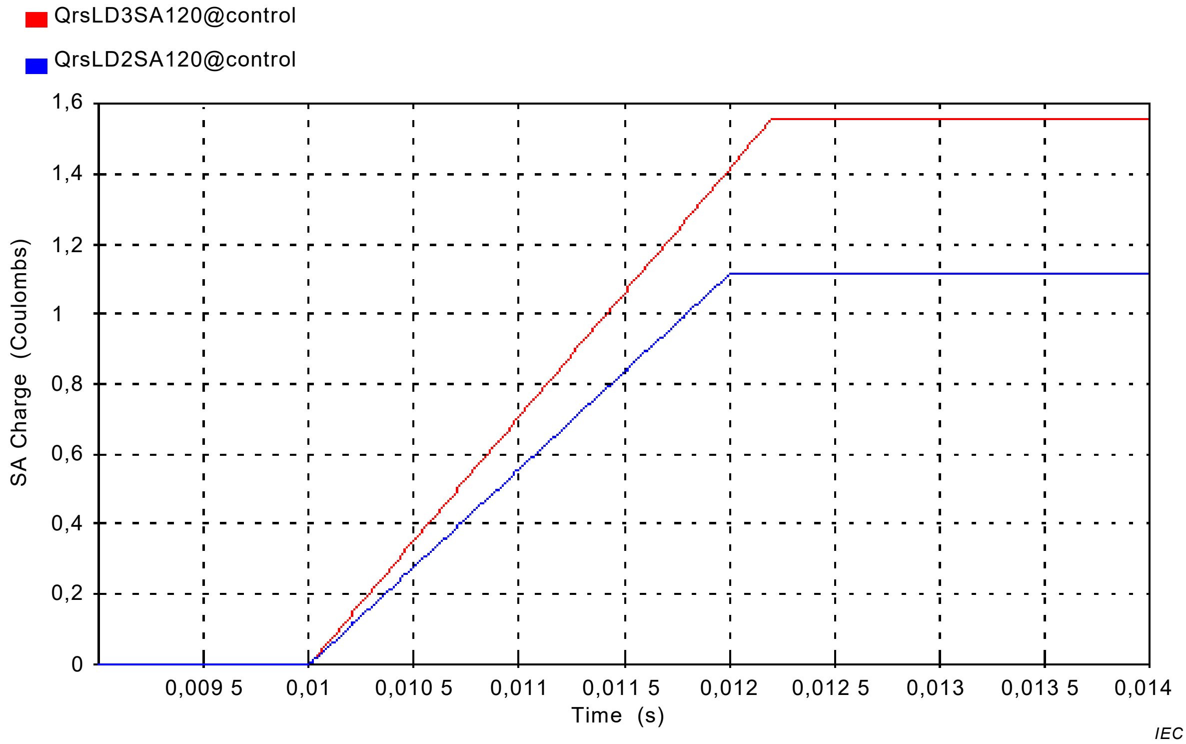


Figure I.7 – Arrester Class 2 & 3 cumulative charges calculated by EMTP simulation: Q_{rs2} and Q_{rs3} (C)

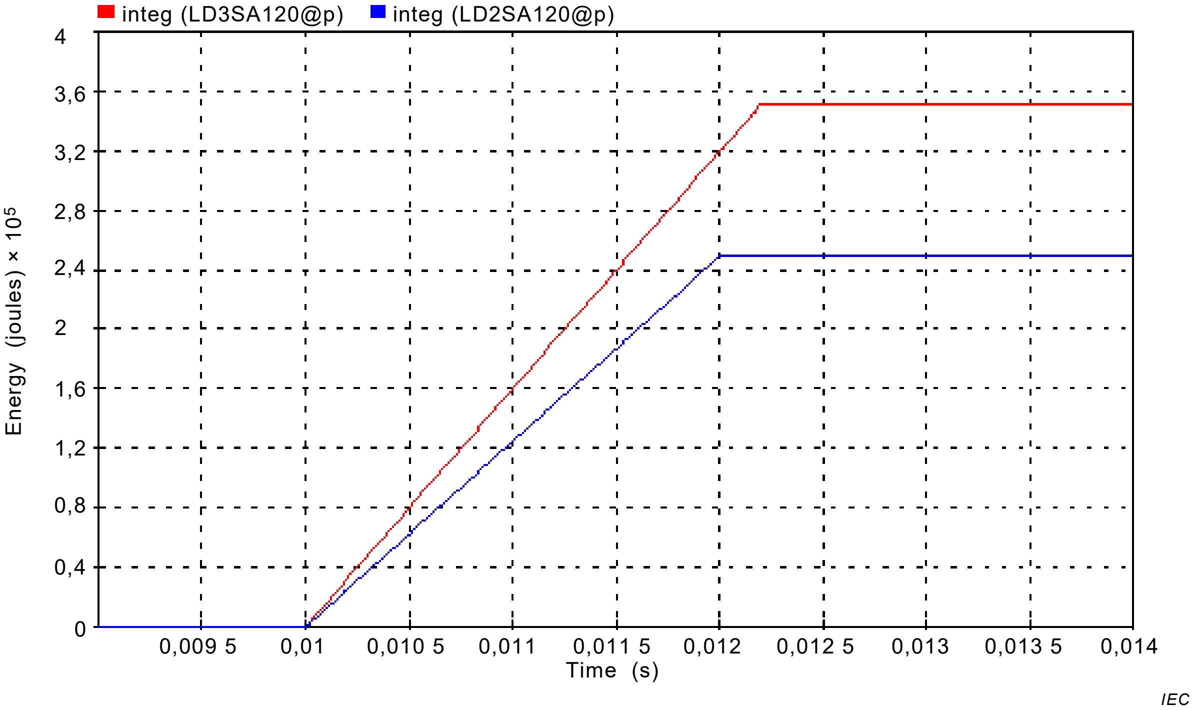


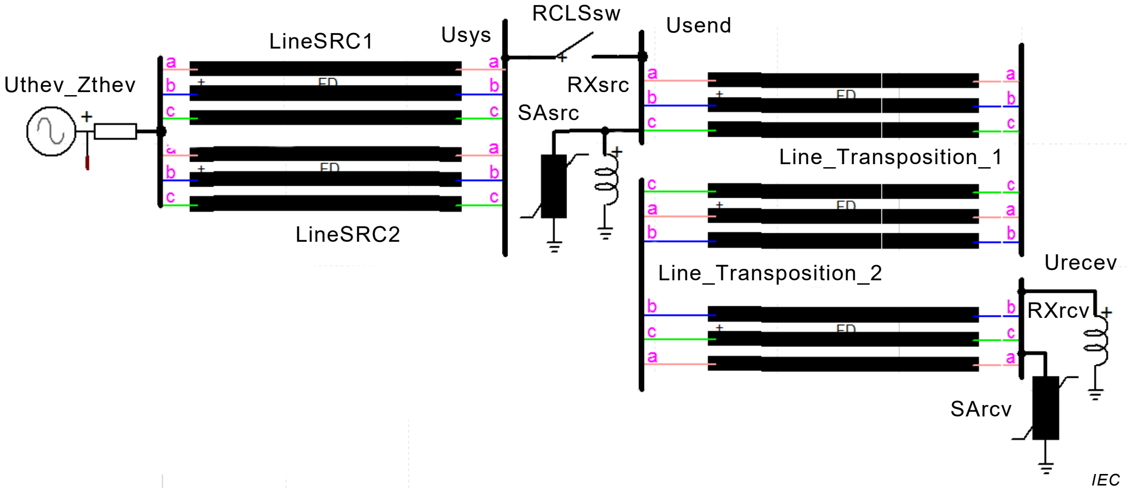
Figure I.8 – Arrester Class 2 & 3 cumulative absorbed energies calculated by EMTP simulation: W_{s2} and W_{s3} (kJ/kV U_r)

I.3 Arrester line switching energy examples

I.3.1 General

A typical computer simulation of a network involving line switching (Figure I.9) usually includes a source network (represented here by two short parallel lines and a Thevenin equivalent source voltage and impedance) and a switch that can be initially closed and subsequently opened with or without a line fault. Opening of the switch may leave close to 1,0 p.u. DC residual voltages from trapped charges on a short-to-medium length line without reactive equipment (shunt reactors, transformers or VTs), or oscillatory voltages on longer lines when shunt reactors are applied to compensate a portion of the line capacitance. When the compensated line is tripped, the line typically displays a lightly damped natural frequency voltage oscillation on the unfaulted phase(s) as energies are exchanged between the reactors and line capacitances, the damping being provided by the line and reactor resistances. During high speed line re-energization operations, if the switch is closed randomly near or at an instant of maximum voltage across the switch (usually when the source voltage is out-of-phase with the line voltage), prospective switching overvoltages may exceed 3 p.u. In practice, however, when switching mitigations are incorporated into the switch (such as closing resistors or point-on-wave controllers), the highest switching overvoltages are usually reduced below 2,5 p.u. Alternatively, if line surge arresters with low protective level are used, switching overvoltages comparable to those achievable with controlled switching (i.e. approximately 2,5 p.u.) can be achieved. If controlled switching and line arresters are used together, overvoltages may be held to 2,0 p.u. or lower.

There exist two fundamental differences in the line voltage/current magnitudes and waveforms occurring for a typical “real world” line re-energization switching operation and those observed with the arrester line discharge tests. Firstly, during actual line switching operations, line transient voltage/current magnitudes do not remain constant over twice the duration of the surge propagation time, nor are they typically similar between two or more successive discharges (which might be caused by surge response to line and source equipment and/or non-simultaneous switching methods).



