Overvoltage Surge Protection: Theory, Selection, Application, Maintenance and Monitoring

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Agenda

Overvoltage Surge Protection

- Theory
- Selection basics
- Applications
- Maintenance and Monitoring

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Overvoltage Surge Protection

- Theory
- Selection basics
- Applications
- Maintenance and Monitoring

Insulation coordination

Insulation co-ordination
is the procedure for the selection of
the most economical level of insulation
for electrical equipment which
permits fault-free operation
during both normal and abnormal operating conditions

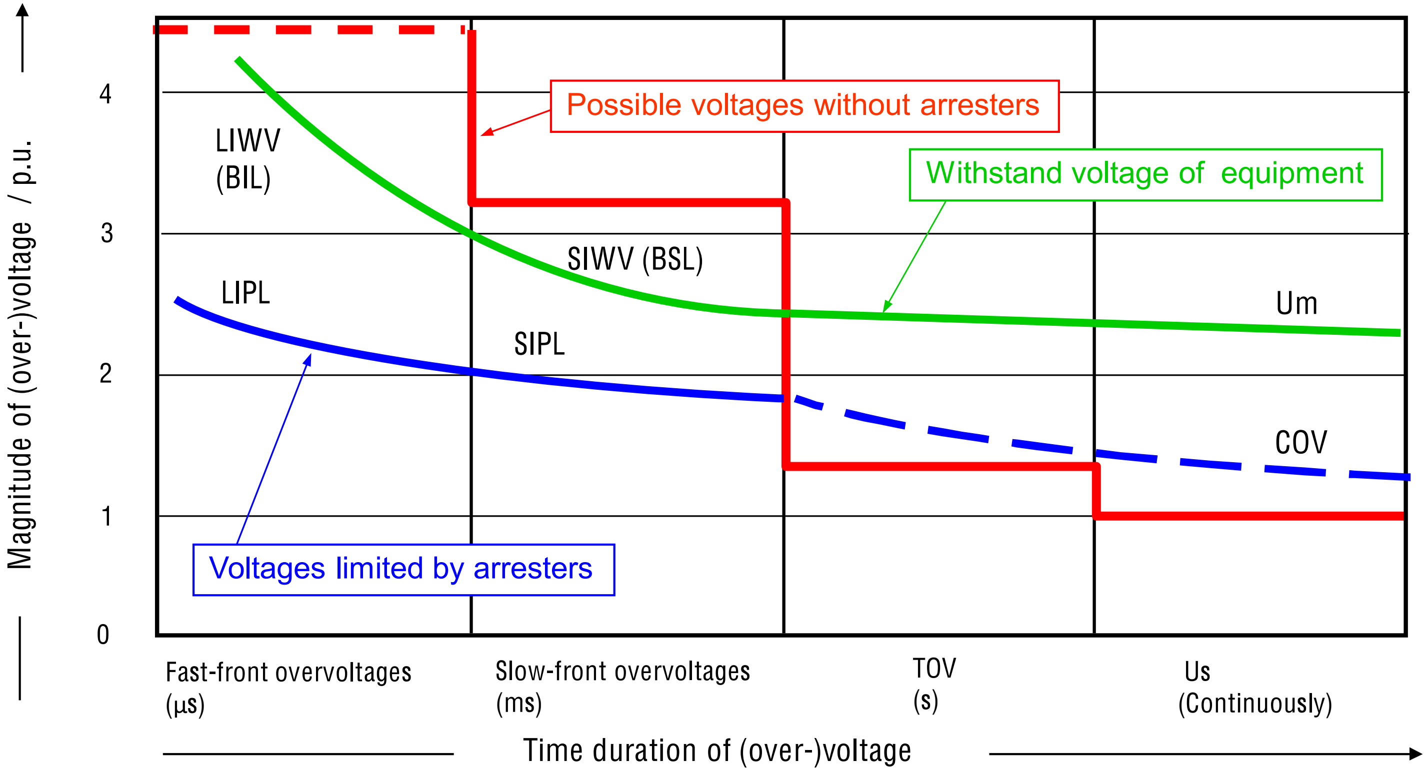
The term can also be extended to encompass the selection of protective devices

All electrical equipment is insulated against a certain value of voltage (amplitude & wave shape)

Select the most economical insulation level by insulation co-ordination

- Dimension the system to withstand all or only certain overvoltages
- Accept some or no flashovers to earth or between phases
- Install overvoltage protection
  - shield wires
  - rod gaps
  - surge arresters

Fundamentals



$$1_{\,p.u} = \frac{U_s \times \sqrt{2}}{\sqrt{3}}$$

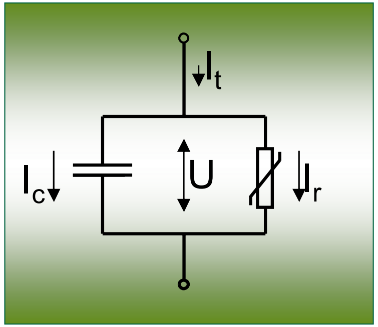
Function

A surge arrester is a protective device

First line of protection against system events of low probability for which the system is not designed.

Designed to limit overvoltages to acceptable levels without voltage dips or interruption of the system operation.

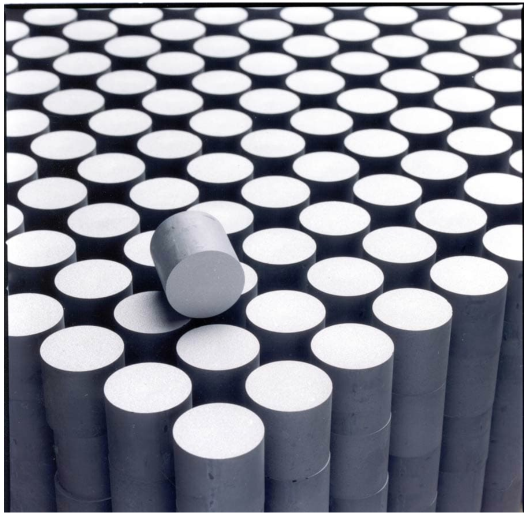
Intended to protect other more expensive apparatus by even sacrificially failing in a safe way for overloads exceeding the design limits.



- High impedance at power frequency voltage
- Low impedance to surge currents
- Today's design based on metal-oxide resistor technology without any gaps (Gapless zinc-oxide surge arresters)

Designed to limit transient surge overvoltages.

MO Resistors



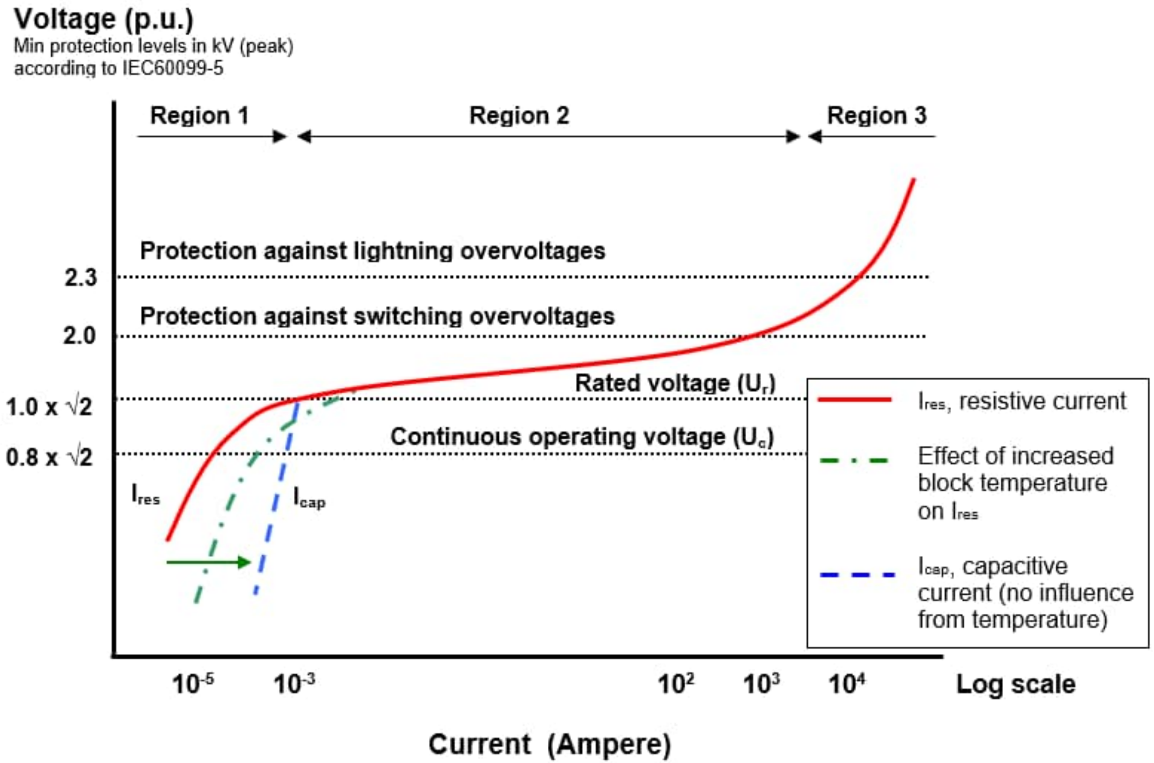
The heart of all operations

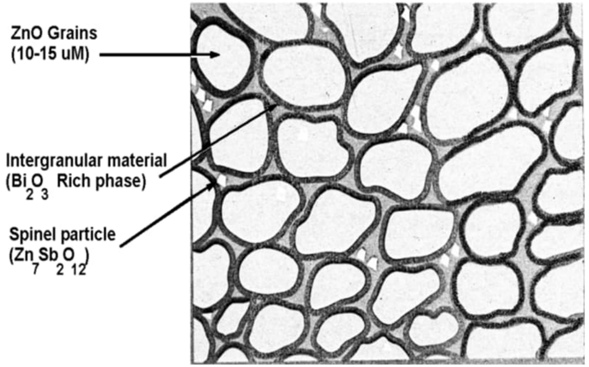
- The metal oxide resistor (also called MO resistor, ZnO varistor, ZnO block, ZnO disc) forms the heart of the modern-day surge arrester
- Consists of approx. 90% ZnO plus 10% other metal oxides
- During the manufacturing process, the oxides transform to form a dense ceramic body with varistor properties

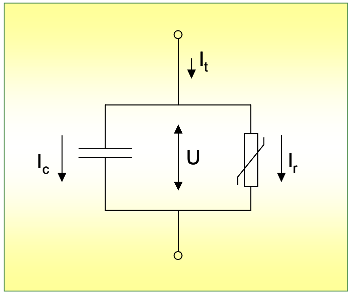
Without detailed knowledge of the block characteristics,
it is not possible to design a reliable high-performance arrester.

MO Resistors

Current - Voltage Characteristic







Distance (separation) effects

Simplified equation

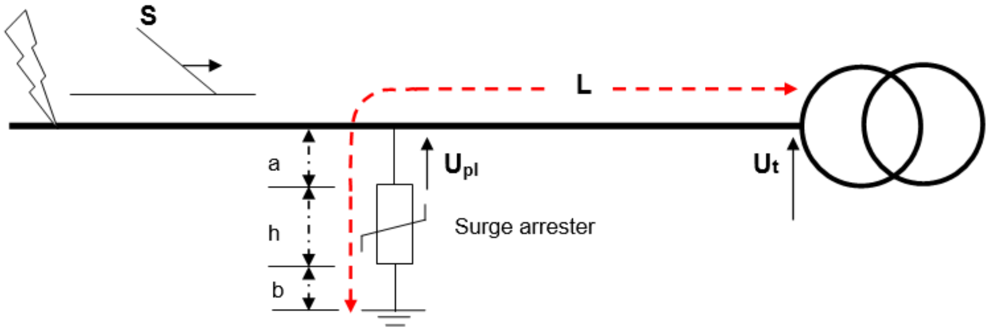
$$U_t = U_{pl} + \frac{(2 \text{ x } S \text{ x } L)}{v}$$

U_{pl} = arrester lightning impulse protection level (kV)

L = electrical distance to object, m
including connection leads and arrester height

S = wave steepness, kV/µs
1200 or 2000kV/µs, determined mainly by risk of backflash or shielding penetration

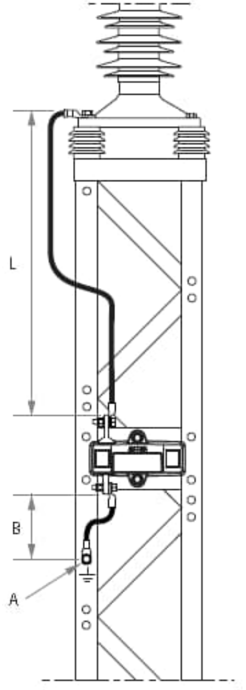
v = wave velocity, m/µs
approx. 300m/µs for lines and 150m/µs for cables



- $U_{t\,max}$ must be less than protected object LIWV(aged)
- Inductance in leads “a” & “b” plus arrester itself of height “h” add to U_{pl}
- Surge capacitance of object, inductance effects, station layout and line impedance may considerably affect protective distance, requiring complex analysis
- U_{ps} margin not affected since front time of switching surge impulse is longer

Earth Cabling

Arrester to surge counter



– Arresters should always be connected to ground by the shortest practical cable length

– When standard counter fitted, arrester and cable must be insulated from ground

– Induced voltage in circuit: Insulated base – cable – structure will be added to arrester protection level and seen by protected object (plus added distance effect)

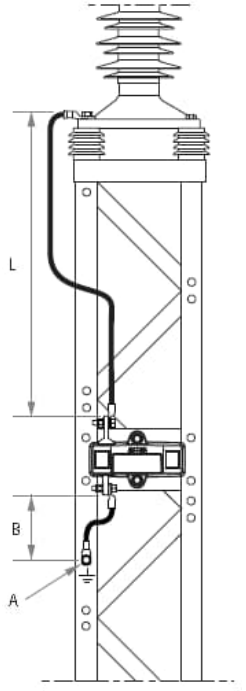
– Maximum length (L) determined by LIWV of insulated base and cable considering foreseen lightning levels
  - Assume 5 kV/m as criteria

– Typical configuration
  Length: 0.5 to max 5 m
  Type: Insulated cable with LIWV > 15 to 25 kVp
  Material: Copper or aluminum
  Cross-section: approx. 25 - 50 mm^2 (eq. copper)

NOTE! Even larger csa may be required, depending on local regulations/practice and consideration to if the cable is to withstand system short-circuit currents without damage

Earth Cabling

Surge counter to ground



- Should be same as other earthing conductors in the station and connected to the common HV earth grid
- Cross-sectional area and type is generally based on the system short-circuit current and duration or as per local regulations
- Whether or not this conductor is insulated has no account with regards to the registration of surges by the counter
- Conductor should also be kept as short as practicable