NOTE Uthev Zthev: Thevenin Equivalent Source Voltages & Impedances

LineSRC#: Line in Source Network

RCLSsw: Line reclosing Switch

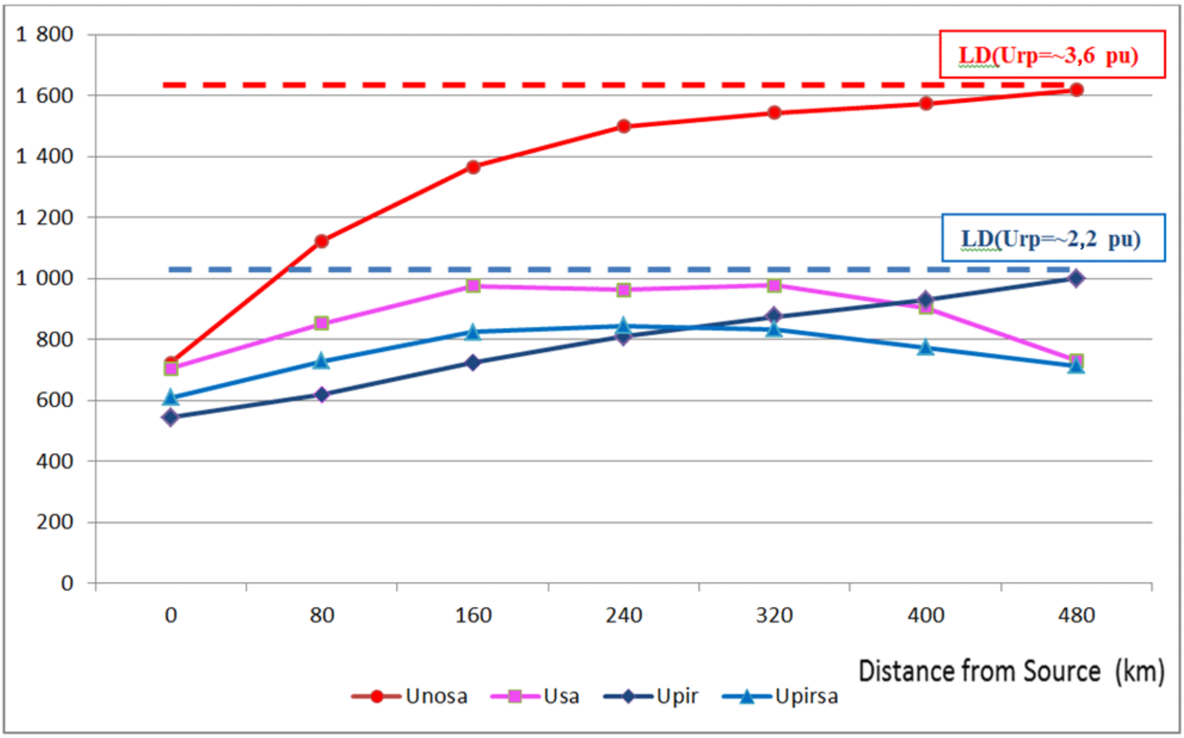
Line_Transposition: Line Phase Transposition Locations for Balanced Line

SAsrc/SArcv: Surge Arresters at Sending & Receiving End of Line terminals

RXsrc/RXrcv: Shunt Reactors at Sending & Receiving End of Line terminals

Figure I.9 – Typical Line Reclosing Computer Simulation Network

Secondly, switching voltage magnitude profiles along the line from the source to the receiving end for cases without line arresters are typically not constant (see Figure I.10) in comparison with the DC voltage condition used in the line discharge test. Consequently, even when the same representative voltage magnitudes are used, the line discharge test methods are expected to produce higher arrester charge and thermal energies and thus are considered to provide a more conservative estimate than those from “real world” switching simulation studies.



IEC

NOTE: Switching Reclosing Operation & Line Components (Source:0km Receive End:480 km)

Unosa: No Switch Control & No Line Surge Arresters

Usa: No Switch Control & Surge Arresters at Line Terminals

Upir: Switch Control with pre-insertion/closing resistors & No Line Surge Arresters

Upirsa: Switch Control with pre-insertion/closing resistors & Surge Arresters at Line Terminals

Figure I.10 – Typical 550 kV Reclose Switching Overvoltage Profile along 480 km Line

The following sub-clauses show some examples of arrester charge transfer, Q_{rs}, and absorbed single switching energy, W_s, obtained from representative line re-energization simulations, and compare these values with those derived using the simplified line discharge method described in I.1. Summary results from arrester charges and energies derived using IEC line discharge conditions from I.1 and using various arrester protective ratios shown in Figure H.1 in Annex H are illustrated in Figure I.11 and Figure I.12. It can be observed that results shown in Table H.3 is based on typical arrester protective ratio of 1,8.

In most cases, four example calculations are given. For the high voltage systems where some switching controls and arresters may be combined, a fifth example is added. The two examples labeled “Formula” represent, respectively, uncontrolled line reclosing (U_{rp} greater than 3 pu) and controlled line reclosing (U_{rp} having the value given for the relevant line discharge test of IEC 60099-4:2009). Each of the “Formula” examples uses a surge impedance typical for the system being studied. The third example, labeled “IEC-2”, “IEC-3”, “IEC-4” or “IEC-5” is for a case where both surge impedance and U_{rp} values are as given for the relevant line discharge tests of IEC 60099-4:2009 (these being stated as multipliers of arrester rated voltage).

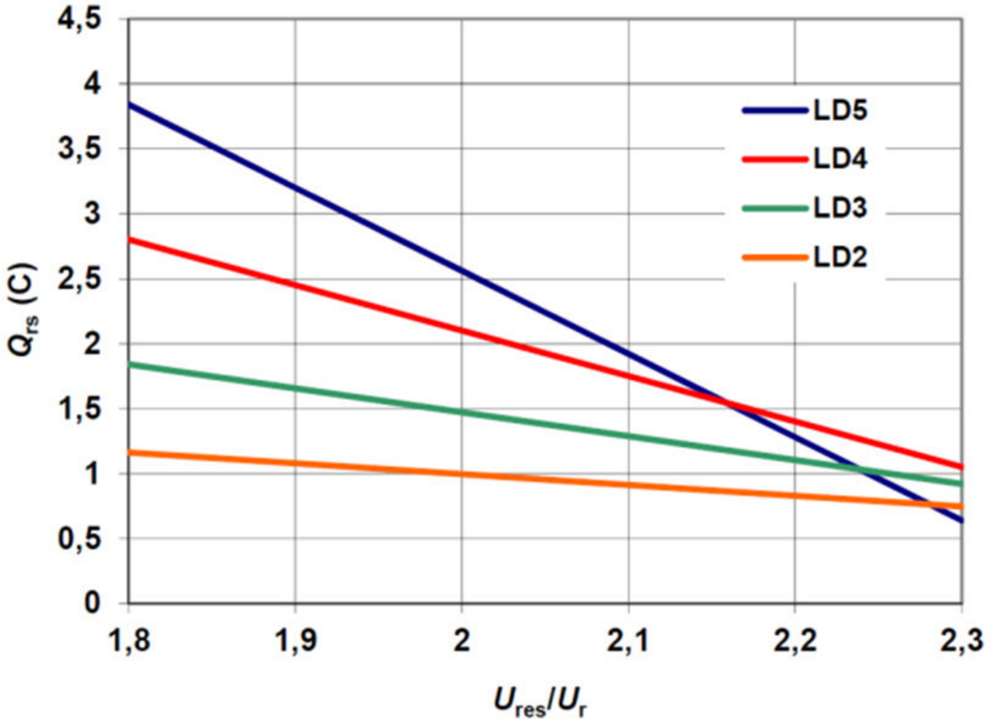


Figure I.11 – IEC LD based charge transfer, Q_{rs} with varying arrester protective ratios

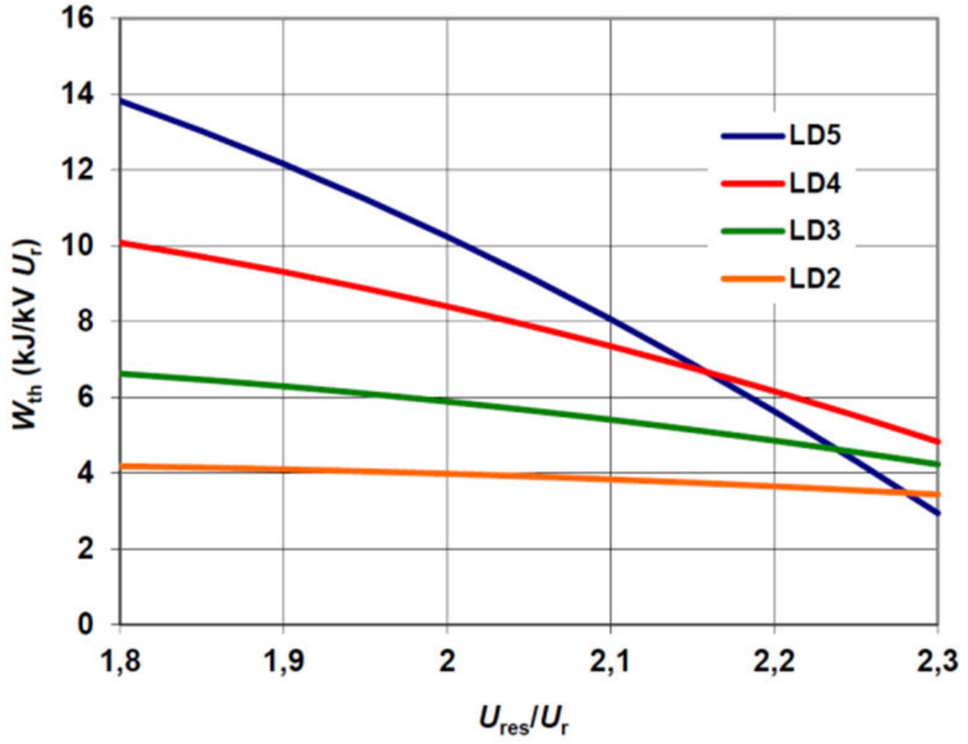


Figure I.12 – IEC LD based switching energy, W_{th} with varying arrester protective ratios

The fourth example, labeled "Simulation", shows the largest arrester charges and energies found from more rigorous computer simulations using statistically uncontrolled random three-phase switch re-closing with residual voltages from trapped charges on unfaulted lines instead of faulted lines which will generally result in larger switching overvoltages. For the 420 kV and 550 kV system cases where some type of switching controls and arresters with low protective level may be applied, possible reduction in the arrester charge and energy requirements in comparison to arresters alone are included in the summary table as the fifth simulation example.

For the 145 kV, 242 kV and 362 kV cases, the lines had no shunt compensation and switching was conducted into lines having trapped charges from an earlier de-energization of the unfaulted line. For the 420 kV and 550 kV cases, the lines were shunt reactor compensated with equal compensation at both line ends to achieve more than 50 percent compensation of the line capacitance, resulting in unfaulted line side voltage oscillations at natural frequencies below power frequency.