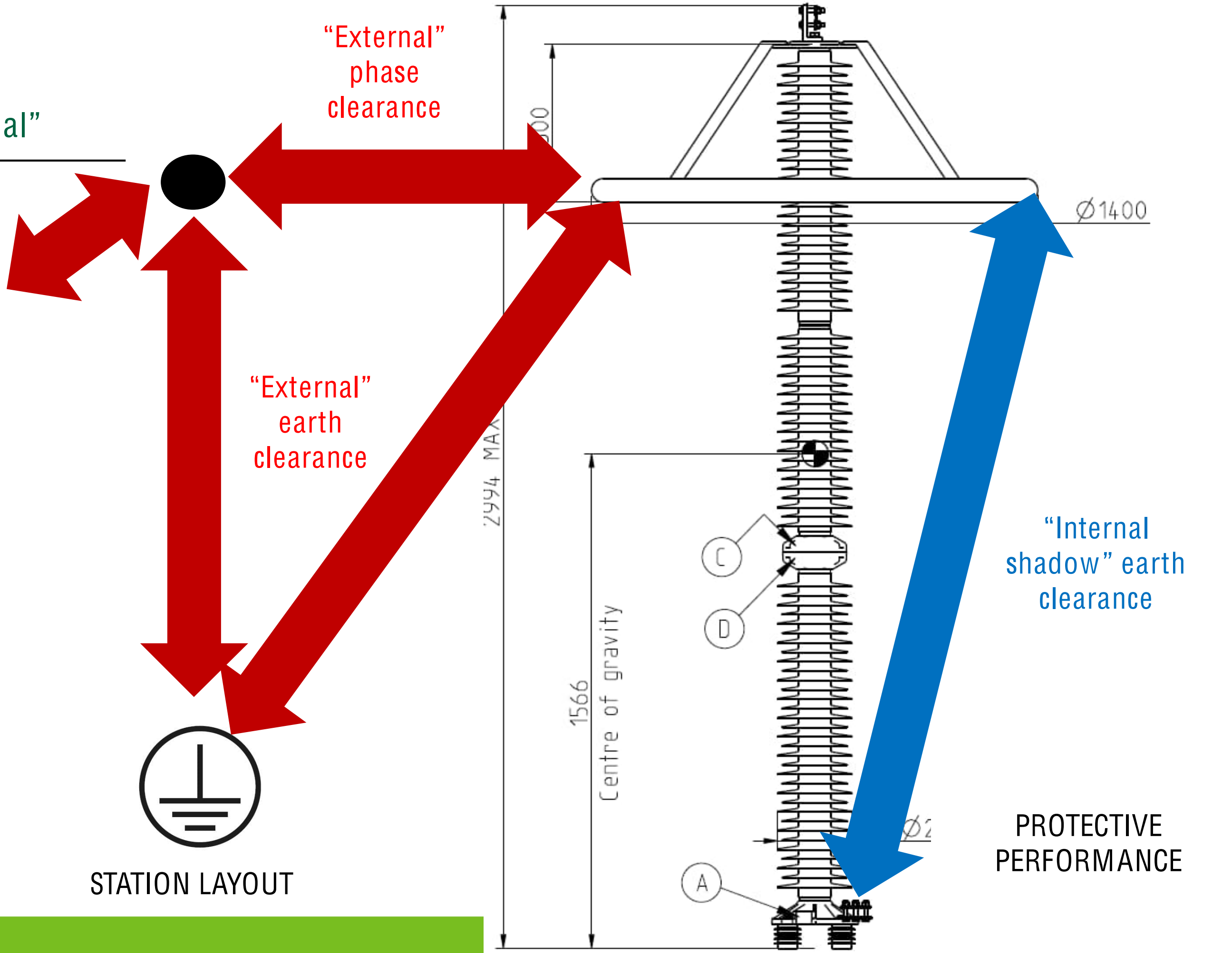
Insulation withstand
Surge arrester specifics

- Arresters are self protecting and have less risk for flashover than other equipment, provided they are dimensioned correctly
  - external insulation of arresters need not fulfil a certain standardized insulation class
  - insulation requirements based on the arrester’s protection levels with a reasonable safety margin added
- Unnecessarily long arresters give less effective protection against steeper surges and undue mechanical stress
- Clearance to other equipment generally according to IEC 60071 guidelines
  - arrester characteristics may permit reduced clearance distances in specific cases

Insulation withstand & clearances of surge arresters

Important distinction between “internal” & “external”

- Standardized clearance requirements refer primarily to other HV equipment or else to the “external” clearance from the arrester outwards to other items, ie. its placement in the station.
- Arrester’s own “internal shadow” clearance across itself does NOT need to uphold a standardized insulation withstand level, and therefore the clearance distance across its own insulation has to be considered differently.
- In general, ”external clearance” for a surge arrester should be the same as selected for other high voltage equipment in a substation
  - If it is not possible in special applications, guidance can be given on ”adequate” clearance, considering the protective characteristics of the arrester.



Withstand & clearances: IEEE C62.11 Clause 8.1

Similar reasoning also stated in IEC:

- IEC 60071-1 Insulation coordination
- IEC 60099-5 SA application
- IEC 62271-1 Common specifications
- IEC 61936-1 Installation rules

As per D8.1: Rationale for tests prescribed by IEEE Std C62.11-2020

Arrester insulation withstand test

Stated purpose: The purpose of this test is to verify that, under usual system conditions, arrester housings will not flashover under defined impulse, switching and power frequency conditions.

Test rationale

The fundamental rationale for this test is to help ensure that the arrester housing can withstand the lightning impulse, switching impulse and power frequency voltages to which it will be subjected over its life.

There is one very different aspect of this test when compared to insulator withstand tests: Consideration is given in this test taking into account that when the MOSA is in service, by its nature, it limits any incoming impulse voltage to levels lower than those generally experienced by insulators on power systems.

It should be noted that the impulse withstand levels of arrester housings are not to be compared to BIL or CFO levels of insulators.
Due to the arrester's self-protecting nature, the arrester housing can have a lower withstand voltage than the rest of the system without any negative impact on the system withstand level.

Also, for this reason, arresters used in standard applications do not generally have a standardized insulation withstand rating.

Surge arrester withstand & clearances Relevant specifics

- Distance effects need not to be considered since the voltage across an arrester can never be higher than that determined by the arrester's protective characteristics.
- Only the need for an additional (statistical) safety factor (margin) including correction for installation altitude can technically justify a higher external insulation strength and flashover distance.
- Formulas are given in IEC 60099-4 / IEEE C62.11 for insulation withstand strength for lightning, switching and power frequency voltage and, provided the calculated flashover distances from the formulas are fulfilled, then the complete arrester (including grading rings, when applicable) is considered to have adequate insulation withstand and flashover distance across its length.
- Any higher value than these is of no practical benefit in service, and all higher values can be considered equivalent; i.e. a higher value is not deemed to improve flashover performance as the arrester housing conceptually has an "infinite impulse withstand" above its protection levels.
- Fully assembled surge arresters with MO resistors in place do not have a BIL/BSL when in service.
  By the definition as per IEEE C62.82.1 insulation coordination:

3.2 basic lightning impulse insulation level (BIL): The electrical strength of insulation expressed in terms of the crest value of a standard lightning impulse under standard atmospheric conditions. BIL may be expressed as either statistical or conventional.

3.3 basic switching impulse insulation level (BSL): The electrical strength of insulation expressed in terms of the crest value of a standard switching impulse. BSL may be expressed as either statistical or conventional.

Surge arrester withstand & clearances IEC 60099-4 / IEEE C62.11

Applicable to surge arresters as per IEC 60099-4 (Clause 8.2) & IEEE C62.11 (Clause 8.1)

The correction factor (Ka) is based on the dependence of the atmospheric pressure at the altitude.

$$K_a = e^{m\left(\frac{H}{8150}\right)}$$

where

H is the altitude above sea level (in metres) and the value of m is

Lightning m = 1,0

Switching (for $\leq$ 1000 m.a.s.l)
$\leq$ 800kV m = 1,0
> 800 kV m according to fig 9 IEC 60071-2

Up to 1000 masl for $\leq$ 800kV

LIWV (dry) $\geq$ 1.3 x Upl

obtained from $1.15 \times e^{(1000/8150)}$

which reflects a 15% co-ordination factor to take into account discharge currents higher than nominal and the statistical nature of the withstand voltage of the insulation, and a 13% margin to account for variation in air pressure from sea level up to normal service altitudes not exceeding 1 000 m and discharge currents higher than nominal.

SIWV (wet) $\geq$ ~1.25 x Ups

obtained from $1.1 \times e^{(1000/8150)}$

which reflects a 10% co-ordination factor to take into account discharge currents higher than normal and the statistical nature of the withstand voltage of the insulation, and a 13% margin to account for variation in air pressure from sea level up to normal service altitudes not exceeding 1 000 m

PFWV (wet) $\geq$ 1.06 x Ups (as peak value), 1 minute withstand

The factor of 1,06 takes into account a safety margin of 1,1 for higher switching impulse currents, an altitude correction factor of 1,13 for 1000 m installation altitude, and a test conversion factor of 0,6×√2 according to Table 2 of IEC 60071-2.

The voltage withstand tests demonstrate the voltage withstand capability of the external insulation of the arrester housing.
This is then a function of the external dimensions and not the internal components. Such tests cannot be performed with the MO resistors inside.

Surge arrester withstand & clearances IEC 60099-4 & IEEE C62.11

- Lightning impulse withstand voltage is deemed inherently sufficient if the flashover distance is larger than the required test voltage U in kV divided by 500 kV/m.

- Switching impulse withstand voltage is only valid for arresters for use on systems of Us > 245 kV but is anyway deemed inherently sufficient if the flashover distance is larger than given by the equation $d = 2.2 \times [e^{(U/1069)} - 1]$, where d is the distance in m and U is the test voltage in kV.

  - Note that testing made since Edition 3.0 of IEC 60099-4 results in the SIWV equation value U/1069 will be changed in future Ed 4.0 to U/1118. Already changed in IEEE C62.11 Ed 2020. Means that a <u>lower flashover distance</u> is sufficient for SI.

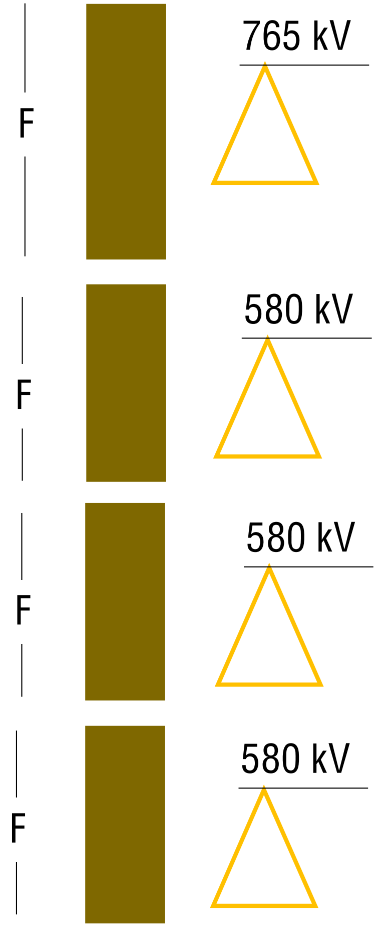
- Power frequency withstand voltage is only valid for arresters for use on systems of Us $\leq$ 245 kV but is anyway deemed inherently sufficient if the flashover distance is larger than given by the equation $d = [1.82 \times (e^{(U/859)} - 1)]^{0.833}$, where d is the distance in m and U is the peak value of the power-frequency test voltage in kV.

- These negate the need to test. But actual test results when made take precedence and used to validate withstand values for a given clearance (flashover distance).

EXLIM P396-GH550 : LIWV

Test on empty unit housings

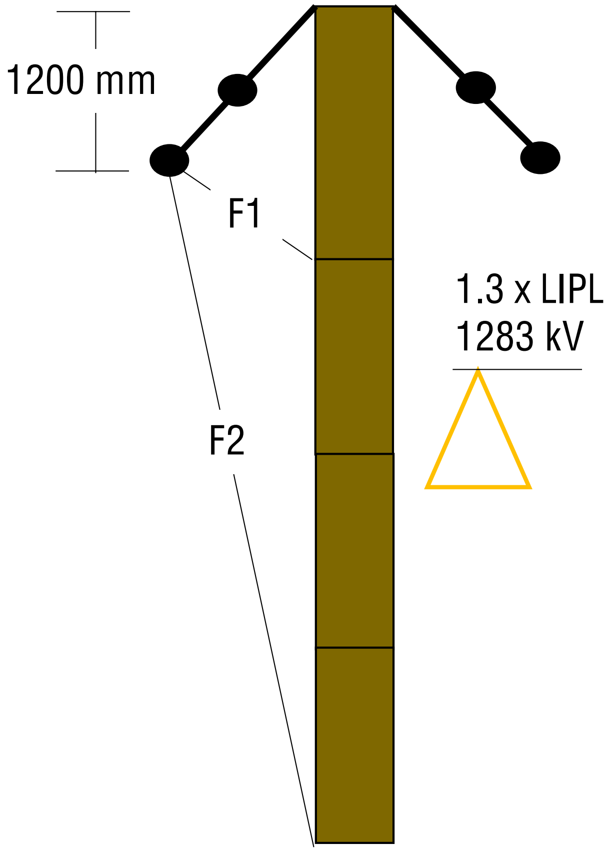
STATISTICAL



Sum of tested values on empty unit housings = 2505 kV

Test on empty assembly

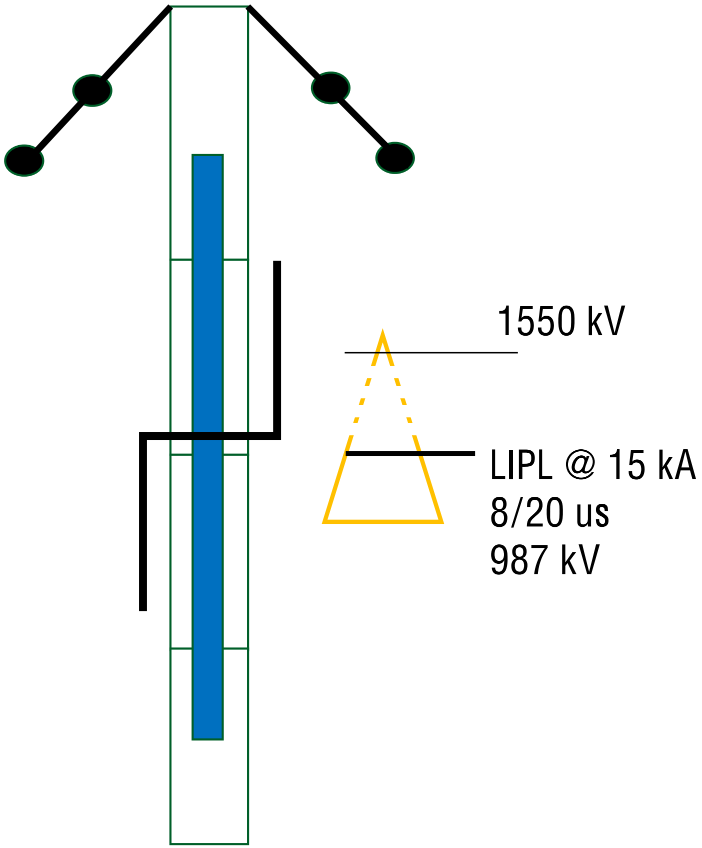
ABSOLUTE



As per IEEE C62.11 = 1283 kV

In service condition (MO resistors installed)

ACTUAL



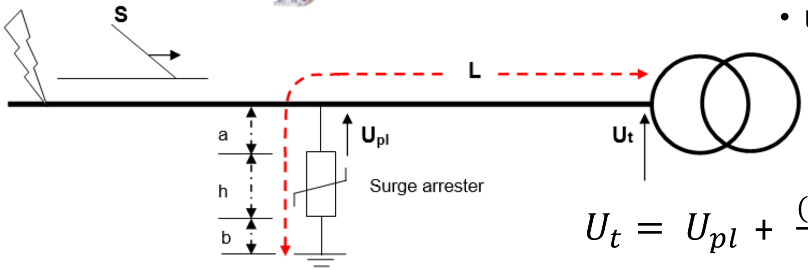
Protected object BIL = 1550 kV
The electrical strength of insulation expressed in terms of the crest value of a standard lightning impulse.