I.3.2 Case 1 – 145 kV

Uncompensated Line Switching: Reclosing into line with DC Trapped Charges

Line length = 300 km, T_d = 2,0 ms:

Arrester U_r = 120 kV, line discharge class 2, residual voltage = 221 kV @ 0,5 kA

Example calculations (result values given in Table I.8):

a) Formula – Typical Z_s U_{rp} = 3,0 pu of system voltage
b) Formula – Typical Z_s U_{rp} as given in Table I.3 for line discharge class 2
c) IEC-2 – Z_s U_{rp} as given in Table I.3 for line discharge class 2
d) Simulation – uncontrolled switching (U_{rp} ~ 3,8 pu) with surge arresters at line terminals (simulation results shown graphically in Figure I.13 to Figure I.16)

I.3.3 Case 2 – 242 kV

Uncompensated Line Switching: Reclosing into line with DC Trapped Charges

Line length = 360 km, T_d = 2,4 ms:

Arrester U_r = 192 kV, line discharge class 3, residual voltage = 362 kV @ 1 kA

Example calculations (result values given in Table I.8):

a) Formula – Typical Z_s U_{rp} = 3,0 pu of system voltage
b) Formula – Typical Z_s U_{rp} as given in Table I.3 for line discharge class 3
c) IEC-3 – Z_s U_{rp} as given in Table I.3 for line discharge class 3
d) Simulation – uncontrolled switching (U_{rp} ~ 3,8 pu) with surge arresters at line terminals (simulation results shown graphically in Figure I.17 to Figure I.20)

I.3.4 Case 3 – 362 kV

Uncompensated Line Switching: Reclosing into line with DC Trapped Charges

Line length = 360 km, T_d = 2,4 ms:

Arrester U_r = 288 kV, line discharge class 3, residual voltage = 564 kV @ 2 kA

Example calculations (result values given in Table I.8):

a) Formula – Typical Z_s U_{rp} = 3,0 pu of system voltage

b) Formula – Typical Z_s U_{rp} as given in Table I.3 for line discharge class 3
c) IEC-3 – Z_s U_{rp} as given in Table I.3 for line discharge class 3
d) Simulation – uncontrolled switching (U_{rp} ~ 3,6 pu) with surge arresters at line terminals (simulation results shown graphically in Figure I.21 to Figure I.24)

I.3.5 Case 4 – 420 kV

Reactor Compensated Line Switching: Auto-reclose into oscillatory Trapped Charges

Line length = 420 km, T_d = 2,8 ms:

Arrester U_r = 336 kV, line discharge class 4, residual voltage = 645 kV @ 2 kA

Example calculations (result values given in Table I.8):

a) Formula – Typical Z_s U_{rp} = 3,0 pu of system voltage
b) Formula – Typical Z_s U_{rp} as given in Table I.3 for line discharge class 4
c) IEC-4 – Z_s U_{rp} as given in Table I.3 for line discharge class 4
d) Simulation – uncontrolled switching (U_{rp} ~ 3,6 pu) with surge arresters at line terminals (simulation results shown graphically in Figure I.25 to Figure I.28)
e) Simulation – controlled switching (U_{rp} ~ 2,6 pu) with surge arresters at line terminals

I.3.6 Case 5 – 550 kV

Reactor Compensated Line Switching: Auto-reclose into oscillatory Trapped Charges

Line length = 480 km, T_d = 3,2 ms:

Arrester U_r = 396 kV, line discharge class 4, residual voltage = 744 kV @ 2 kA

Example calculations (result values given in Table I.8):

a) Formula – Typical Z_s U_{rp} = 3,0 pu of system voltage
b) Formula – Typical Z_s U_{rp} as given in Table I.3 for line discharge class 5
c) IEC-5 – Z_s U_{rp} as given in Table I.3 for line discharge class 5
d) Simulation – uncontolled switching (U_{rp} ~3,6 pu) with surge arresters at line terminals (simulation results shown graphically in Figure I.29 to Figure I.32)
e) Simulation – controlled switching (U_{rp} ~ 2,4 pu) with surge arresters at line terminals

Table I.8 – Results of calculations using the ndifferent methods described for different system voltages and arrester selection

U_s (kV)	Estimation method	U_r (kV)	Z_s (Ω)	T_d (ms)	L (km)	U_{rp} (p.u.)	U_{rp} (kV)	I_{ps1} (kA)	U_{ps1} (kA)	I_{ps2} (kA)	U_{ps2} (kA)	U_o (kV)	I_{ps} (kA)	U_{ps} (kV)	Q_{rs} (C)	W_{th} (kJ/kV Ur)
145	a) Formula	120	450	2,0	300	3,0	355	0,125	209	0,5	221	205	0,31	215	0,62	1,12
	b) Formula	120	450	2,0	300	3,2	379	0,125	209	0,5	221	205	0,36	217	0,72	1,30
	c) IEC-2	120	288	2,0	300	3,2	384						0,56	222	1,12	2,10
	d) Simulation	120	450	2,0	300	~3,8	~450							220	0,61	1,10
245	a) Formula	192	400	2,4	360	3,0	593	0,5	351	1,0	362	340	0,70	353	1,44	2,65
	b) Formula	192	400	2,4	360	2,8	554	0,5	351	1,0	362	340	0,51	351	1,21	2,22
	c) IEC-3	192	250	2,4	360	2,8	538						0,73	356	1,76	3,25
	d) Simulation	192	400	2,4	360	~3,8	~750							360	1,40	2,60
362	a) Formula	288	350	2,4	360	3,0	887	1,0	539	2,0	564	514	1,20	543	2,4	4,5
	b) Formula	288	350	2,4	360	2,8	828	1,0	539	2,0	564	514	0,84	535	2,0	3,7
	c) IEC-3	288	206	2,4	360	2,8	806						0,74	532	1,8	3,3
	d) Simulation	288	350	2,4	360	~3,8	~1 124							541	2,3	4,3
420	a) Formula	336	325	2,8	420	3,0	1 029	1,0	605	2,0	645	601	1,20	628	3,5	6,5
	b) Formula	336	325	2,8	420	2,6	892	1,0	605	2,0	645	601	0,84	620	2,3	4,3
	c) IEC-4	336	269	2,8	420	2,6	874						0,94	621	2,6	4,9
	d) Simulation	336	325	2,8	420	~3,6	~1 235							602	3,1	5,6
	e) Simulation	336	325	2,8	420	~2,6	~892							620	2,1	3,5
550	a) Formula	396	300	3,2	480	3,0	1 348	1,0	723	2,0	744	702	2,00	744	6,4	12,1
	b) Formula	396	300	3,2	480	2,4	1 078	1,0	723	2,0	744	702	1,20	727	3,7	6,9
	c) IEC-5	396	198	3,2	480	2,4	950						1,20	726	3,7	6,7
	d) Simulation	396	300	3,2	480	~3,6	~1 620							726	6,2	11,2
	e) Simulation	396	300	3,2	480	~2,4	~1 078							727	2,8	4,8

NOTE W_s is the cumulative energy absorbed by arrester during one single line switching. The required thermal energy rating of the arrester, W_{th}, is two times W_s.

Figure I.13 to Figure I.16 show 145 kV high speed line re-energization switching transients with 120 kV surge arresters.

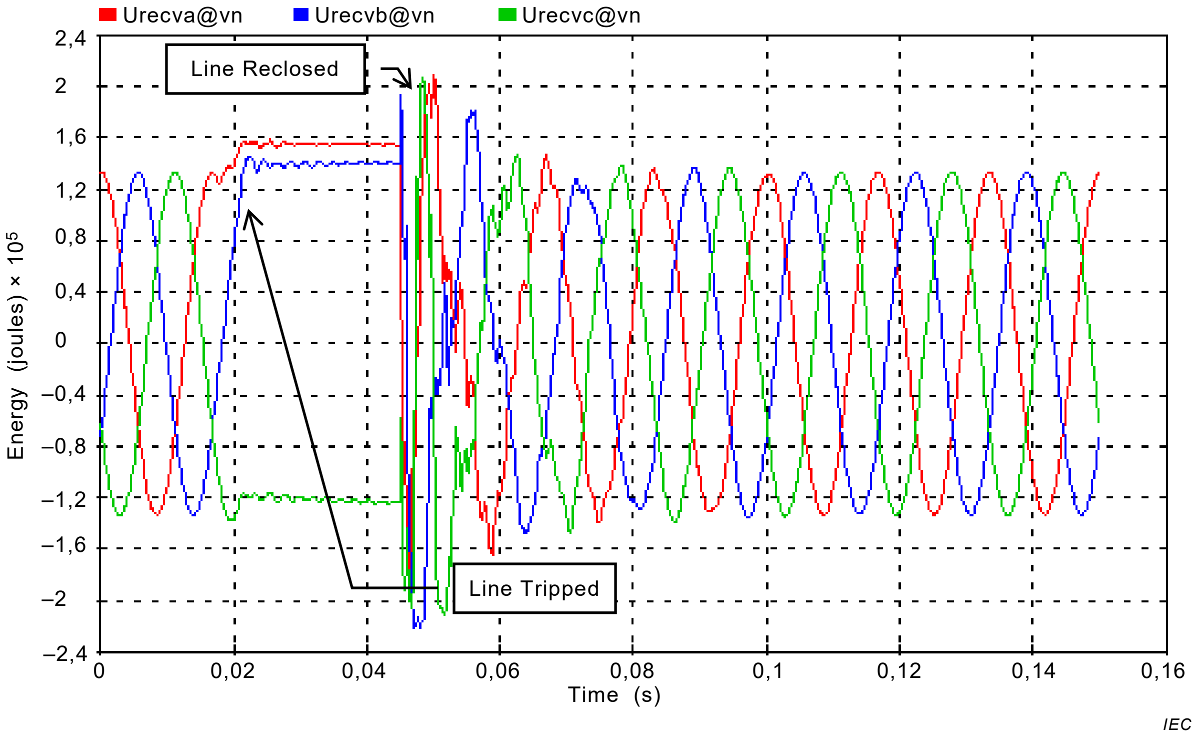


Figure I.13 – U_{ps} for 145 kV system simulation (V x 10^5)

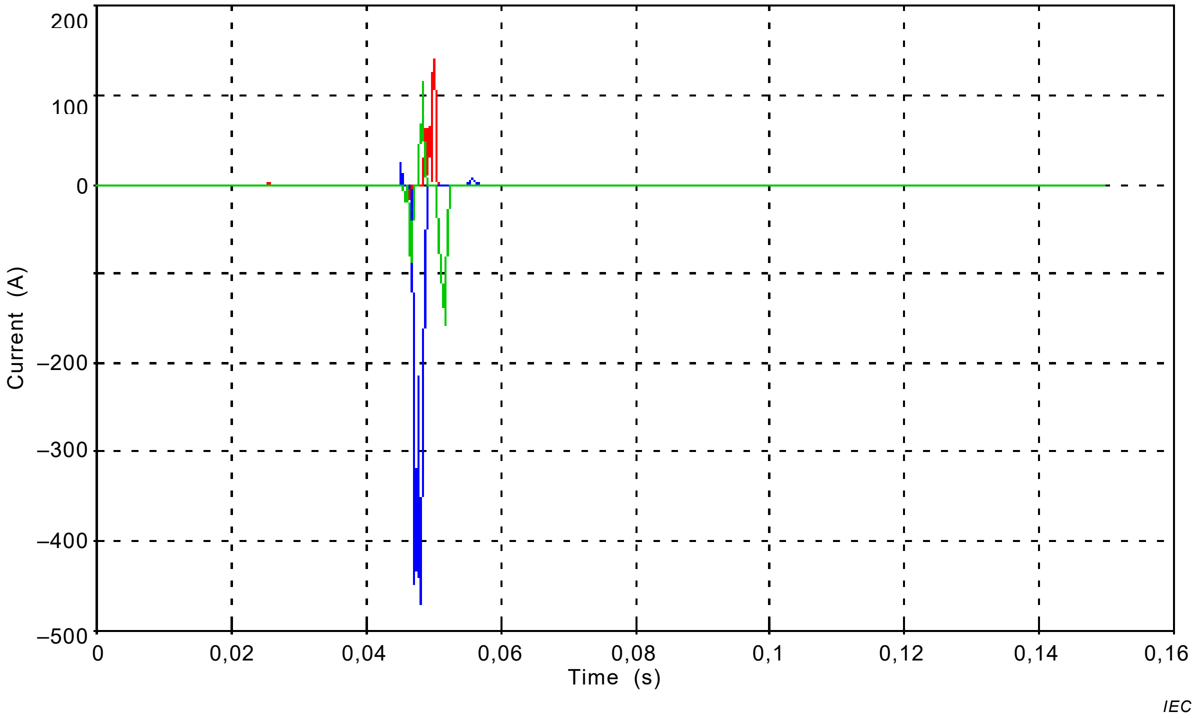


Figure I.14 – I_{ps} for 145 kV system simulation (A)