Overdimensioning of surge arresters Drawbacks

- Defining a higher value than that determined by coordination with the arrester's protective characteristic is <u>technically unwarranted</u> with respect to mitigation of acceptable flashover risk

➔ Results in notable drawbacks on system performance

- Higher inductance and inductive voltage drop
  - less effective protection to the primary equipment for steep-fronted surges
  - +10 kV/m for 10 kA arrester & +20 kV/m for 20 kA arrester
- Lower mechanical load capability may require re-configuration
  - taller arrester of a given design copes with less bending moment
  - seismic capability affected by increased mass and length: $F_a = ma$, $M_a = F_a \times h_{cog}$
- Larger diameter grading ring and/or larger down-hang may be required
  - maintaining clearances can become troublesome (across and to other equipment)
  - adverse axial voltage distribution and possibly more critical performance under polluted conditions
- Higher cost to provide a workable solution
  - unnecessary financial burden to project build



$$U_t = U_{pl} + \frac{(2 \text{ x } S \text{ x } L)}{v}$$

- $U_{t\,max}$ must be less than protected object LIWV(aged)
- Inductance in leads "a" & "b" plus arrester itself of height "h" add to U_{pl}

Agenda

Overvoltage Surge Protection

- Theory
- **Selection basics**
- Applications
- Maintenance and Monitoring

IEEE C62.11: 2020

Development

Edition 1993 only considered porcelain-housed arresters

Edition 1999
- New mechanical definitions
- Considers short circuit test for polymer distribution class

Edition 2005
- Weather ageing test for polymer arresters
- Moisture ingress test for polymer arresters

Amendment 1 2008
- Short circuit testing defined

Edition 2012
- Transmission line discharge test for station and intermediate arresters replaced by Switching surge energy capability
- Single impulse withstand capability
- Revised design test procedures

Edition 2020
- Closer harmonization with IEC 60099-4 testing
- Usual service altitude 1000 masl instead of 1800 masl (changes criteria for insulation withstand voltages)
- Duty cycle test eliminated for station and intermediate class arresters


IEEE SA
STANDARDS ASSOCIATION

IEEE Standard for Metal-Oxide Surge Arresters for AC Power Circuits (>1 kV)

IEEE Power and Energy Society

Developed by the
Surge Protective Devices Committee

IEEE Std C62.11™-2020
(Revision of IEEE Std C62.11-2012)

STANDARDS

Arrester classification: IEEE C62.11

Application based classification

- Station class — HV system (substation) use
- Intermediate class — HV system use with demands between Station and Distribution
- Distribution class — Distribution system use (Gapless/Gapped)
  - Heavy duty — OH system, exposed to severe lightning
  - Normal Duty — OH system, exposed to normal severe lightning
  - Light Duty — UG system, where there is another arrester at the line/cable junction

- Liquid immersed type — Designed for use immersed in an insulating liquid
- Deadfront type — Assembled in a shielded housing, intended to be installed in an enclosure for the protection of underground and pad-mounted distribution equipment and circuits
- Riser pole type — Pole mounted, normally used to protect underground distribution cable and equipment

Table 3—Distribution arrester classifications

Distribution class arrester	Lightning impulse classifying current I_{class} (kA)	High current impulse (kA)	Minimum single impulse charge transfer rating Q_{rs} (C)	Minimum thermal energy withstand rating Q_{th} (C)
Heavy Duty (HD)	10	100	0.4	1.1
Normal Duty (ND)	5	65	0.2	0.7
Light Duty (LD)	5	40	0.1	0.45

Table 4—Station and intermediate arrester impulse classifying currents

Arrester class	MCOV range (kV rms)	Lightning impulse classifying current I_{class} (kA)	Switching impulse classifying current (A)
Station	>448	20	2000
Station	246–448	15	2000
Station	116–245	10	1000
Station	2.55–115	10	500
Intermediate	2.55–115	5	500

Table 5—Station and intermediate arrester thermal energy ratings (W_{th})

Energy class	Minimum thermal energy withstand rating (W_{th}) kJ/kV-MCOV
A	3
B	4.5
C	6
D	7.5
E	9
F	11
G	13
H	15
J	18
K	21
L	24
M	27
N	30

IEC 60099-4 Edition 3.0 2014-06

Development

Edition 1 only considered porcelain-housed arresters and much testing of ZnO arresters was based on the old gapped arrester standard 99-1

Edition 2 : 2004

- Polymer arresters considered
- Amendment 1 – 2006 Edition 2.1
    - Short circuit testing defined
- Amendment 2 – 2009 Edition 2.2
    - Mechanical testing defined

Edition 3.0 : 2014

- New concept of arrester classification and energy withstand testing
- Requirements and tests for UHV arresters


IEC 60099-4

Edition 3.0 2014-06

INTERNATIONAL STANDARD

NORME INTERNATIONALE

colour inside

Surge arresters –
Part 4: Metal-oxide surge arresters without gaps for a.c. systems

Parafoudres –
Partie 4: Parafoudres à oxyde métallique sans éclateur pour réseaux à courant alternatif

Arrester classification: IEC 60099-4

Duty based 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)	$\geq$ 2.4	$\geq$ 1.6	$\geq$ 1.0	$\geq$ 0.4	$\geq$ 0.2	$\geq$ 0.1
W_{th} (kJ/kV)	$\geq$ 10	$\geq$ 7	$\geq$ 4	--	--	--
Q_{th} (C)	--	--	--	$\geq$ 1.1	$\geq$ 0.7	$\geq$ 0.45

- Previous Line Discharge Class replaced by a classification based on
  - Repetitive charge transfer rating (Qrs) for station and distribution class
  - Thermal energy rating (Wth) for station class
  - Thermal charge transfer rating (Qth) for distribution class

Distribution class typically Us $\leq$ 52kV
Station class typically Us $\geq$ 72.5kV
(but not only)

The concept clearly differentiates between impulse and thermal energy handling capability.

Type / Design Testing

Arrester standards define well the tests to be performed on
- Elements
- Sections
- Complete design

... to represent actual performance as applicable for
- Individual test
- Design concept

An arrester test object may therefore look different depending on the intended test

Surge arrester standards are “standalone” and (unless they reference another standard for methods) it is not necessary or relevant to refer to other standards for defining the applicable tests to be performed.

IEC 60099-4 : 2014

Requirements for test objects
Polymer-housed arresters

IEC 60099-4 clause	Test	Test section according to IEC	Test section used by Hitachi Energy
10.8.2	Insulation withstand	Longest individual arrester unit housing (for Us ≤ 245 kV)	Each individual housing size
10.8.3	Residual voltage	Individual MO resistor	Individual MO resistor
10.8.4	Test to verify long term stability under continuous operating voltage (Accelerated ageing)	Individual MO resistor	Individual MO resistor
10.8.5	Repetitive charge transfer withstand (Qrs)	Individual MO resistor	Individual MO resistor
10.8.6	Heat dissipation of test sample (Thermal equivalency)	Arrester unit and thermally prorated section	Arrester unit & thermally and dielectrically prorated section
10.8.7	Operating duty (Wth)	Thermally prorated section	Thermally and dielectrically prorated section
10.8.8	Power-frequency voltage versus time (TOV characteristic)	Thermally prorated section	Thermally and dielectrically prorated section
10.8.10	Short-circuit	HC: Longest mechanical and electrical unit LC: Any unit length	Longest mechanical & electrical unit
10.8.11	Bending moment	Longest electrical unit	Longest electrical & mechanical unit
10.8.13	Seal leak rate	Arrester unit of any length	N/A to PEXLIM solid “Design B” type
10.8.14	Radio-interference	Representative arrester	Various. Arresters with highest electrical field stress tested and validation shown.
10.8.15	Internal dielectric withstand	Dielectrically prorated section or included in Operating duty test	Included in Operating duty test as test sample used is also a dielectrically prorated section
10.8.16	Internal grading component stability	Components	N/A (no such components used in PEXLIM arresters)
10.8.17	Weather ageing	a) 1000 h salt fog: Longest electrical unit b) 1000 h UV light: Shed and housing material	a) Longest electrical unit b) SiR material used for sheds and housing (all PEXLIM have utilized the same SiR material since 1992)

IEEE C62.11 : 2020 Design test	Station and intermediate class		Distribution class			
	Porcelain	Polymer	Porcelain	Polymer	Liquid-immersed	Deadfront
Arrester insulation withstand test	8.1.2.4	8.1.2.4	8.1.2.1	8.1.2.1	8.1.2.2	8.1.2.3
Discharge-voltage characteristics test	8.2	8.2	8.2	8.2	8.2	8.2
Power-frequency sparkover test	8.3	8.3	8.3	8.3	8.3	8.3
Impulse protective level voltage-time characteristic test	8.4	8.4	8.4	8.4	8.4	8.4
Accelerated aging test of metal-oxide disks	8.5	8.5	8.5	8.5	8.5	8.5
Accelerated aging test of polymer-housed distribution arresters with exposure to light and electrical stress	—	—	—	8.6	—	—
Accelerated aging test of polymer-housed arresters with exposure to salt fog	—	8.7	—	8.7	—	—
Contamination test	8.8	8.8	—	—	—	—
Distribution arrester seal integrity design test	—	—	8.9	8.9	—	—
Radio-influence voltage (RIV) test	8.10	8.10	—	—	—	—
Switching impulse energy rating test (W_{th})	8.11	8.11	—	—	—	—
Single-impulse charge transfer rating test (Q_{rs})	8.12	8.12	8.12	8.12	8.12	8.12
Operating duty test for distribution arresters (Q_{th})	—	—	8.13	8.13	8.13	8.13
Temporary overvoltage (TOV) test	8.14	8.14	8.14	8.14	8.14	8.14
Short-circuit test	8.15	8.15	8.15	8.15	—	—
Failure mode test for liquid-immersed arresters	—	—	—	—	8.16	—
Deadfront arrester failure mode test	—	—	—	—	—	8.17
Distribution arrester disconnector test	—	—	8.18	8.18	—	—
Maximum design cantilever load (MDCL) and moisture ingress test for polymer-housed arresters	—	8.19	—	8.19	—	—
Ultimate mechanical strength-static (UMS-static) test for porcelain-housed arresters	8.20	—	8.20	—	—	—
Seismic capability verification	8.21	8.21	—	—	—	—

Valid standard

IEC and IEEE surge arrester standards remain different in specifics

- Classified, defined and tested differently
- Design and test standards should be matched across the network and between apparatus
- An arrester should not be chosen based on IEEE for an IEC system, and vice-versa

IEC and IEEE standards are in a constant state of revision

- Arrester standards are starting to approach a common philosophy and harmonization
- Difficult to harmonize completely, but attempting to bring them closer

Regardless of which standard is applied, it is increasingly important that users understand their system parameters to correctly select a suitable arrester for a specific application.

Specification

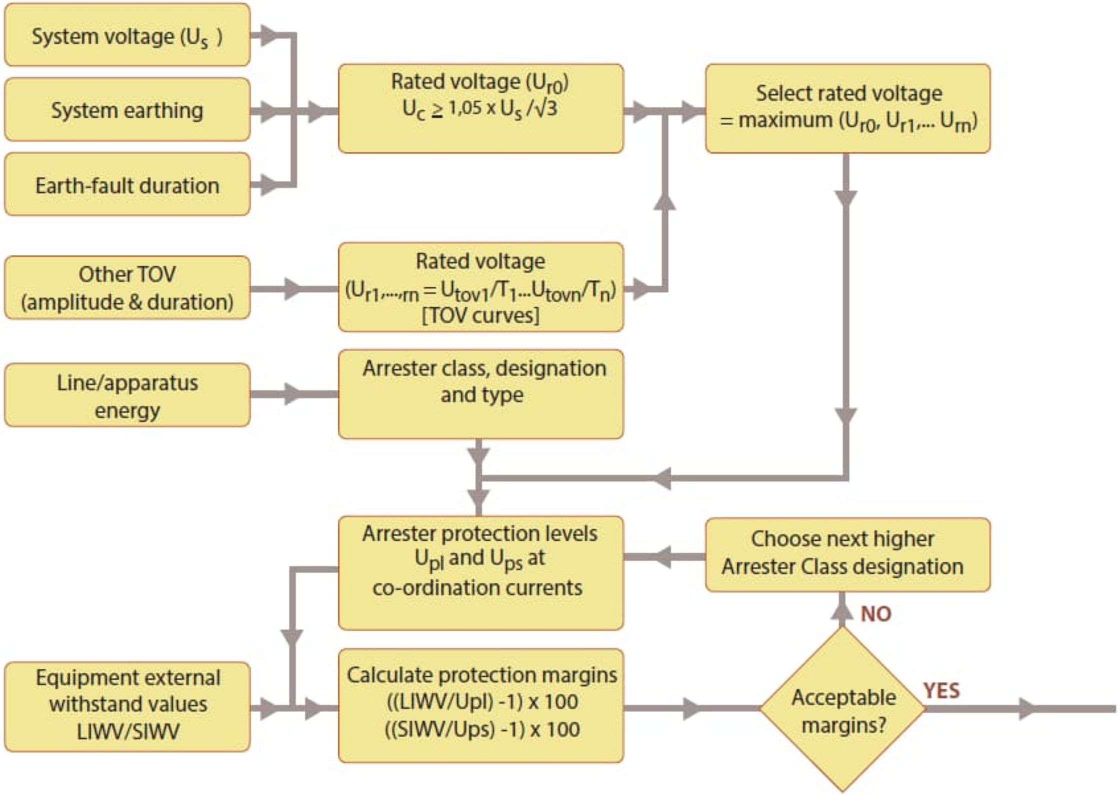
Surge arrester selection parameters: HVAC arrester user specification

- Application and connection configuration
- Arrester standard
  - as applicable (not both nor either/or)
- System voltage Us => define arrester COV
  - Uc no more than Us/√3 needed for typical use (plus added 5% for regulation, harmonics as per IEC 60099-5)
- System TOV (voltage and duration)
  - Important to be correctly determined and specified
  - With or without prior duty to be clear
- Insulation level(s) to be protected and desired protection levels
  - Realistic and relevant
- Arrester Classification
  - Higher gives better protection for most important equipment

- Energy demands
  - Realistic, relevant & well-defined; no unnecessary added margin
- Mechanical load demands
  - Limited wherever possible by installation
- Environmental considerations
  - Ambient temperature, altitude, pollution, etc.

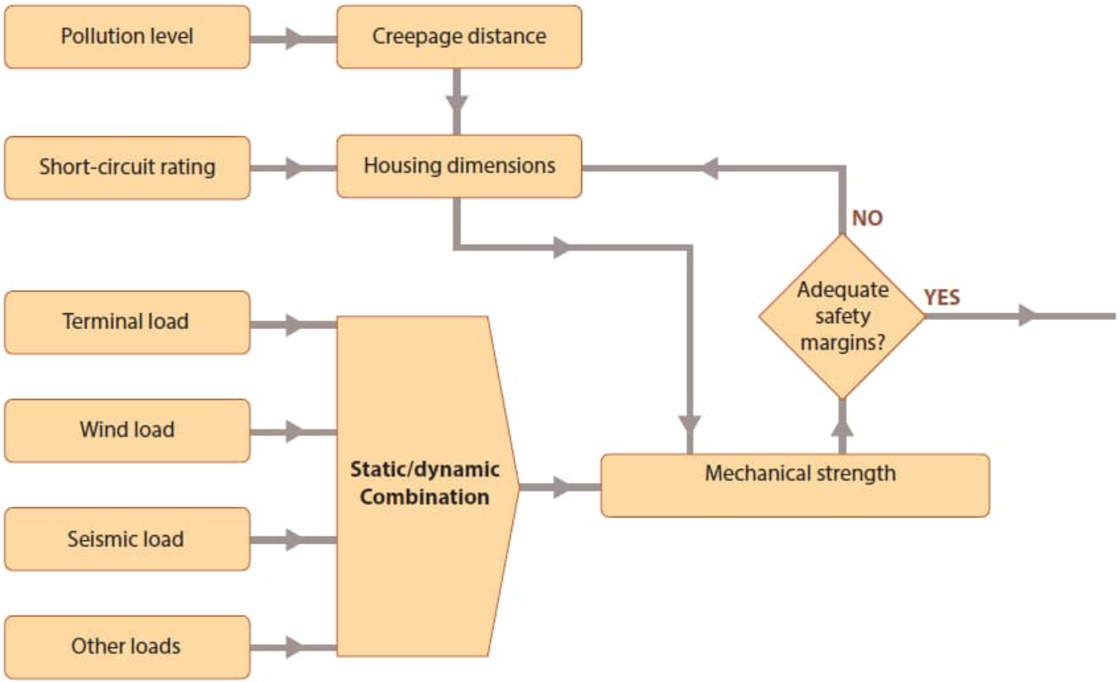
- Thereafter, manufacturer ideally to be given freedom to optimize his design
  - higher COV is unnecessary
  - rated voltage not hard-specified by user
- Otherwise risk for “sub-optimized” solutions since users cannot know design specifics

Match the electrical characteristics



Electrical
selection complete

Match the mechanical characteristics



Mechanical selection complete

Properly chosen and installed arrester

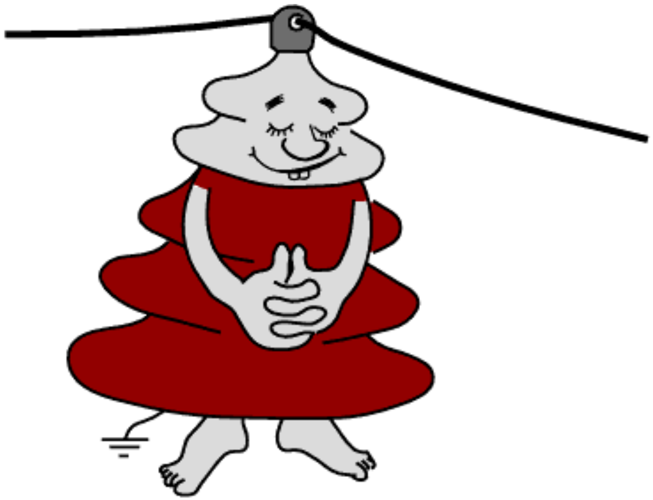
System Parameter	Matching arrester selection parameter	Consequences of improper selection
Application and equipment to be protected	Type of arrester and connection	Failure or inadequate protection
Maximum system voltage, Us	Uc. Minimum 1.05x Us/√3 for ph-E connection	Overstressed or shortened life
Maximum temporary overvoltage, TOV TOV = k x Us/√3 for ph-E connection k factor for various fault conditions and duration	Ur. Minimum TOV/Tr. Tr is arrester TOV withstand for the duration. Dependent on arrester & prior energy duty.	Overstressed or shortened life
Energy / Charge requirements	Wth and Qrs (or W for specifics) = MO resistor size	Overstressed or shortened life
Insulation withstand levels to be protected	Protective margins for Upl and Ups	Inadequate protection
Mechanical loads (terminal, s/c, wind, seismic, etc). Terminal limited by appropriate installation method. Realistic static and dynamic combinations.	Housing strength, including short-circuit rating. Terminal loads Max Fts 400 N, Ftd 1000 N sufficient. Polymer arrester can flex with applied load.	Physically break or overstressed. Sealing compromised. Deflection compromises clearance.
Installation arrangement, placement and orientation	Type of arrester and connection. Advise not intended as a bus support. Housing shed orientation pre-arranged at production. Protective distance checked and adequate.	Physically break or overstressed. Sealing compromised. Deflection compromises clearance. External flashover. Inadequate protection.
Environmental conditions (pollution, altitude, ambient temperature, etc)	Housing design. Creepage distance matched to pollution level. Housing insulation withstand matched to altitude with consideration to arrester own protection levels. De-rating may need to apply for extremes.	External flashover. Housing breakdown, damage. Excessive internal PD shortens life. *) Thermally overstressed.

Inherently presumes the arrester design concept is secure, robust and well proven.

*) PD may not always be completely eliminated in practice and the design must cope during pollution episodes

Selection summary

1. Determine application/type of equipment to be protected
2. Match the electrical characteristics
3. Determine the energy requirements
4. Calculate protection levels
5. Check protection margins
6. Match the mechanical characteristics
7. Consider environmental factors



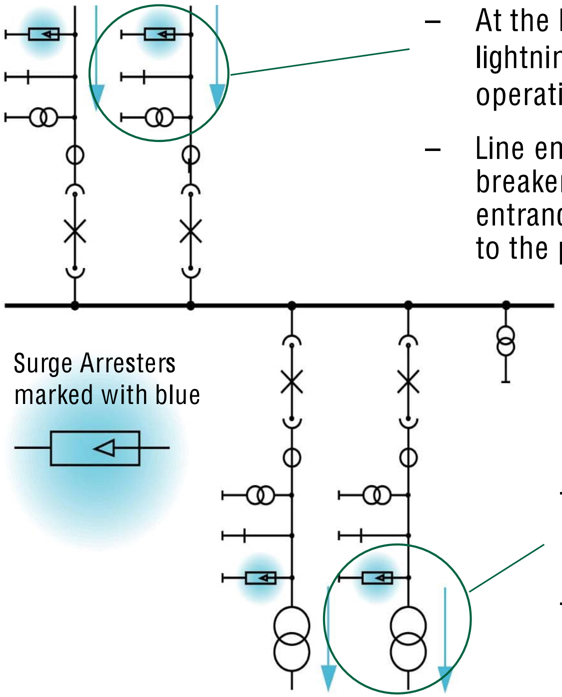
Choose the surge arrester that provides optimum protection with suitability to the application at a value for money price and not simply based on up-front cost.

Agenda

Overvoltage Surge Protection

- Theory
- Selection basics
- **Applications**
  - Transformer station
  - Underground cables
  - Capacitor and filter banks
  - Transmission lines
- Maintenance and Monitoring

Station Protection



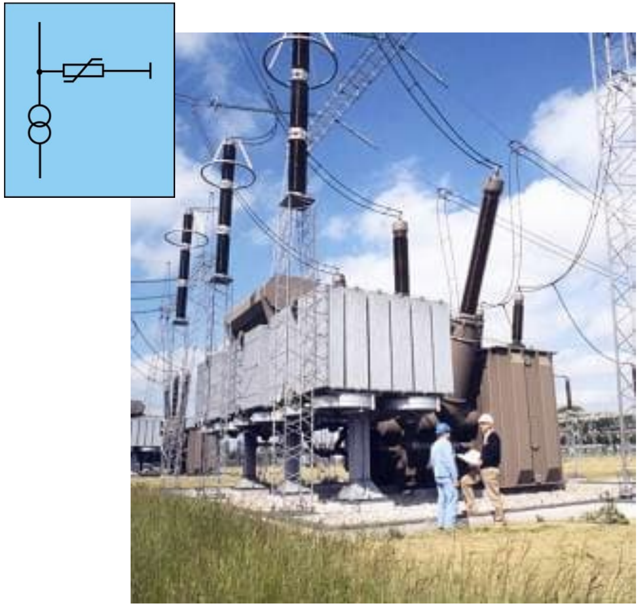
Surge Arresters marked with blue

- At the line entrance bay to take care of multiple lightning strokes in combination with circuit breaker operations
- Line entrance surge arrester protects the line breaker and the instrument transformers at the entrance. Furthermore, it gives improved protection to the power transformer

- Always as close as possible to the power transformer
- With safe silicone insulated arresters, optimal place is on the power transformer

Station Protection

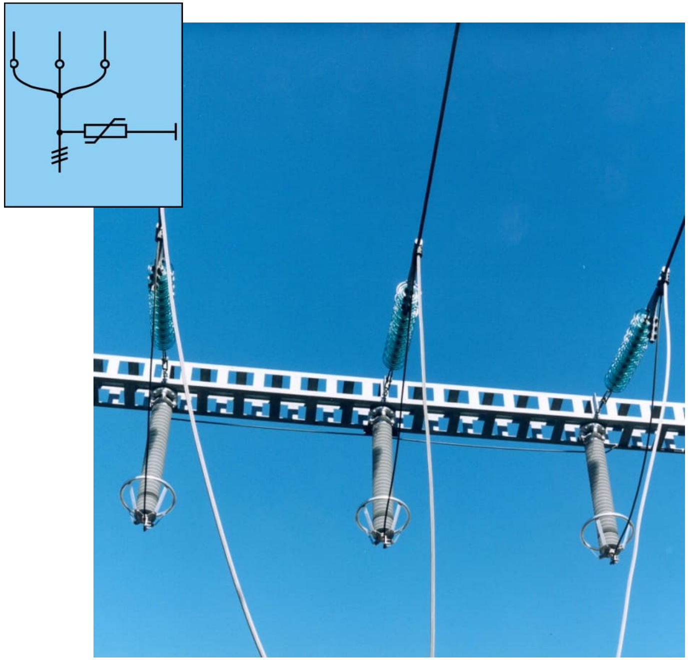
Protection of transformers

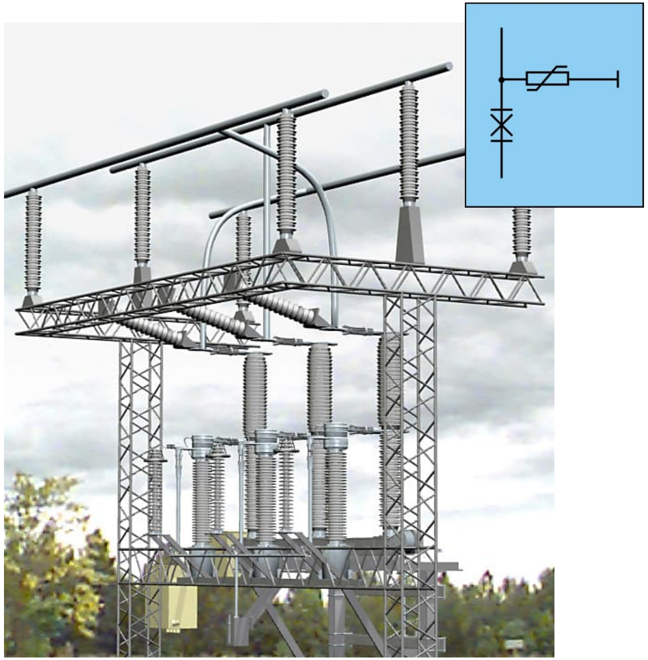


– Arresters always located adjacent to the power transformer; being the most costly item of plant

Station Protection

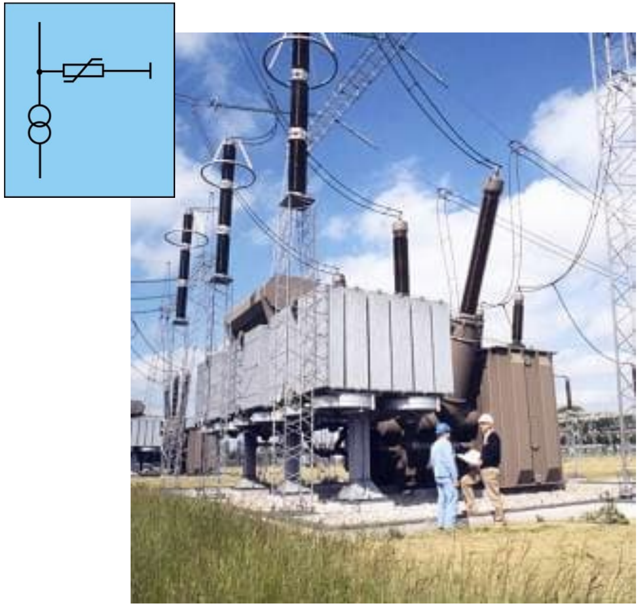
Protection of line entry and circuit breakers





Station Protection

Line entry bay



- With line breaker closed,
  arresters located adjacent to the power transformer are often all that is needed to protect apparatus connected to the same line within the substation

- With the breaker opened,
  no protection exists for the line side of the breaker making it and other equipment vulnerable

  - Incoming lightning surge may cause flashover of the breaker or insulation failure of other line-side equipment

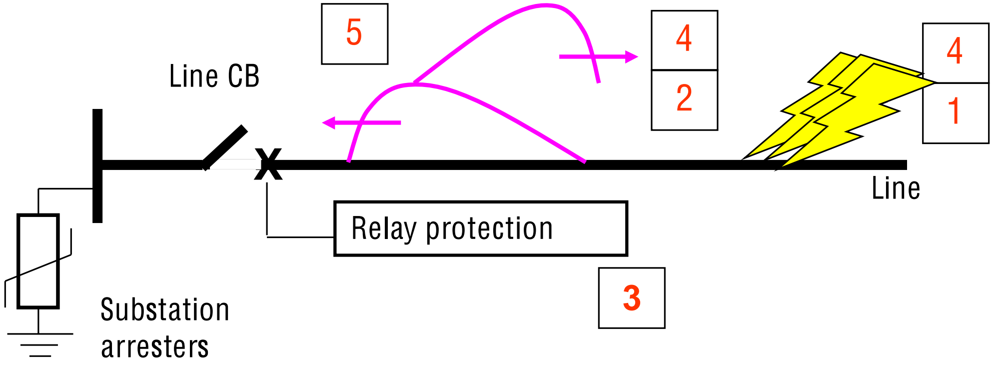
Station Protection

Line entry bay

- Prolonged opened breaker condition normally dictates that the breaker disconnecting switches are also opened and grounded
    - If not, some form of protection should be used to prevent surges impinging on the breaker
- More likely during normal operation is that damage to the line breaker occurs as a result of subsequent strokes of the lightning flash during the open-close cycle
- Flashover across the line breaker is particularly severe since the consequence will normally be a busbar fault in the substation
- With the breaker open, equipment on the line side is also unprotected

Station Protection

Line entrance bay – A likely scenario



1. Lightning strikes the line, resulting in a flashover and earthfault.

2. Lightning surge travels into the substation.
   Line CB is closed and substation arresters function to limit the overvoltage.