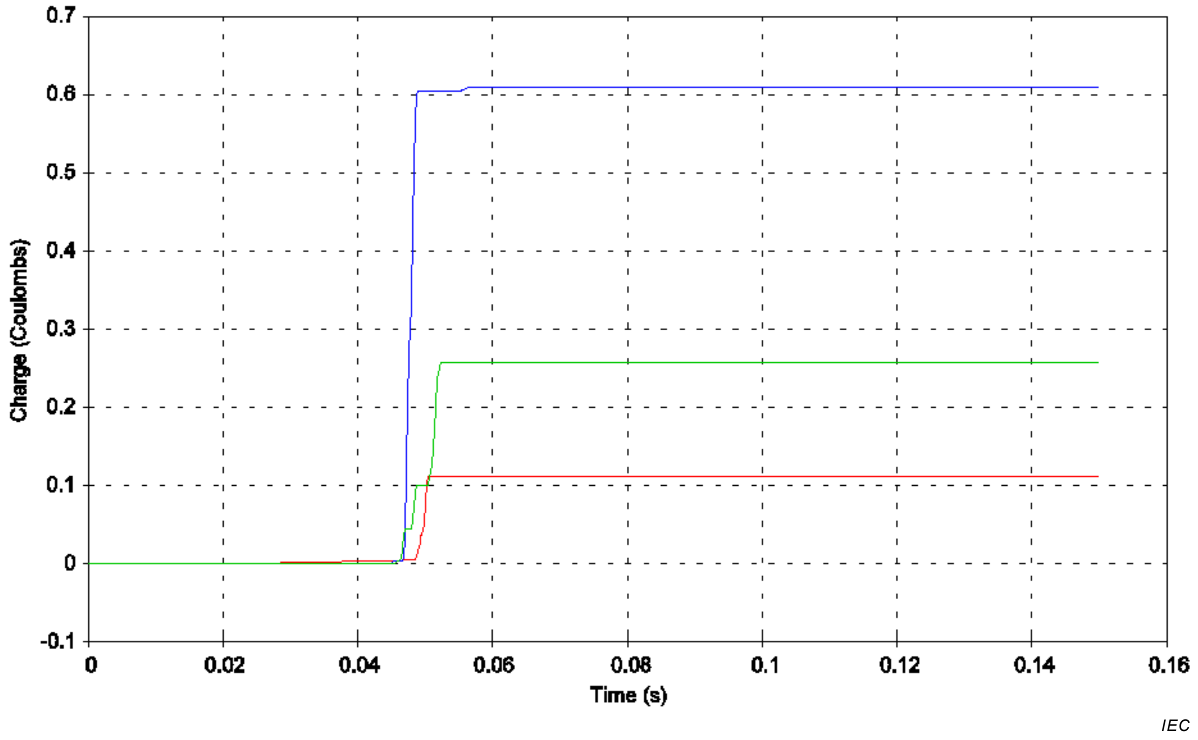


Figure I.15 – 1 Cumulative charge (Q_{rs}) for 145 kV system simulation (C)

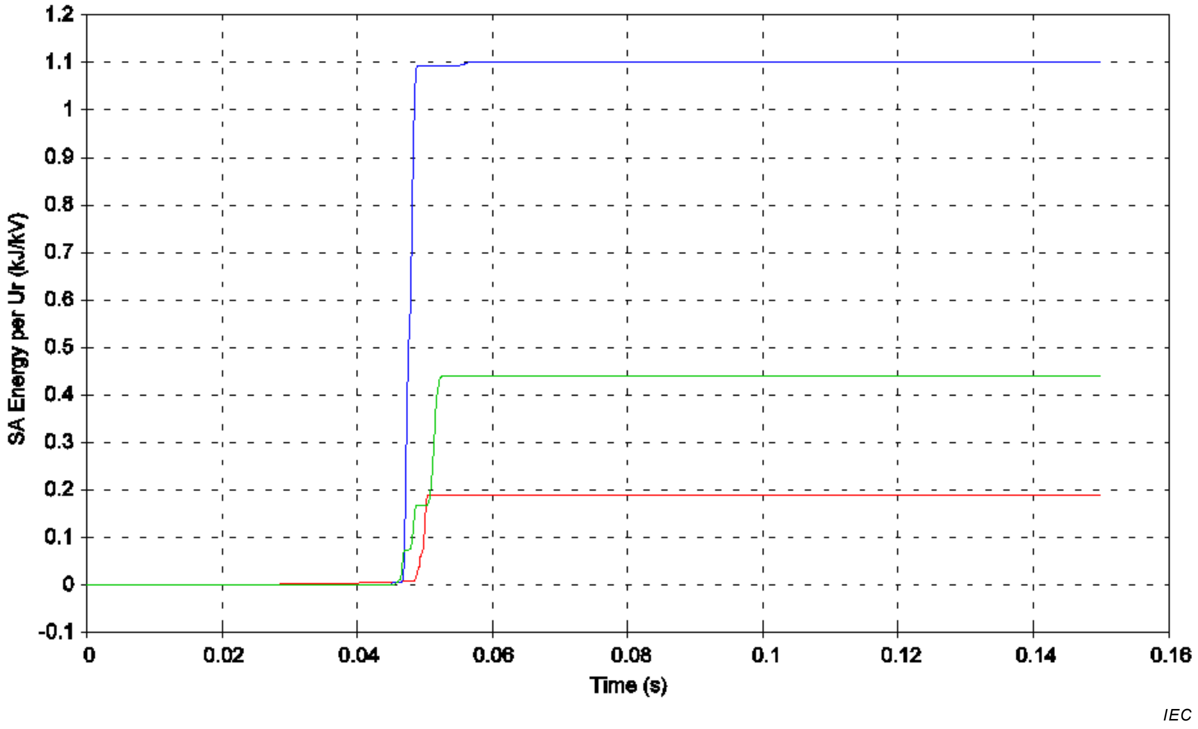
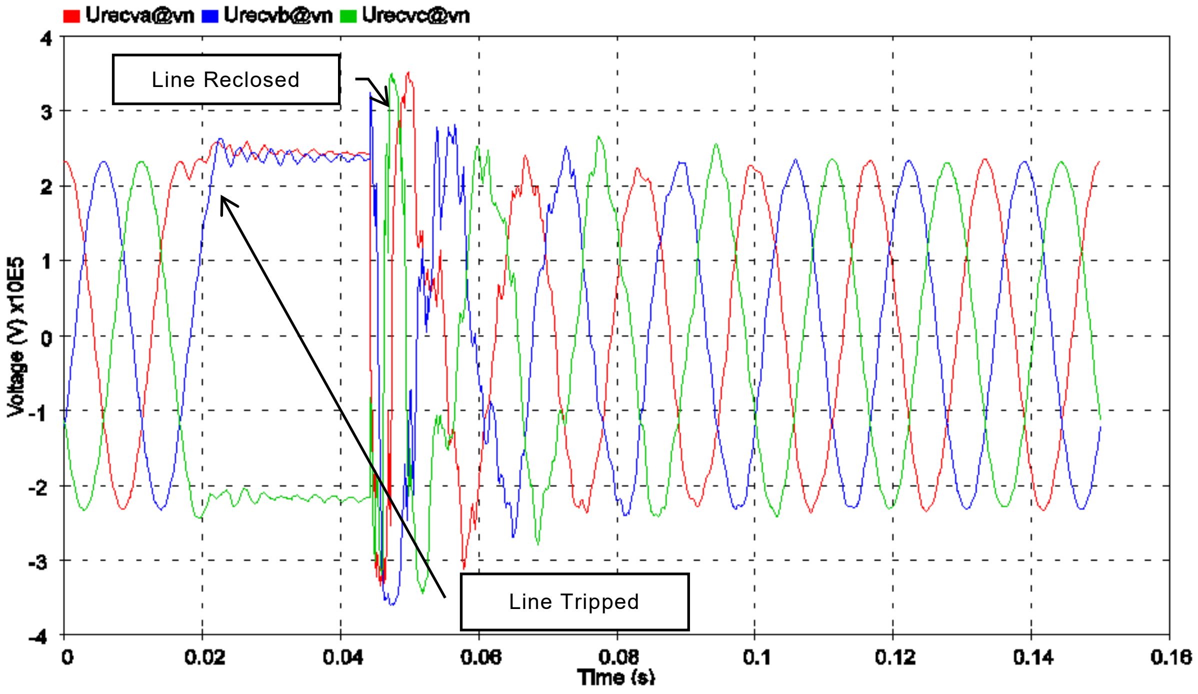


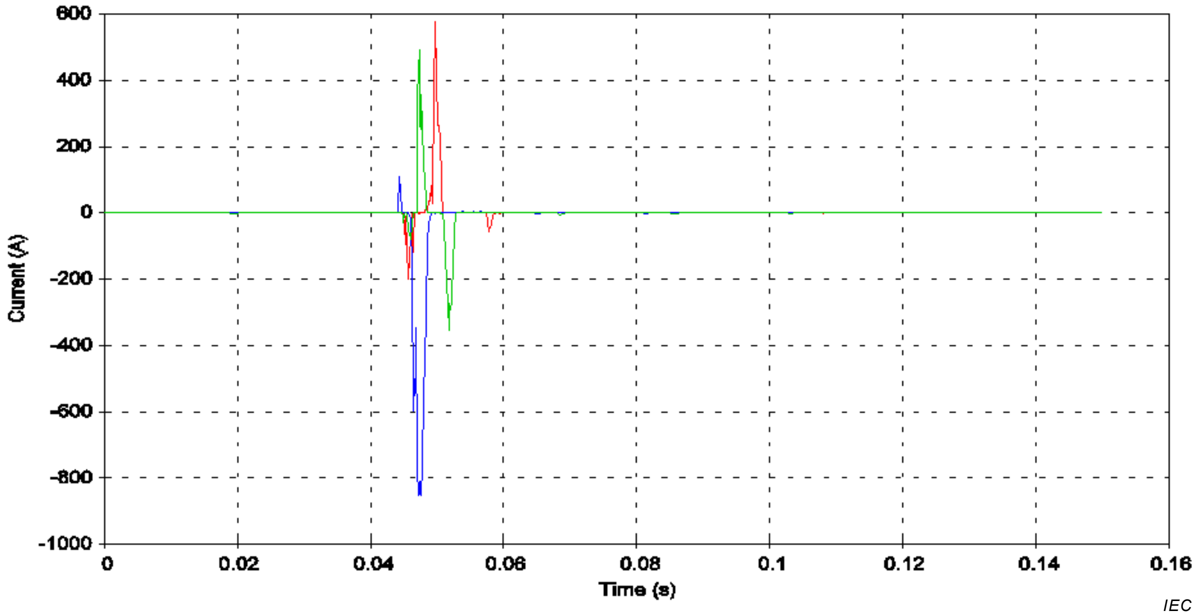
Figure I.16 – Cumulative energy (W_{th}) for 145 kV system simulation (kJ/kV U_r)

Figure I.17 to Figure I.20 show 245 kV high speed line re-energization switching transients with 192 kV surge arresters.



IEC

Figure I.17 – U_{ps} for 245 kV system simulation (V x 10^5)



IEC

Figure I.18 – I_{ps} for 245 kV system simulation (A)

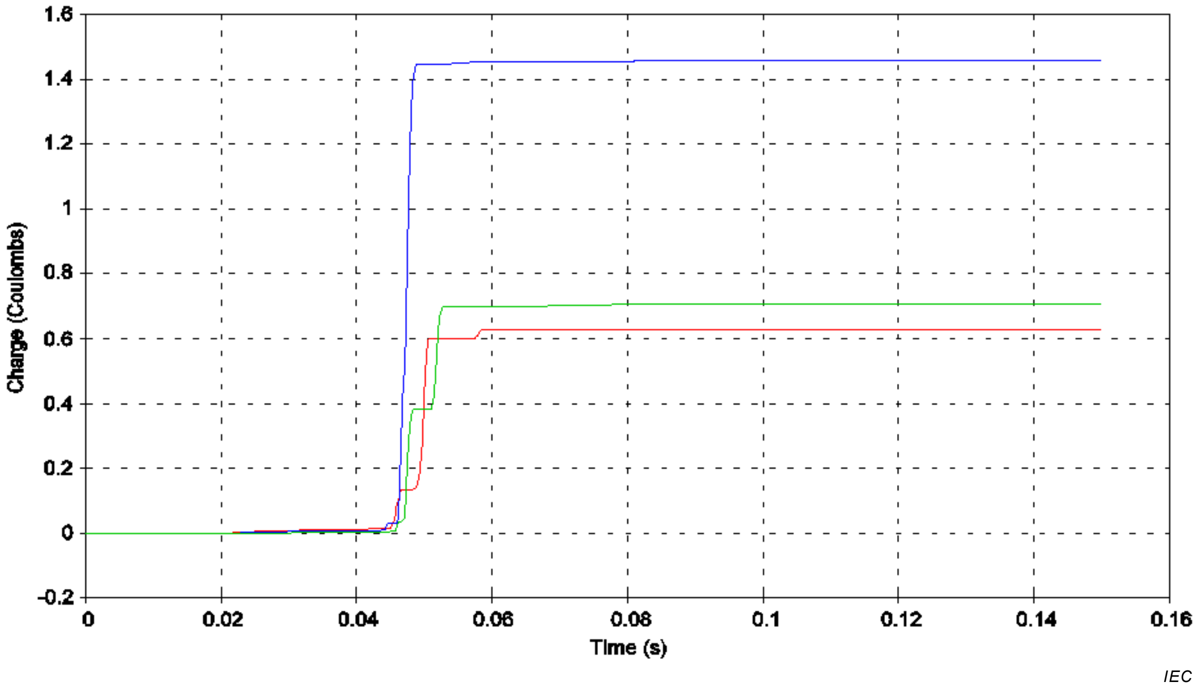


Figure I.19 – Cumulative charge (Q_{rs}) for 245 kV system simulation (C)

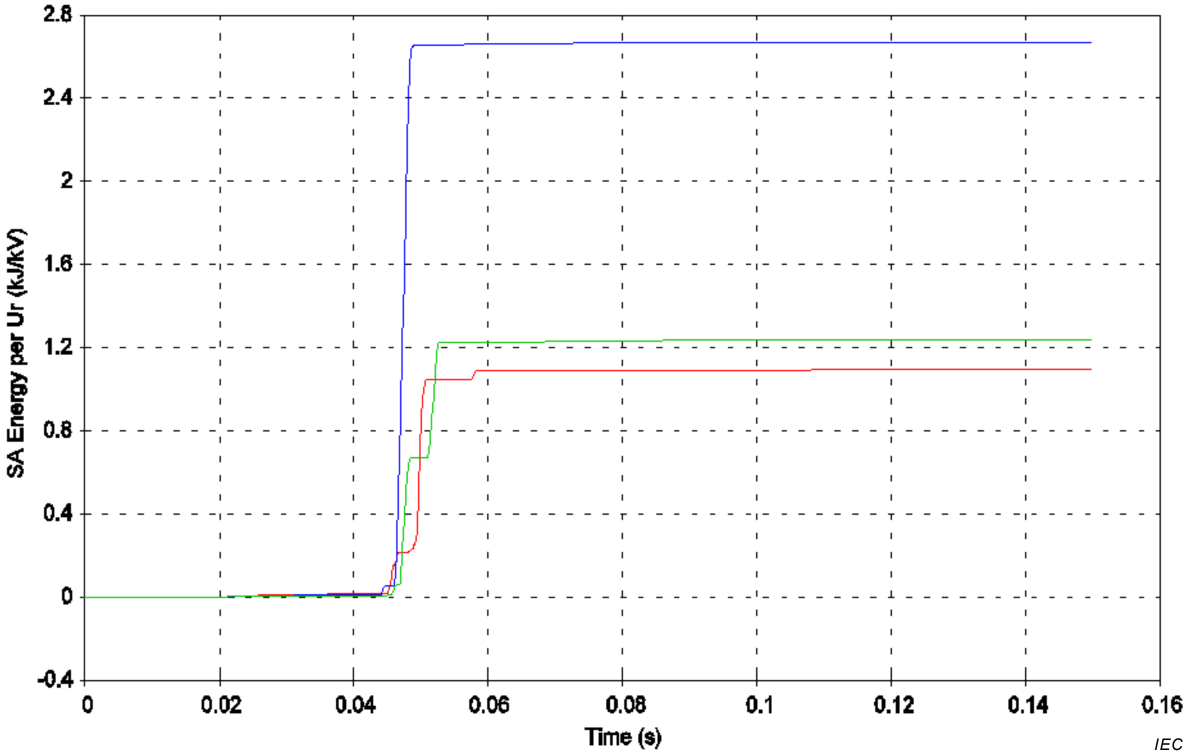
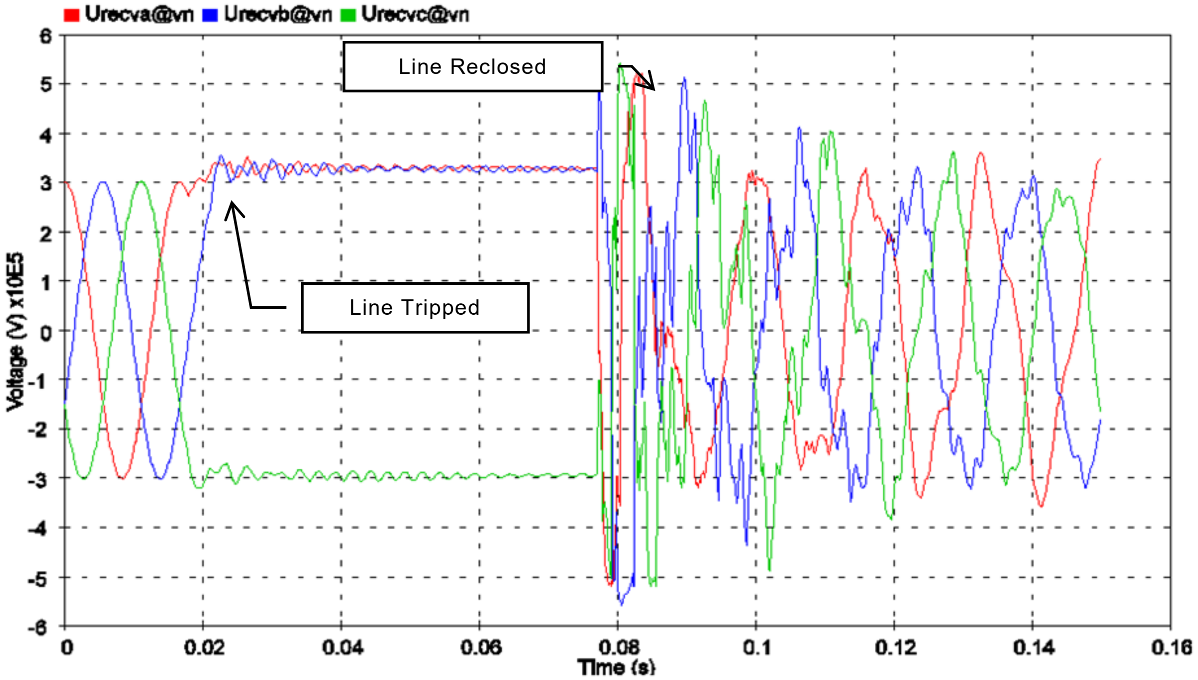


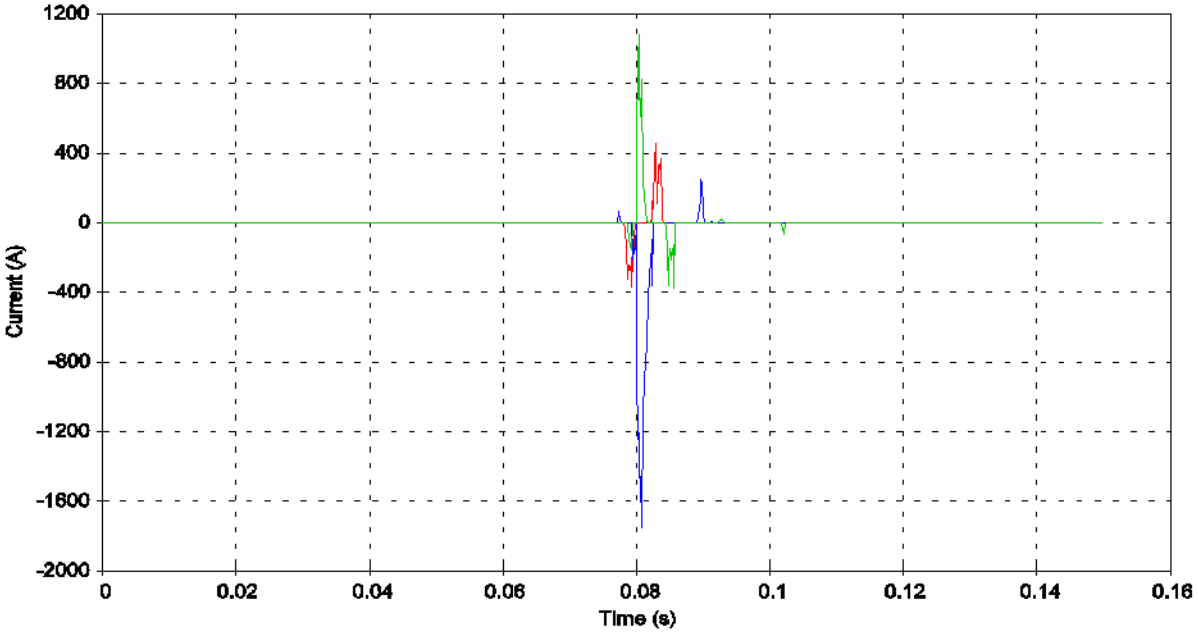
Figure I.20 – Cumulative energy (W_{th}) for 245 kV system simulation (kJ/kV U_r)

Figure I.21 to Figure I.24 show 362 kV high speed line re-energization switching transients with 288 kV surge arresters.