3. Relay protection senses the fault and line CB opens (in about 50ms). Fault current is cleared by the CB. Autoreclosure would normally occur in about 300ms.

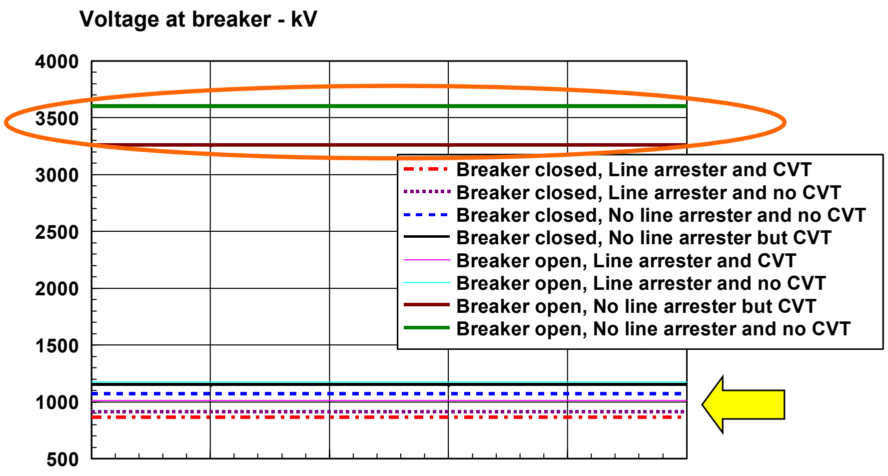
4. Multiple lightning stroke occurs in the same channel as before in the interval 30 – 300ms after initial stroke. Subsequent surges occur while the CB is open (dead time during autoreclose operation)

5. The lightning overvoltage is reflected at the open line end, doubling the amplitude. Line breaker is unprotected and overvoltage exceeds the breaker insulation withstand strength.

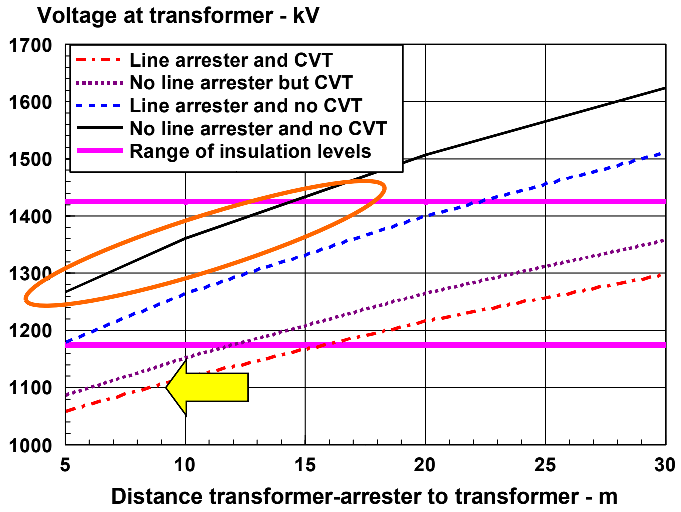
Station Protection

Line entry example

Voltage at breaker



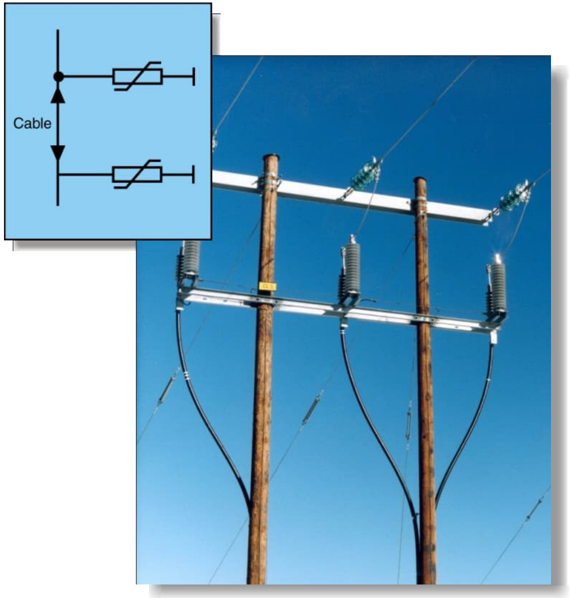
Voltage at transformer

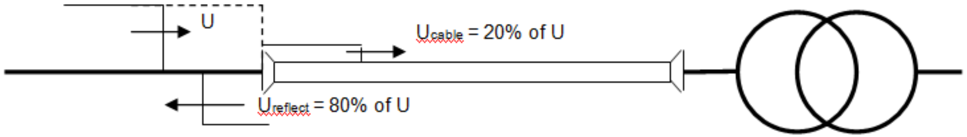


Clear advantage with additional arresters (and CVT) in front of the line breaker

Example 420kV (LIWL 1175 – 1425kV)
Incoming surge 2000kV, 2000kV/μs

Cable protection





- For simplification, assume the incoming wave to be rectangular and the surge impedance of the transformer as infinite, so that total reflection occurs at the transformer terminals.

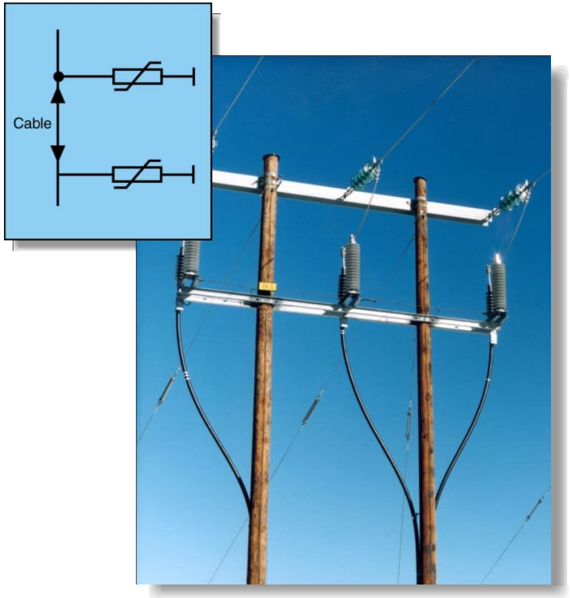
- The result is a step-wise increase in the voltage, up to potentially double the initial incident voltage, U.

- For a cable connected between two overhead lines, the voltage reflected in both ends of the cable will increase to the value of the incoming voltage, U.

- Generally, a cable can be considered as a concentrated capacitance, which will be able to bring down the steepness of the incoming wave, but if the wave energy is sufficiently high, the cable does not limit the voltage rise.

In practice, the wave front is not rectangular, but has a rate of rise. This rate of rise will change the way the cable is charged, but not the value.

Cable protection



- Cables should be treated as station equipment and protected against lightning by well-specified surge arresters.
  - 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.

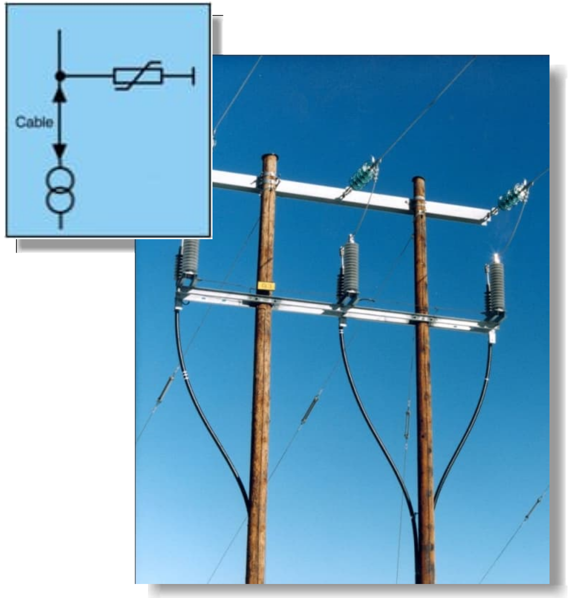
- As a general rule, surge arresters are recommended to be mounted at both ends of the cable; especially where the cable is exposed to lighting from either end.

- On cables into transformers, single-ended protection may be possible on a “short cable” (transformer end) or necessary with internally connected cable boxes (remote end).
  - Many defining parameters are involved, and a certain higher degree of associated risk for insulation failure may have to be accepted.

Lightning charge is often between 1 – 10 A sec.
Only in the case of very large cable networks can the danger of atmospheric overvoltages be reasonably neglected.

Ex. A 1km long cable with 0.25 μF/km needs only 0.25 As to be charged to a value of 1000 kV.

Cable protection – Remote end only



To achieve the greatest possible protection zone for cables operating at 72.5kV and above:

– Incoming overhead line should have a zone out from the substation equipped with shield wires
    - 2km zone for cables lengths of up to 1000m.
    - For longer cables, the length of line with shield wires should be equivalent to at least double the length of the cable.
    - Inside the zone, the footing resistance of the towers must be kept low, i.e. a few ohms.

– The incoming lines should be fitted with surge arresters to limit the overvoltages actually transferred into the substation.

– The location of the arresters for cable protection must be as close as possible to the cable terminal in order to achieve the maximum degree of protection.

Selection Criteria

Cable connected to a line

Phase-to-phase operating voltage	Un	**132**	kV rms		
Phase-to-earth operating voltage	Uo	**107.8**	kV peak		
Cable inductance		**0.411**	mH/km	2.2605	mH
Cable capacitance		**0.000246**	uF/km	0.001353	μF
Cable length		**5.5**	km		
Cable BIL		**650**	kV		
Cable BSL			kV		
Incoming line length		**1.2**	km	4	Transmission time l/c μs
Surge Impedances					
Line	Zl	**400**	ohm		
Cable	Zc	1292.57	ohm	3.23	Ratio Zc/Zl
		LIPL		SIPL	
Incident voltage at coordinating current		**282**	kV	**232**	kV
Incident current		705.0	A		
Transmission co-efficient		1.53			
Reflection co-efficient		0.53			
Transmitted voltage		430.7	kV		
Reflected voltage		148.7	kV		
Transmitted current		333.2	A		
Reflected current		-371.8	A		
Speed of propagation into cable		3144.9	m/us		
Cable local end protective ratio		1.51	(should be >1.2, and preferably >1.5)		
Arrester Rated Voltage	Ur	**120**	kV rms		
Equivalent duration of lightning flash	T	**3.0E-04**	s		Typical value 3 × 10^{-4} s.
Number of incoming lines	N	1			
Overvoltage Factor	k	**2.8**			
Line charging voltage	U_L	**336**	kV		
Required Arrester Charge Absorption Capacity for lighting acc. IEC 60099-5 cl 6.3.2.4					
Q = [2xUf-NxUresx(1+ln(2xUf/Ures))x(UresxT/z)		1.2E-04	C	W = QxUres/Ur	2.9E-04 kJ/kV Ur
Required Arrester Charge Absorption Capacity for cable switching acc. IEC 60099-5 cl 6.3.2.5 (Wth = 2x Ws)					
Q = ((UL-Ures)/z)x2xl/c		2.1E-03	C	Wth = 2xQxUres/Ur	8.0E-03 kJ/kV Ur

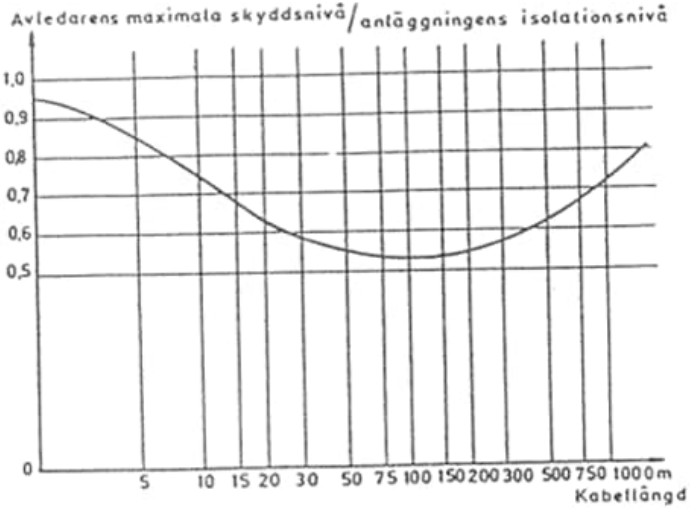


Fig 11. Högsta tillåtna skyddsnivå för avledare som enbart placeras vid kabelns övergång till friledning. Förhållandet mellan friledningens och kabelns vågimpedans har antagits till 5 och våghastigheten på kabeln till 150 m/μs. Högre vågimpedansförhållande ger en något högre tillåten skyddsnivå. Längdskalan är proportionell mot våghastigheten.

Cable sheaths
Sheath Voltage Limiters (SVL)

- 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.

- The open ends as well as the cross bonding points should be protected against slow- and fast-front overvoltages by suitable surge arresters.

- Uc for cable sheath arresters can be calculated from

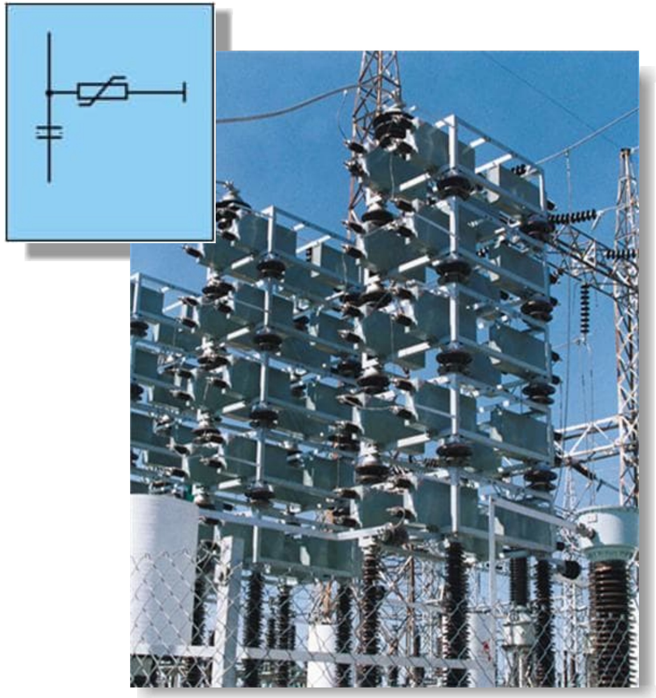
$$U_c \geq \frac{U_i \times I_k \times L_k}{T_c}$$

where

- Uc is the continuous operating voltage of the surge arrester in kV
- Ik is the max. short circuit current of the cable (single phase) in kA
- Lk is the length of the unearthed cable section in km
- Ui is the voltage induced in the per unit length of cable sheath in kV/(kA × km)
- Tc is the TOV factor of the MO-surge arrester (e.g. for t = 3 s in distribution systems
- Tc = UTOV / Uc

- Ui reaches in maximum 0.3 kV per kA of fault current and km of cable length.
- 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.