IEC

Figure I.21 – U_{ps} for 362 kV system simulation (V x 10^5)



IEC

Figure I.22 – I_{ps} for 362 kV system simulation (A)

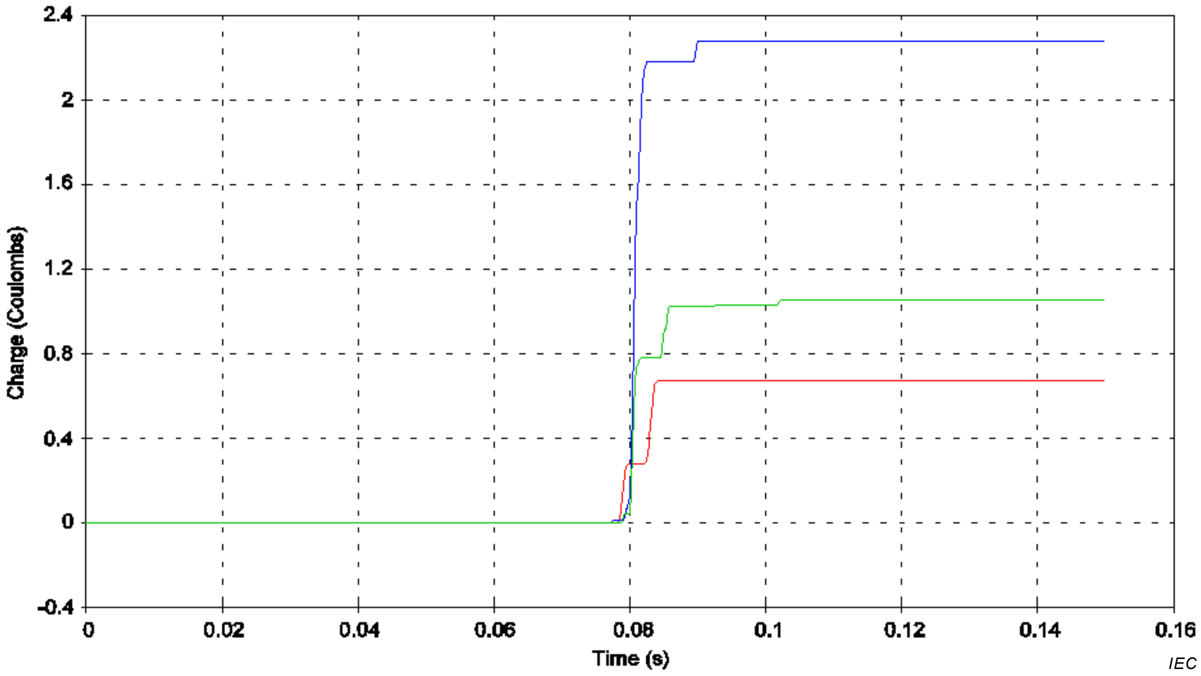


Figure I.23 – Cumulative charge (Q_{rs}) for 362 kV system simulation (C)

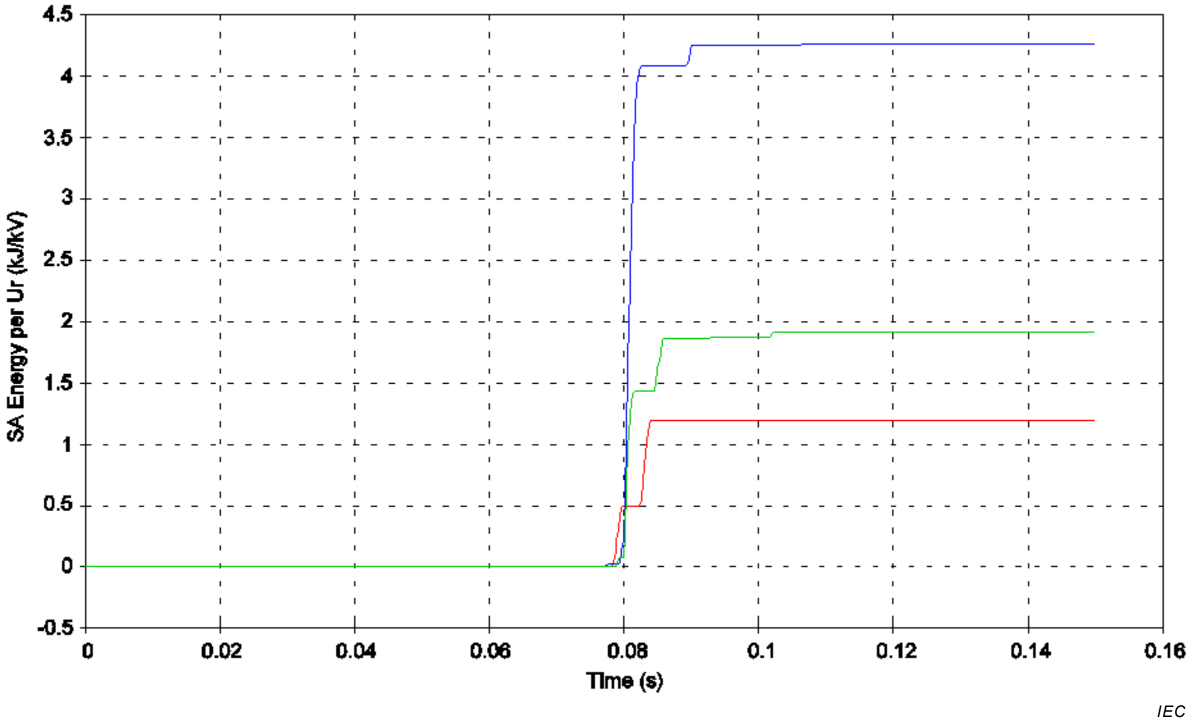


Figure I.24 – Cumulative energy (W_{th}) for 362 kV system simulation (kJ/kV U_r)

Figure I.25 to Figure I.28 show 420 kV high speed line re-energization switching transients with 336 kV surge arresters.

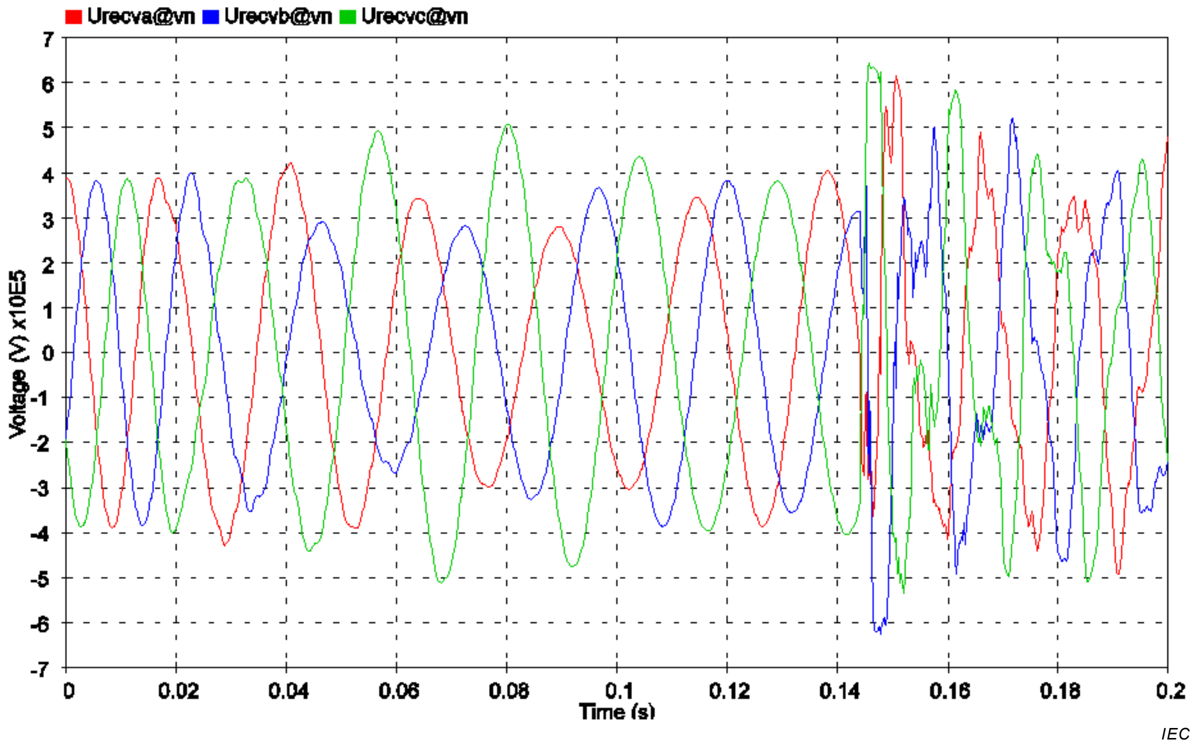


Figure I.25 – U_{ps} for 420 kV system simulation (V x 10^5)

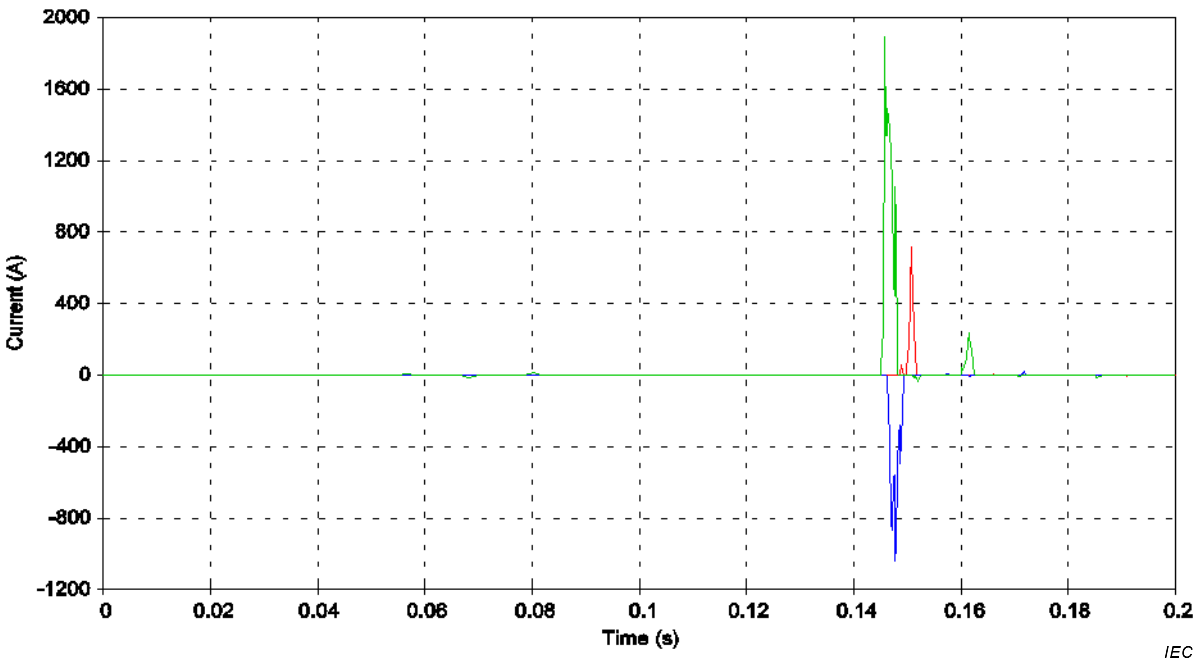


Figure I.26 – I_{ps} for 420 kV system simulation (A)

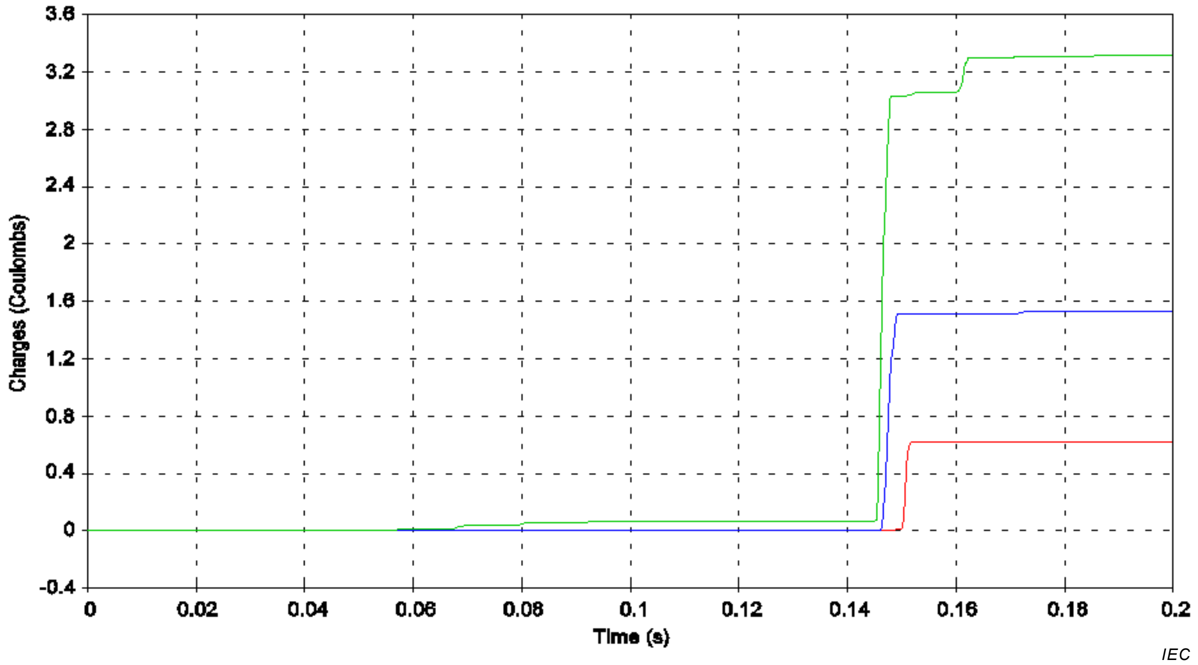


Figure I.27 – Cumulative charge (Q_{rs}) for 420 kV system simulation (C)

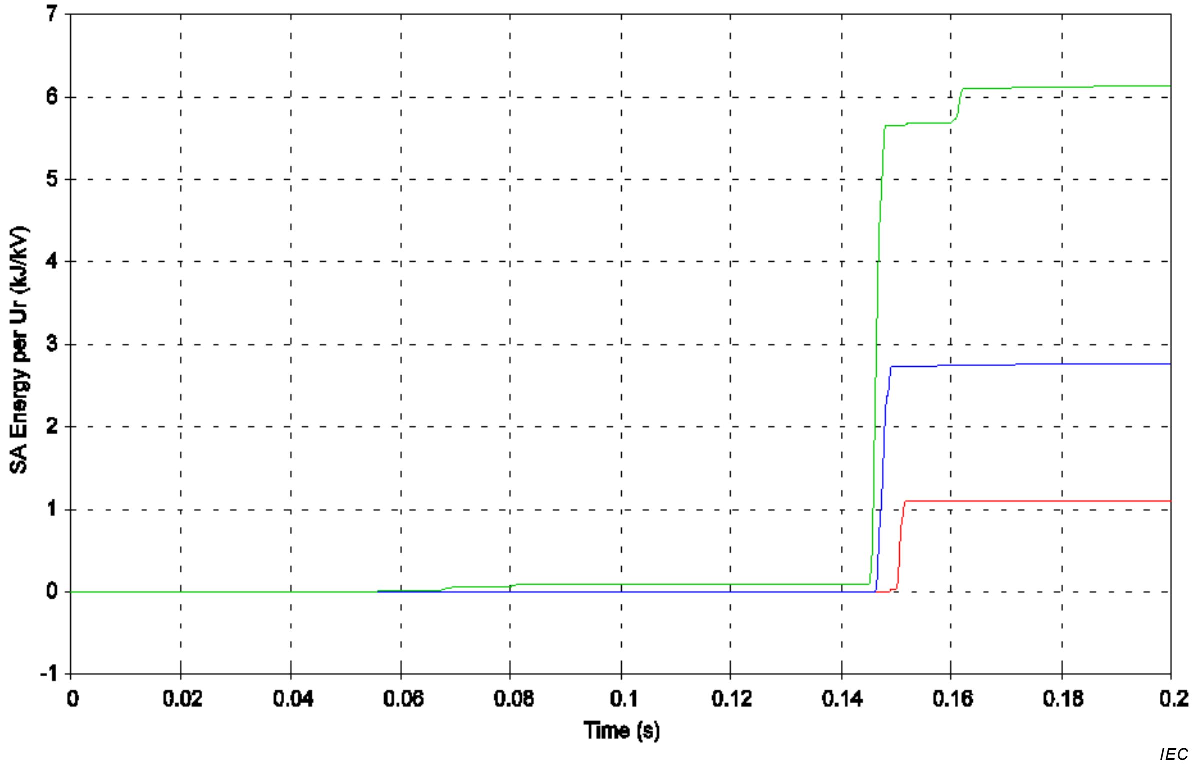


Figure I.28 – Cumulative energy (W_{th}) for 420 kV system simulation (kJ/kV U_r)

Figure I.29 to Figure I.32 show 550 kV high speed line re-energization switching transients with 396 kV surge arresters.

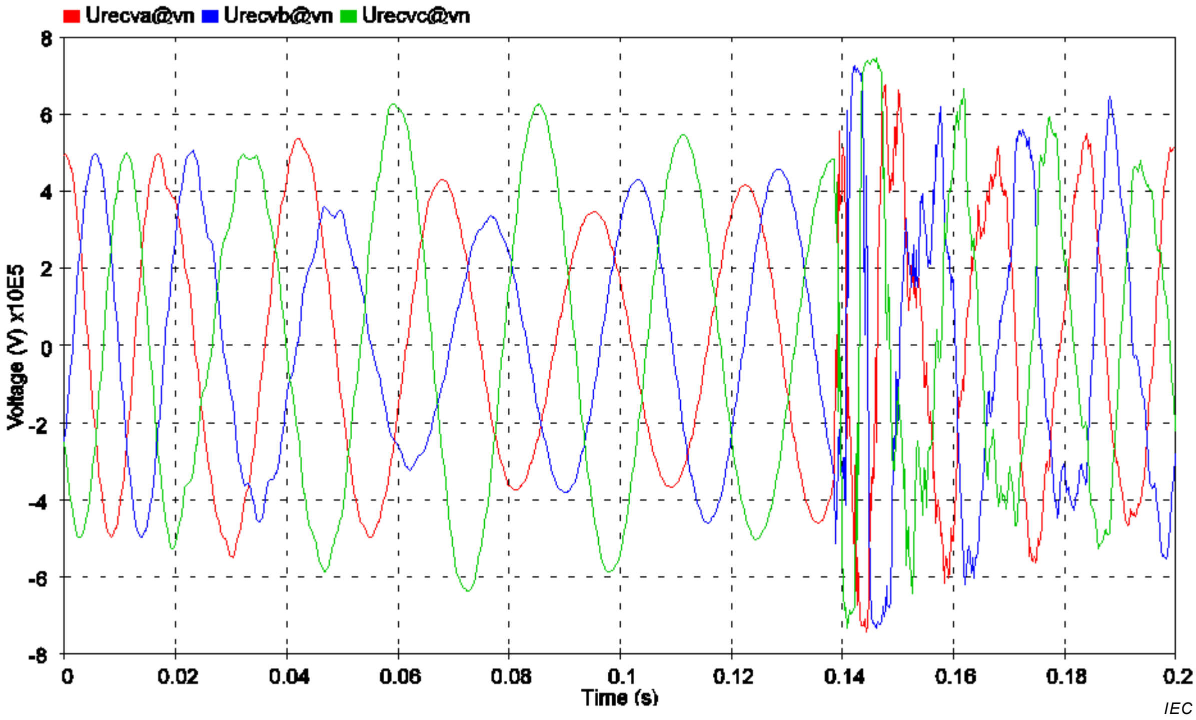


Figure I.29 – U_{ps} for 550 kV system simulation (V x 10^5)