Protection of shunt capacitor and filter banks



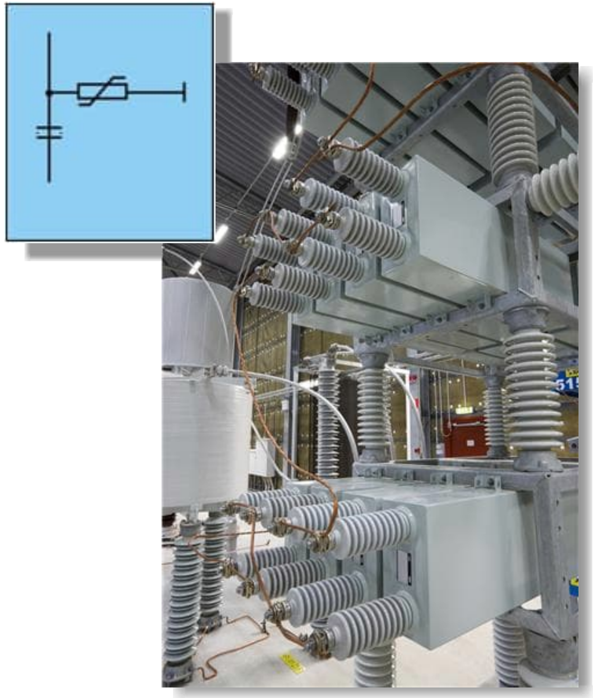
Shunt Capacitor banks and Harmonic Filter banks are used to an increasing extent at all voltage levels

- growing need for power transfer
- avoiding transfer of reactive power
- better use of existing power systems
- improved voltage stability
- voltage control and compensation of reactive loads
- improved power quality

Thyristor-controlled as well as breaker-switched capacitors are used

- Detailed studies justified for thyristor-controlled capacitors due to the large cost savings possible
- General guidelines deal only with the protection of breaker-switched equipment
- Resonance conditions assumed to be limited by system design and operating procedures

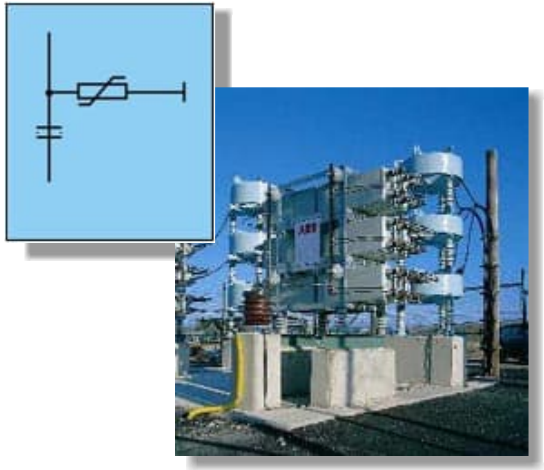
Protection of shunt capacitor and filter banks



- Prevent capacitor failures at breaker restrike or failure
- Limit the risk of repeated breaker restrikes
- Prolong the service life of the capacitors by limiting high overvoltages
- Serve as an "insurance" against unforeseen resonance conditions which otherwise would lead to capacitor failures
- Overall limitation of transients related to capacitor bank switching which can be transferred further in the system and cause disturbances in sensitive equipment
- Optimize BIL of components
- Serve as protection against lightning for capacitor banks connected to lines

Many capacitor banks are operated without surge arresters, however there are definite benefits and advantages to installing arresters.

Protection of shunt capacitor and filter banks



Placement and connection configuration may depend on transient to be protected against and if adequate protective margin can be achieved.

Existing upstream arresters may additionally assist to protect against direct lightning strikes.

Special design and selection considerations

COV

- Maximum permissible operating voltage allowed under normal conditions is usually 5% to 10% above the nominal voltage level
- In case of harmonics, arrester continuous operating voltage (Uc) to be $\geq$ peak voltage across the arrester divided by $\sqrt{2}$
- Series reactor effects

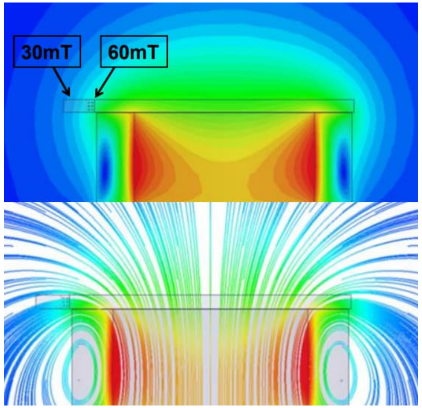
Rated voltage

- Arrester rated voltage (Ur) is selected based on temporary overvoltages, TOV
- Dependant on earthing & connection configuration

Protection levels

- Expected arrester currents related to capacitor transients are high, so nominal protection levels for the arrester are typically taken at 3kA switching surge (if nothing else specified)

Effect of series reactor



Special design and selection considerations

- Many capacitor banks are supplied with series air-core reactors to either limit the current when switching-in with parallel banks connected or for nearby external faults or to form a filter with the capacitors
- If the primary aim is to protect the capacitors, arresters positioned in front of the reactors will not protect the capacitors
  - The voltage may be twice as high at the capacitors than at the arresters
  - A separate set of arresters may be warranted to protect the reactors
- For dimensioning, especially Uc of the arresters, it must be taken into account that the voltage phase-ground will be higher at the capacitor than at the reactor
- When placing the arrester, details of the “magnetic flux map” around an air-core reactor determines the necessary magnetic clearance
  - Permitted magnetic flux density (B) at the arrester < 0.2 mT; depending on actual applied COV.
  - Effect of higher values is risk for additional heating, which in turn reduces the arrester's energy and TOV withstand capacity.
  - Even if the value is high at the reactor itself, the magnetic field strength tends to drop rapidly with distance.

Protection of shunt capacitor and filter banks

Special design and selection considerations

Energy capability

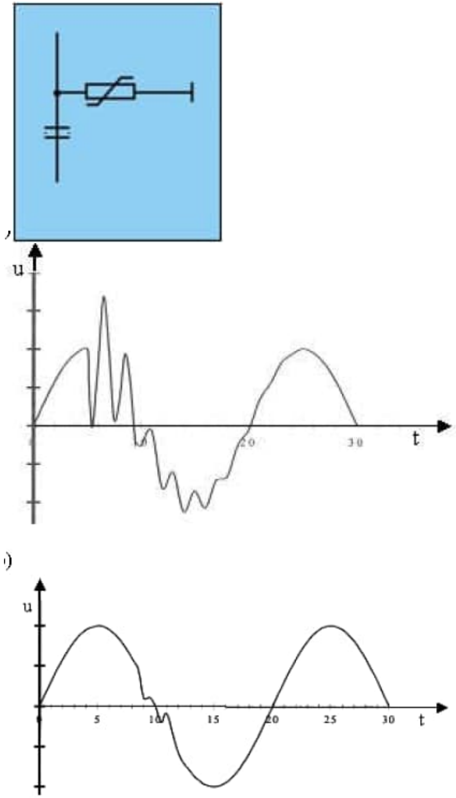
- Caution is recommended when selecting an arrester type to meet energy requirements
- Switching surges of different origins can occur but, in general, it is the restrike cases that result in the highest arrester duties
- Usually the duration of arrester discharge currents resulting from capacitor transients is much shorter and the currents higher than obtained in the long-duration current withstand test as per IEC
  - A derating of energy capability may be necessary if given rated energy is based on existing IEC standard tests or even much longer current impulses
  - “Single-impulse” energy capability for Hitachi Energy types 4ms duration equivalent energy from Qrs test or Lightning Impulse Discharge Capability Test consisting of 18 impulses with a duration of 200µs
  - 80% of single impulse energy for capacitor discharge ?

Arrester energy based on a breaker restrike and transient overvoltage with:
- full voltage of opposite polarity on the capacitor due to a previous break
- sequence of a three-phase break of capacitive load followed by multiple restrikes in two phases

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

The energy capability of MO resistors is somewhat dependent on the discharge current amplitude i.e. for shorter durations of an impulse, the energy capability is less.

Circuit breaker restrike

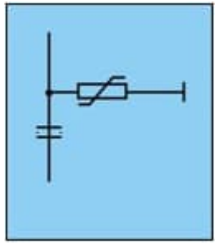


- Interruption of capacitive currents is generally an easy duty for a circuit breaker as currents are normally small
  - There is, however, a risk that restrikes will occur, which may lead to undesirable overvoltages in the network
  - Energizing of capacitive loads may also lead to overvoltages or high currents
- To reduce the risk of restrike, the lowest possible voltage should be across the breaker
  - Preference is to not generate switching overvoltages on the capacitor bank to begin with

Solution 1 (recommended)

- ”Low probability restrike” breaker rated C2
- POW sychronous switching with adaptive control

Circuit breaker restrike



Solution 2

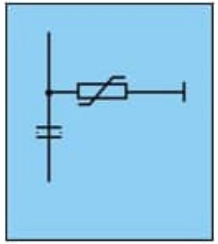
- Arresters over CB poles

Issues

- Risk for long term outage in case of arrester overload
- Troublesome physical installation
- Difficult to select sufficiently low Ur for arrester

- In practical terms, not an ideal solution to mount an arrester over the CB pole

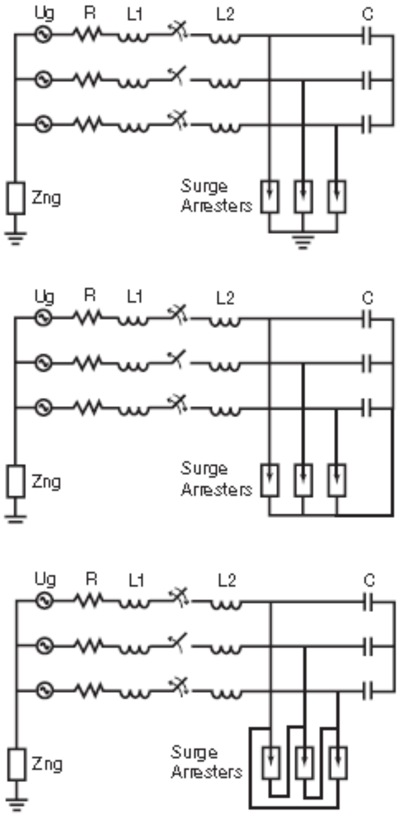
Circuit breaker restrike



Solution 3

- Limit the voltages over the capacitors as much as possible with the aid of arresters
  - Phase - Phase (most effective for restrike)
  - Phase - Neutral
  - Phase - Ground

Decisive case is a two-phase restrike with full charge on capacitors due to a previous break



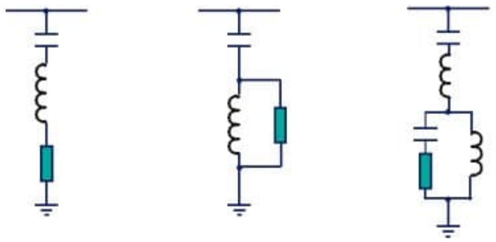
- Most practical is with arresters connected Phase – Ground

- Even with POW switching and a ”low probability re-strike” breaker, arresters function as a back-up protection
  - Restrike is a statistical function , so the more switching the greater the risk for any breaker
  - Adaptive POW switching may miss on occassion

Best ”compromise solution” to also protect against external events is therefore arresters connected Phase-Ground.

Protection of other elements

Resistor, Reactor, etc



For an arrester protecting a series reactor in the bank or filter,

- 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.
- In the event of a capacitor discharge into an earth fault, the energy absorbed by the arrester may be very large.

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

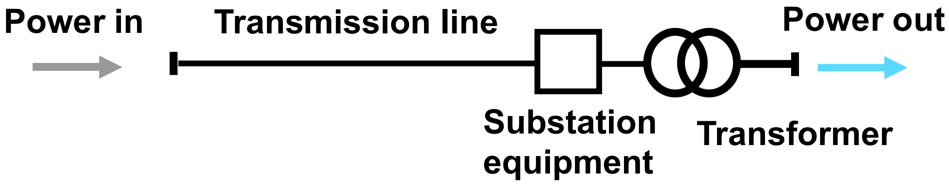
C is the single-phase capacitance of the bank;
Usw is the slow front protection level phase-to-earth at the capacitor bank

- Resistor/reactor in a filter circuit may not be fully insulated for system events and should be protected by an arrester
- Arrester in parallel may essentialy be short-circuited by the lower-impedance element in normal service
  - Arithmetrical sum of the rms voltage over the element will define the minimum Uc for the arrester
  - TOV can be defining of arrester Ur as usual
  - In case of a capacitor discharge into an earthfault, a high energy capability for the arrester is advantageous
- Arrester Ur is often chosen based on the BIL group by system voltage and then catalog value max Ur within the voltage class
  - Protective margin 120 – 150 % usually adequate

Line Protection

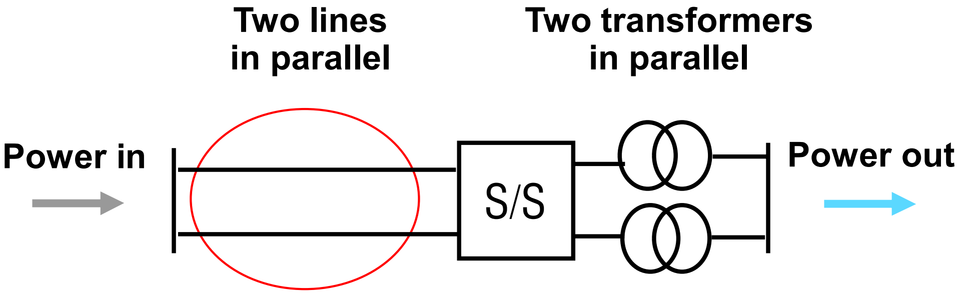
Acceptable outage rate is a moving target

Single circuit



- Typically poor overall availability
- Substation equipment is not the critical factor during normal operation
- Line and transformer are dominating causes for unavailability

Double circuit



- Lightning is a significant contributing factor to the outage rate
- Line availability remains critical with common towers
- Double line failures must be avoided

Line Surge Arresters

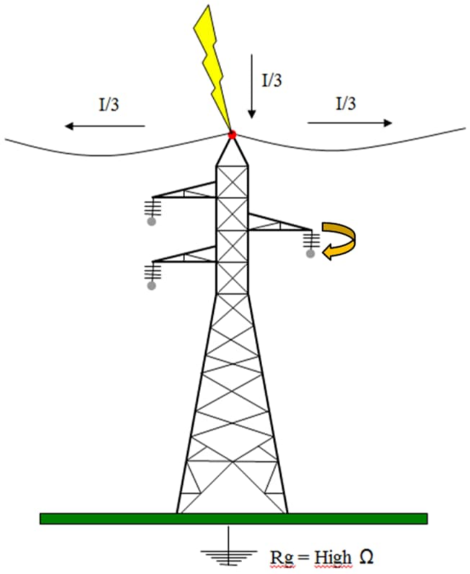
A future necessity to help keep the lights on?

- Sensitive processes are all the more dependent on constant and reliable energy supply
- Momentary loss of supply may be as costly as a prolonged blackout to a process industry
- Consumers have become more conscious and demanding and are likely to be even more so into the future
- Deregulation of the electricity market allows for performance based contracts with stiff penalties for Utilities that don’t measure up

Sources of Lightning Flashovers on Transmission Lines

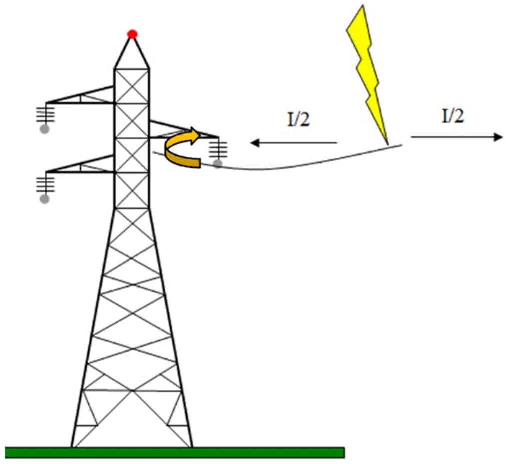
Backflashover

- High footing resistance



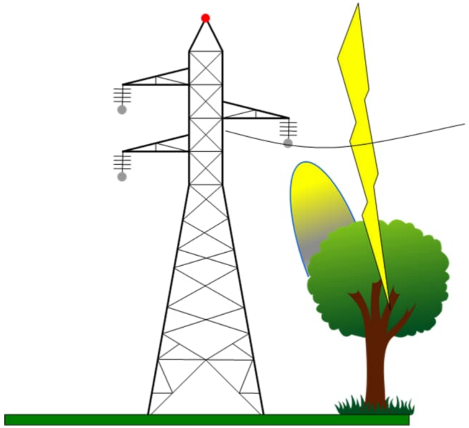
Shielding failure

- No OHSW
- Poor shielding angle



Induced flashover

- Lightning flashes to ground seldom exceed 200 kV
- Neglected on HV transmission lines due to high LIWV



Transmission Lines

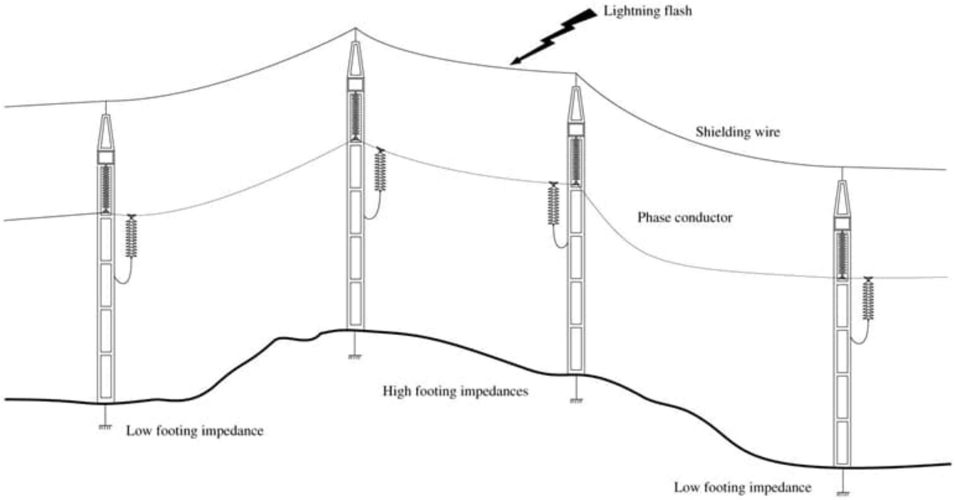
Reliability and availability improvements

Method	Comment
Duplicate system	Very expensive and often impractical. Compromise with two lines on one tower.
Increase insulation withstand	Expensive and creates insulation co-ordination problems.
Improve footing impedance	Often difficult and expensive.
Shield wires	Requires low tower footing impedance. Problems of their own. Difficult to retrofit. Unlikely to achieve demanded reliability. Do not improve switching performance.
Protect line insulation by surge arresters	Arresters connected in parallel with line insulators at selected towers = Line Surge Arresters (LSA)

Line Protection

Line Surge Arrester (LSA)

- Arresters installed on selected towers eliminates disturbances caused by overvoltages
- Prevents lightning-induced flashover across line insulators on the tower
- Assists to extend line circuit breaker life and maintenance-interval
- Gapless design preferable
- Controlled switching surge overvoltage profile along the line (possible)



Gapped vs Gapless

Cigré TB 696: MO Surge Arresters – Metal Oxide Resistors and Surge Arresters for Emerging System Conditions WG A3.25, August 2017

Externally Gapped Line Arrester (EGLA)

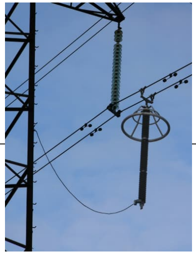
Advantages:

- Absence of permanent stress on the SVU by power frequency voltage
- The rated voltage of the surge arrester is lower than the operating voltage, which makes it possible to shorten the length of the live part
- Ageing of the housing is slower and reliability is enhanced. If the housing becomes contaminated or coated with ice, the absence of voltage stress means there is no increase of leakage current to cause degradation along the creepage length.
- No disconnector needed (disconnector is kind of complicated to design for heavy duty)
- Suitable for multi circuit towers with cross arm's clearance issues

Disadvantages:

- Difficult insulation co-ordination, requires a careful coordination of the voltage-time curve of the insulator with the one of the air gap
- Difficult to install and, if so, may reduce live working clearances after installation
- No control of switching overvoltages (no ignition of gap, only at lightning impulses)
- does not share the energy evenly in case of lightning; however, for shielded application energy sharing by the arresters may not give a significant benefit, because most part of the lightning surge will go to the ground via the tower or the overhead ground wires
- it may be technically difficult to locate an EGLA with a failed SVU; However, some utilities use SVU equipped with a fault indicator

Non-gapped Line Arrester (NGLA)



Advantages:

- easy installation, in some cases with live-line work methods
- control of slow front over-voltages
- failed NGLA can be detected by helicopter or long-range visual inspection when the disconnect link has fallen away from the arrester
- all NGLA participate in energy sharing

Disadvantages:

- the disconnector
  - and flexible lead which removes the arrester from service in case of arrester failure is often a weak point; it may fail mechanically due to vibration, galloping, conductor restraint, corrosion or other stress
  - may not operate if there is insufficient short circuit current on the line
  - may have an internal explosive device which can be an issue for transportation in some countries
- MO resistors are permanently stressed by power-frequency voltage, occasional temporary over-voltages and slow front over-voltages
- contamination may be an issue in heavy polluted areas; snow or ice accretion in cold climates

Choice EGLA or NGLA is often based on user preference or prejudice.
Added value to be had with NGLA and the long positive service experience with the robust solution from Hitachi Energy.

**) 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 the complete arrester*

LSA vs Station applications

Station-located arresters

- Protection performance vital
- Lightning energy and current limited
- Mechanical strength can be an issue

Line surge arresters (LSA)

- Protection important but not critical
- Automatic disconnection of a failed arrester necessary
- Energy and current from lightning may reach very high values depending on shielding conditions of the line and tower footing resistance
- Mechanical strength of secondary consideration, but robustness of complete solution vital
- Demands high reliability during a long service life

LSA Example

ESKOM (South Africa) 275kV Transmission lines with PEXLINK

Line name (275 kV)	Line length (km)	Units installed	Performance (Faults/100km/year	
			Before	After
Eiger-Prospect	11.25	12	13.33	2.93
Eiger-Fordsburg	19.38	12	4.44	1.70
Glockner-Olympus	26.70	9	N/A	6.97
Taunus-Princess	12.83	12	14.50	3.90
Esselen-Pelly	100.00	33	2.90	2.50
Bighorn-Pluto	65.57	72	13.42	2.44
Hera-Watershed	177.36	45	5.47	3.00

Source: Cigré 5th Southern Africa Regional Conference, October 2005

Application Example

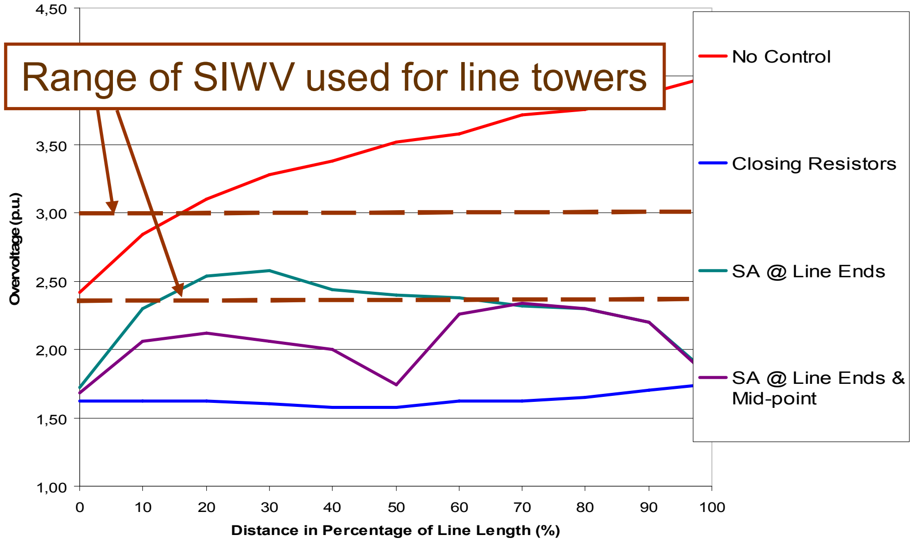
EHV and UHV line switching

- Traditional solution for limitation of switching overvoltages is to fit pre-insertion resistors on the line breakers

- Decreases the amplitude of the travelling wave induced during closing /reclosing

- Effective, but can be problematic

Modern, innovative and more robust alternative is instead to place TLA's on specific towers along the line



3-phase fast reclosing of 200 km, 550 kV non-compensated line 1-phase ground fault

Application Example

Compact insulation line

- Reduced right-of-way
  - Environmentally friendly
- Low acquisition costs
  - Overall economy
- Blend better with surrounding landscape
- Increased power transfer possible by increasing system voltage on existing lines
- Reduced outages due to lightning (lightning protection obtained without additional cost)

400kV compact test line at STRI, Sweden
PEXLIM Q LSA, SM (LDC 3)

Applicable Standards

IEEE PES Power & Energy Society® | IEEE

EGLA

IEC

IEC 60099-8

Edition 2.0 2017-11

INTERNATIONAL STANDARD

colour inside

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

NGLA

IEC

IEC 60099-4

Edition 3.0 2014-06

INTERNATIONAL STANDARD

NORME INTERNATIONALE

colour inside

Surge arresters –
Part 4: Metal-oxide surge arresters without gaps for a.c. systems

IEC TC37 / IEEE – Project 60099-11
Dual Logo Line Arresters Standard

IEC/IEEE CD PT 60099-11 IN PROGRESS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

SURGE ARRESTERS –

Part 11: Metal-oxide line surge arresters to protect power line insulation of systems above > 1kV a.c. or > 1.5kV d.c.

The target of the project is to publish a Committee Draft (CD) during 2024.

Once IEC 60099-11 is published, it will become the sole IEC/IEEE standard for LSA, making IEC 60099-8 for EGLA obsolete and supersede references to NGLA in IEC 60099-4.

No IEEE standard is currently published that considers LSA specifics

Agenda

Overvoltage Surge Protection

- Theory
- Selection basics
- Applications
- **Maintenance and Monitoring**

Surge arrester maintenance and monitoring

A properly chosen
and installed arrester
is to be regarded
as practically
maintenance-free
during its lifetime.

But ....

Inspection and cleaning

- Cleaning of the insulator is not normally necessary.
  - Porcelain insulators: Under conditions of heavy marine or industrial pollution, where thick layers of pollutants are built up, periodical cleaning may be advantageous.
  - Silicone insulators: The surface may appear to be dirty, but this is typically of no significance to pollution performance.

- In especially harsh environments, e.g C5 and CX defined according to ISO 12944-2
  - Regular inspection of the condition of the arresters may be warranted, including the fixing hardware, during each scheduled plant outage.
    - Depending on the nature of the pollutants, it may be advantageous to clean away heavy solid deposits, e.g. salt, by washing with low pressure clean water with low salt-content.
    - The metal fasteners shall be checked for tightness and re-tightened, as necessary.
    - At the same time, check for signs of possible deterioration of all metal parts, e.g. due to corrosion or wear, and clean or replace the effected part(s), as necessary.

- Arresters may be subjected to live washing, but observe the following in addition to normal precautions for live washing:
  - Arrester insulators usually have shorter flashover distances than other insulators for the same system voltage, which means higher risk for external flashover during washing.
  - Arresters must be spray-washed evenly in order to avoid overheating, and series-connected units especially must have all units spray-washed simultaneously.
  - Do not concentrate high pressure water at one point otherwise parts may be damaged or dislodged.

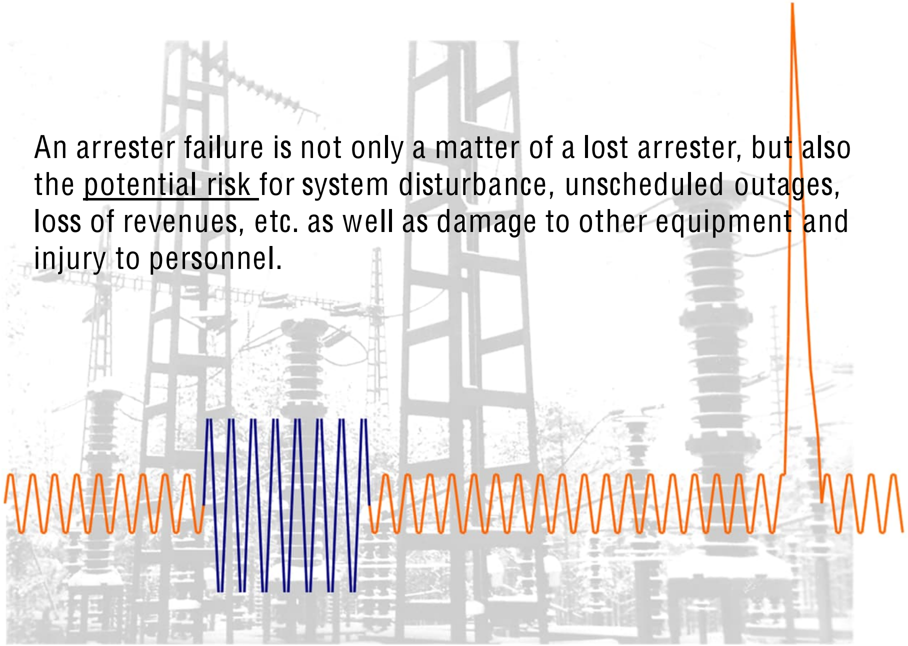
- Indications of arrester failure due to overstress
  - Soot or arc marks around the venting ducts or on the housing.
  - Indicating plates included on arrester venting ducts are blown off (ensure these are in position at installation).

Surge arrester monitoring

Are counters / indicators / monitors needed on surge arresters?