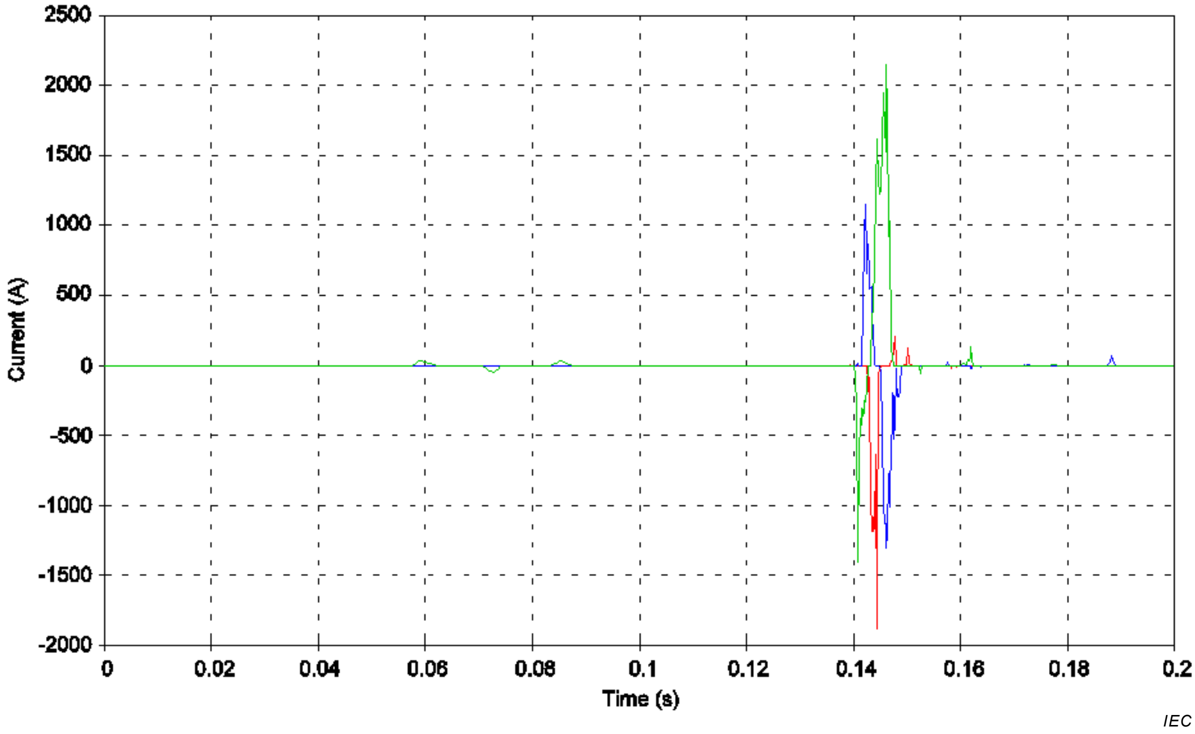


Figure I.30 – I_{ps} for 550 kV system simulation (A)

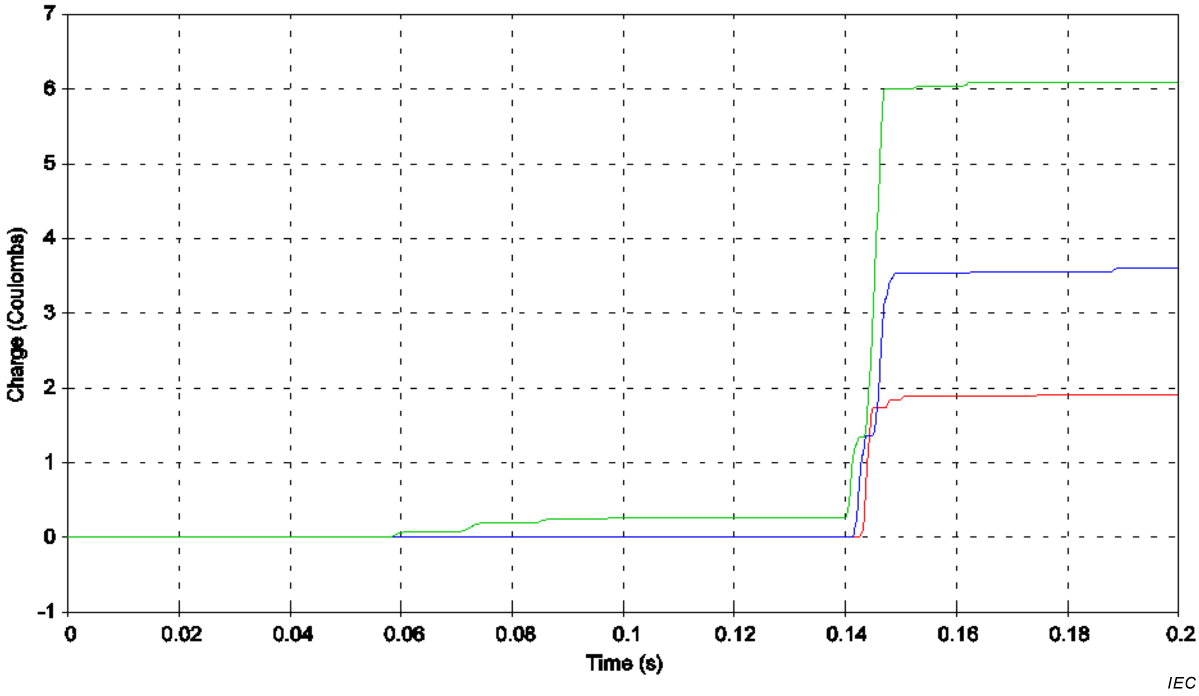


Figure I.31 – Cumulative charge (Q_{rs}) for 550 kV system simulation (C)

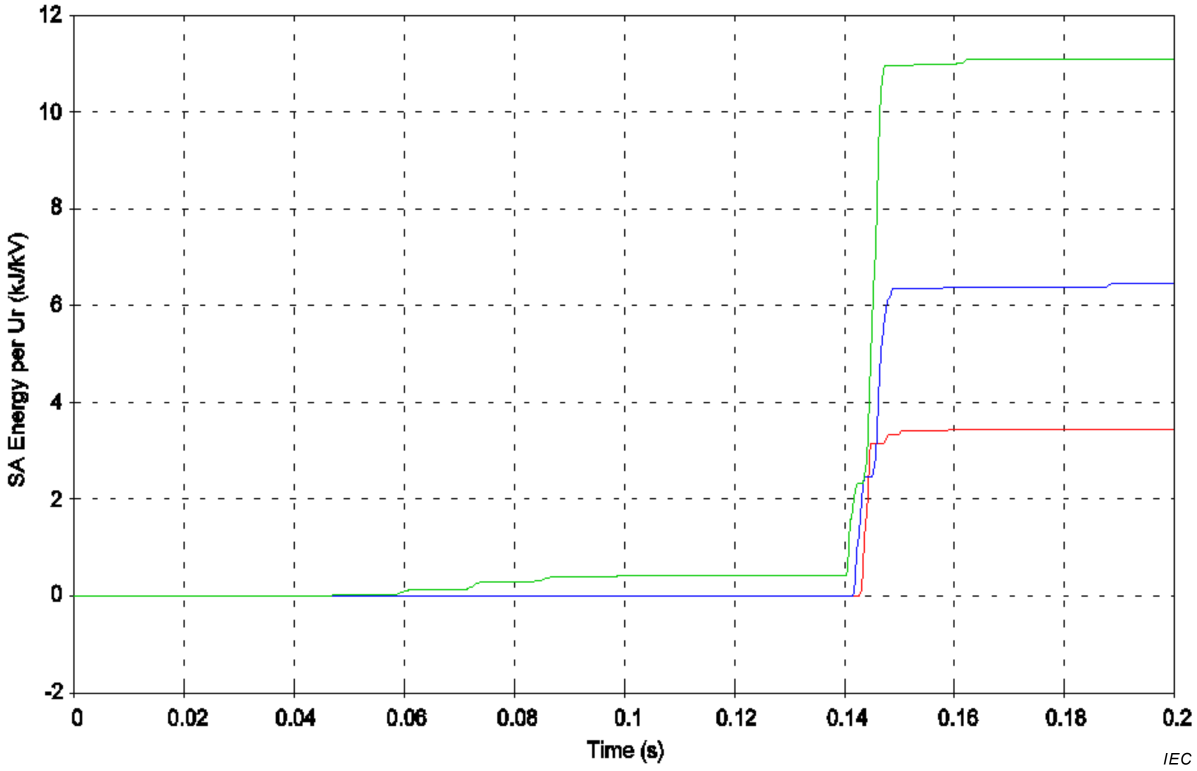


Figure I.32 – Cumulative energy (W_{th}) for 550 kV system simulation (kJ/kV U_r)

Annex J
(informative)

End of life and replacement of old gapped SiC-arresters

J.1 Overview

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.

J.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 J.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.

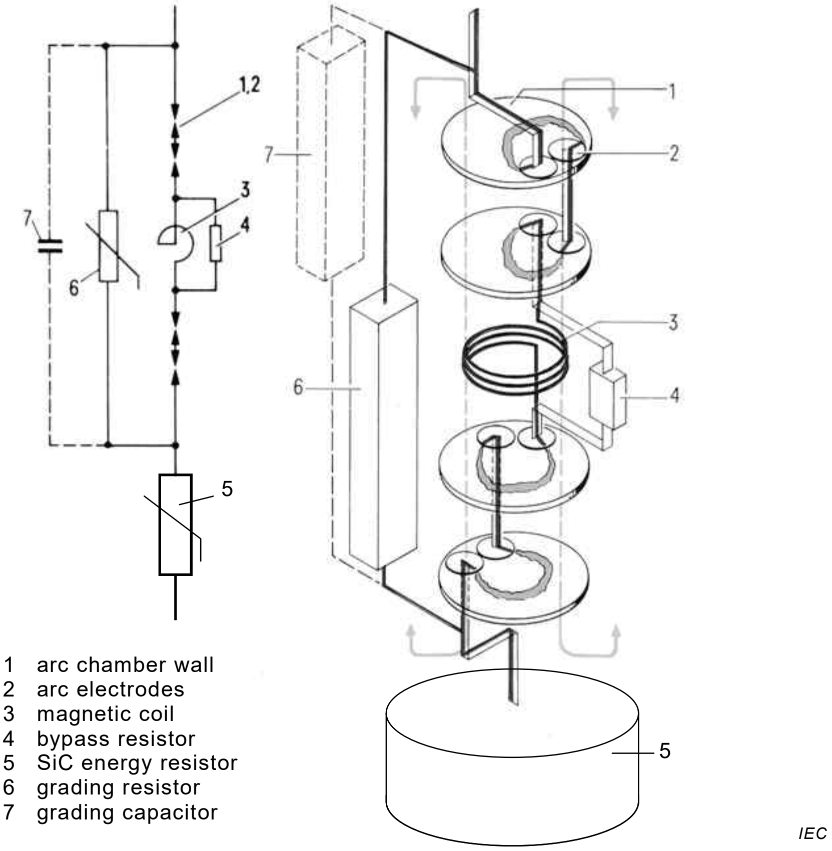
J.3 Failure causes and aging phenomena

J.3.1 General

There are many potential causes for possible malfunction and/or failure because of the number of components used for these arresters.

J.3.2 Sealing problems

This has been the most common failure reason for SiC arresters, a typical construction of which is illustrated in Figure J.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.



1 arc chamber wall
2 arc electrodes
3 magnetic coil
4 bypass resistor
5 SiC energy resistor
6 grading resistor
7 grading capacitor

Figure J.1 – Internal SiC-arrester stack

J.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.

J.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.

J.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.

J.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.

J.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.

J.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.

J.5 Advantages of planning replacements ahead

J.5.1 General

A well-planned replacement programme gives many advantages.

J.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.

J.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.

J.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 arresters can be sold with a zero claimed short-circuit rating, but a 1 second test is still required with any current per IEC 60099-4. 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.

J.6 Replacement issues

J.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.

J.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.

J.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 charge transfer rating, Q_{rs} and rated thermal energy, W_{th}: Unless shunt banks have been added or the system has been extended, there is no need to change the energy requirements. 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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