- A surge arrester is intended to protect other, more expensive, apparatus from dangerous overvoltages
- As a last resort, arresters can sacrificially overload in a safe way if design limits are exceeded
- A rare apparatus in a substation that is permitted to fail as part of its normal operating duty

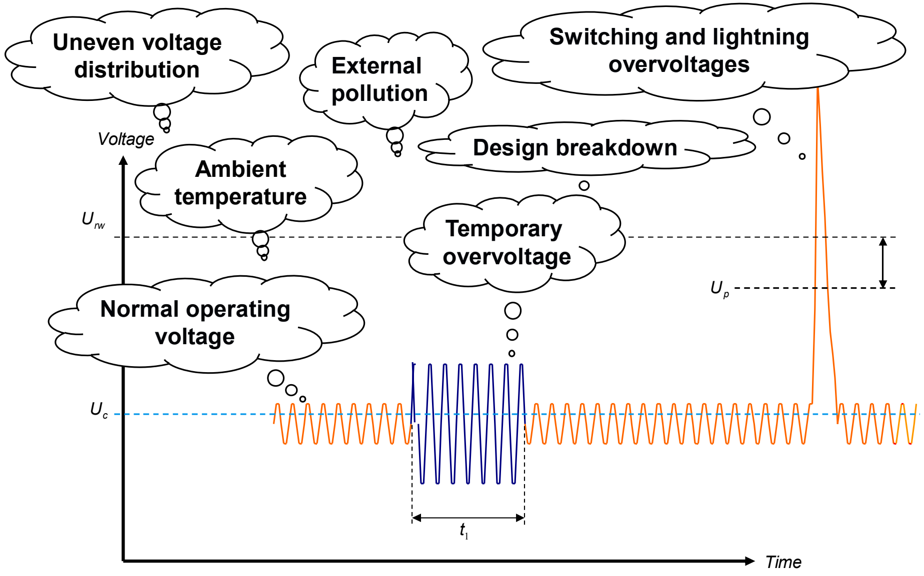
An arrester failure is not only a matter of a lost arrester, but also the potential risk for system disturbance, unscheduled outages, loss of revenues, etc. as well as damage to other equipment and injury to personnel.



Even a safe arrester overload will cause a loss of power.

Need for surge arrester monitoring

Stresses risk deterioration or overload



- Modern substation equipment are more reliable than ever, including surge arresters
  - The nature of the operating conditions under which switchgear must perform can lead to stresses applied which result in a deterioration over time, and ultimately overload and power outage
- Users of electrical apparatus have become increasingly interested to perform online monitoring, with the aim to prevent unplanned loss of power and revenue
  - No single monitoring system fits all applications, and each piece of apparatus requires appropriate consideration regarding the applicable parameters to be monitored
- Much work has been done to implement online monitoring systems for key equipment within the substation
  - Clear desire to include surge arrester activity and condition monitoring
  - Performing online measurements on surge arresters upon which meaningful evaluations can be made has historically been difficult

There are good reasons for monitoring the condition of surge arresters, but it should be meaningful

Surge arrester condition monitoring

Commonly used methods	Worth as a diagnostic on an installed arrester	Measurement taken
DC resistance (Megger)	Nothing meaningful (gapless MO resistance inherently high)	De-energized Only on site
AC hipot (10 kV)	Nothing meaningful (too low down on HVSA characteristic)	De-energized Only on site
Power losses	Too subjective (dependent on external factors; meaningless at non-significant test voltage)	De-energized Only on site
Thermo-vision	Too subjective (perhaps as comparative between phases)	Energized Generally on site
Partial discharge	Minimal (also due to external or benign causes; not always present with deterioration)	Energized or source Uc Generally on site
Surge count	Usually only tells part of the story. Potential extended analysis of impulses.	Energized On site or remotely
Total leakage current	Limited use	Energized On site or remotely
Resistive leakage current	Meaningful and reliable method *)	Energized On site or remotely

Conflicts inherent in arrester monitoring:

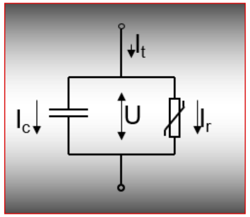
- Don’t want to take a power outage to avoid a power outage
- Make unnecessary readings on a (likely) healthy arrester
- Approach an arrester that is being evaluated due to concern that it could overload unexpectedly

*) IEC 60099-5 Method B2 – Third order harmonic analysis with compensation for harmonics in the voltage

Surge arrester condition monitoring

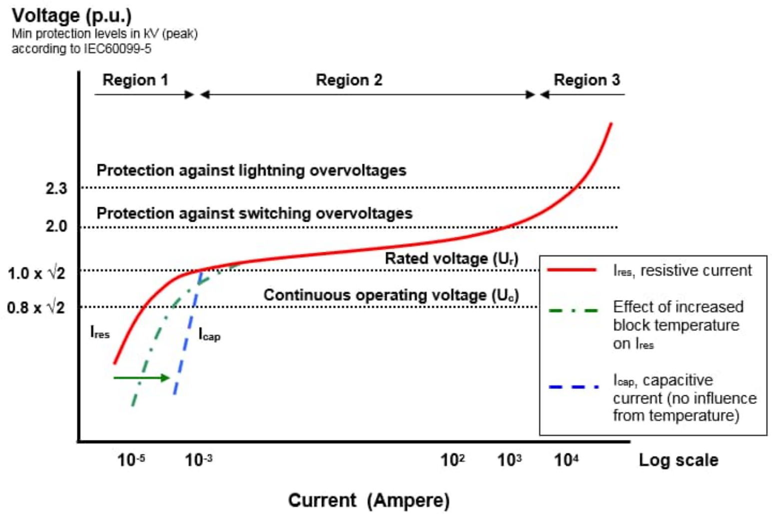
Leakage current

Leakage current measurement methods (IEC 60099-5)

Leakage current measurement method	Method No.	Sensitivity to			Diagnostic efficency		Service experience	Ref. No.
		harmonics in the voltage	phase shift in measurement of voltage or current	surface currents	information quality	handling complexity		
Separate d.c. voltage source		n.a.	n.a.	high	high	high	limited	1
Service voltage or separate a.c. voltage source								
Measurement of total leakage current		low	low	mean	low	low	extensive	
Measurement of resistive leakage current								
- using voltage reference	A1	mean	high	high	mean	high	limited	2
- using capacitor compensation	A2	mean	high	high	mean	high	limited	3
- using synthetic compensation	A3	mean	high	high	mean	low	n.i.a	4
- using capacitive current cancellation	A4	high	high	high	low	low	limited	5,6
Harmonic analysis of leakage current								
- using third harmonic	B1	high	low	low	mean	low	extensive	7
- using third harmonic with compensation	**B2**	**low**	**low**	**low**	**high**	**mean**	**extensive**	**8,9**
- using first order harmonic	B3	low	high	high	mean	high	limited	10
Measurement of power loss	C	low	high	high	mean	high	n.i.a	11

NOTE - n.a. = not applicable; n.i.a = no information available.

I_{res} is a meaningful diagnostic indicator



Surge counters and arrester condition monitors

Historical development

Passive | Combined | Online investigative | Online real time remote monitoring

Local reading only

EXCOUNT-C

Count Surges

EXCOUNT-I

Count Surges

Leakage current

EXCOUNT-II

Count Surges
(with amplitude categorization and time stamp)

Leakage current

Resistive Leakage current

EXCOUNT-IIIM

Real-time remote monitoring

Count Surges
(with amplitude categorization and time stamp)

Leakage current

Resistive Leakage current

EXCOUNT-IIIA

Real-time remote monitoring

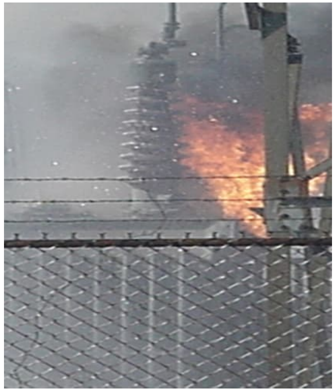
Count Surges
(with amplitude, steepness and time stamp)

Leakage current

Resistive Leakage current

Surge current impulse analysis
(enables overvoltage analysis)

The need for online monitoring



- The electrical industry faces unprecedented challenges to ensure secure and reliable delivery of power
- Many electrical networks are significantly aged, including first generation MO surge arresters
  ➔ increased risk of breakdown
  - An arrester failure is not only a matter of a lost arrester, but also the <u>potential risk</u> for system disturbance, unscheduled outages, loss of revenues, etc. as well as damage to other equipment and injury to personnel
- Proactive rather than reactive decision making is needed to plan when an outage should occur
  - Improved power grid intelligence through data gathering by online monitoring of substation apparatus has a vital role to play in reducing unplanned outages
  - Knowledge forms the basis of a maintenance, repair or replacement program for the individual equipment being monitored
  - Added benefit if the monitoring of one apparatus could also assist maintenance personnel to make informed decisions about necessary work not only on it, but also other equipment affected by it

Unplanned outages are costly and should be avoided.
The goal of an online monitoring system is to provide useful information,
with the ultimate aim to detect and determine any trend towards failure.

Remote real-time online condition monitoring

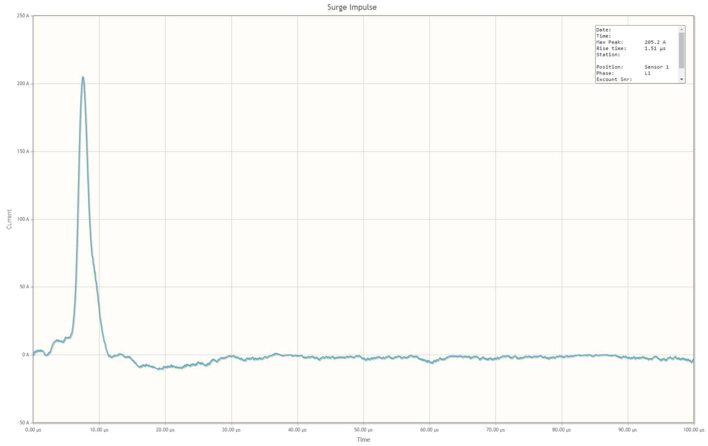
Diagnostics and analysis

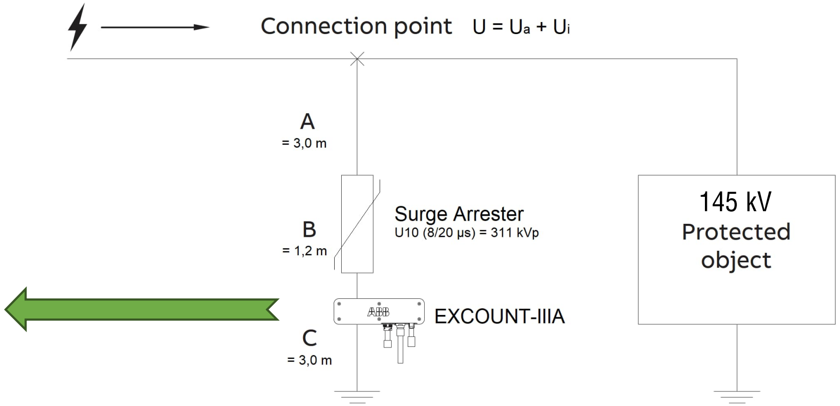
Online

Focused
Optimized
Relevant

Diagnostic	Analysis	Asset management benefit
Surge count	Many and/or high current registrations may indicate a line, bay or phase is being subjected to an unreasonably large number of overvoltages.	Empowers implementation of preventative counter measures, eg. additional arresters, improved line shielding, reduced tower footing impedance, controlled switching, etc.
Surge amplitude and wave-steepness	Overvoltage estimation for a more detailed evaluation of insulation coordination. Assist in cause-and-effect input to RCA of primary equipment failure/deterioration.	Ability to verify the station has adequate surge protection. Empowers implementation of preventative counter measures. Justifies optimization of surge arrester selection and/or placement.
Resistive leakage current	Identification of a change in arrester operating characteristic able to be detected early.	Reduced system downtime. Proactive replacement planning, instead of reactive after failure and unplanned outage.
Total leakage current measurement	High value may indicate a polluted housing and cleaning could be warranted.	Focused planning of work on "as needed" basis rather than on a schedule.

EXCOUNT-IIIA



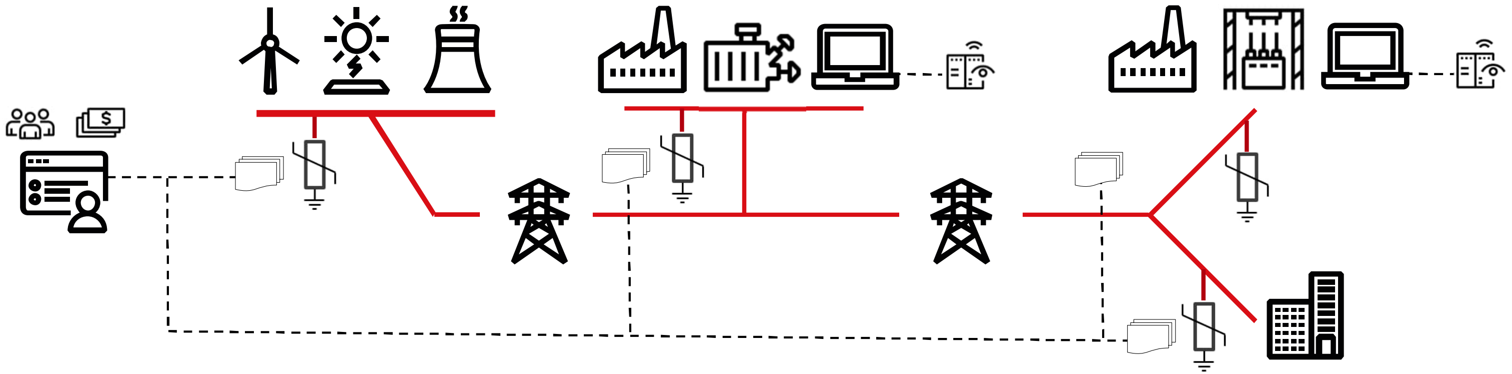


- Registration of surge amplitude and wave-steepness defined the residual voltage across the arrester (U_a) for the actual surge
- For fast-front overvoltages, inductive voltage drop (U_i) added contribution from the arrester's internal inductance and inductance in the connecting conductors; determined by L x *di/dt*
- Built-in algorithms estimated voltage (U) at the arrester's connection point to be 265 kV_p

- Better estimation of actual overvoltages than has been possible in the past
- More detailed evaluation of insulation co-ordination possible based on real surge events
- Ability to verify the station has adequate protection against potentially damaging surges or not
- Advantageous as part of root cause analysis to know what surges were applied during the equipment's lifetime (arrester and protected object)

If genuine surge activity can be identified as a concern, steps can be taken to actively mitigate e.g. review surge arrester selection, quantity and/or placement.

Modern surge arrester monitoring



- Taking all possible steps to avoid even a rare unplanned outage is considered justifiable.
- Digitization of substations aids the asset lifecycle management to improve power grid reliability.
- Systems are being pushed harder and climate change is affecting lighting activity. Arresters can expect to be stressed more as a result.
- Monitoring arresters is worthwhile and online monitoring allows deterioration to be detected sooner. Tangible benefits to perform remotely.
- Smart online arrester monitoring which can also assess the consequences of overvoltages on the primary equipment is of real value.

Remote retrieval of data eliminates the need for substation visits solely to monitor arrester condition, while also enabling the highest possible safety standard for personnel.

Conclusion and Further Reading

https://www.hitachienergy.com/products-and-solutions/surge-arresters
https://guide.arrestersonline.com/

Surge arresters which are correctly specified, designed and installed provide secure and robust primary protection for HV electrical equipment as insurance against damage from uncontrolled overvoltages.

Q & A

Welcome with your questions