MEP 1543

Chapter 4

ZnO Surge Arresters

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Part I: Tasks and Operating Principles of MO Arresters

Voltage-current Characteristics

Protective Level

Energy Absorption Capability

2 TYPES OF INSULATION

Insulation may be classified as **internal** or **external** and also as **self-restoring** and **nonself-restoring.**

Per ANSI C92.l (IEEE 13 13.1)

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- Aid to insulation coordination (Fig. 1)

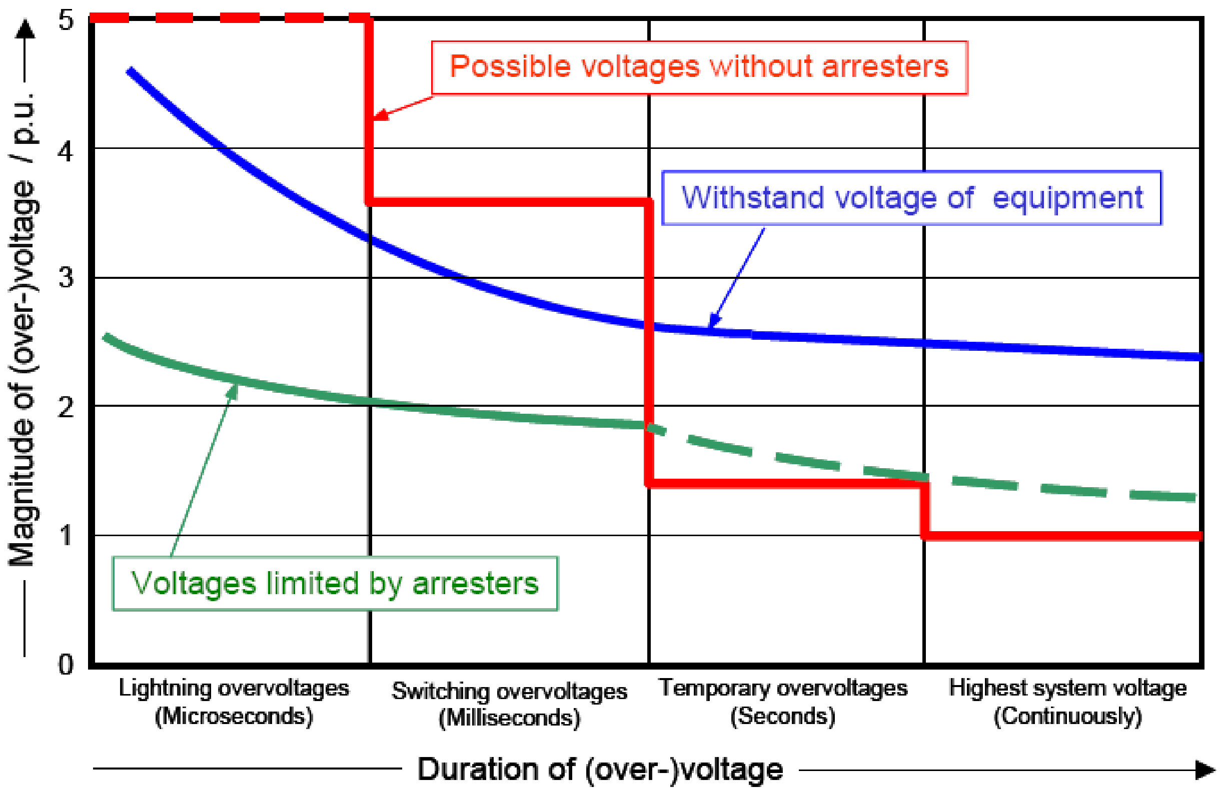


Fig. 1: Schematic representation of the magnitude of voltages and overvoltages in a high-voltage electrical power system versus duration of their appearance (1 p.u. = $\sqrt{2} \cdot U_s / \sqrt{3}$)

- Older gapped silicon-carbide (SiC) arresters still in-use
- Extremely non-linear U-I characteristic of metal-oxide (MO) resistor make gapless design possible
- An example of U-I characteristic for a 420kV system is shown in Fig. 2

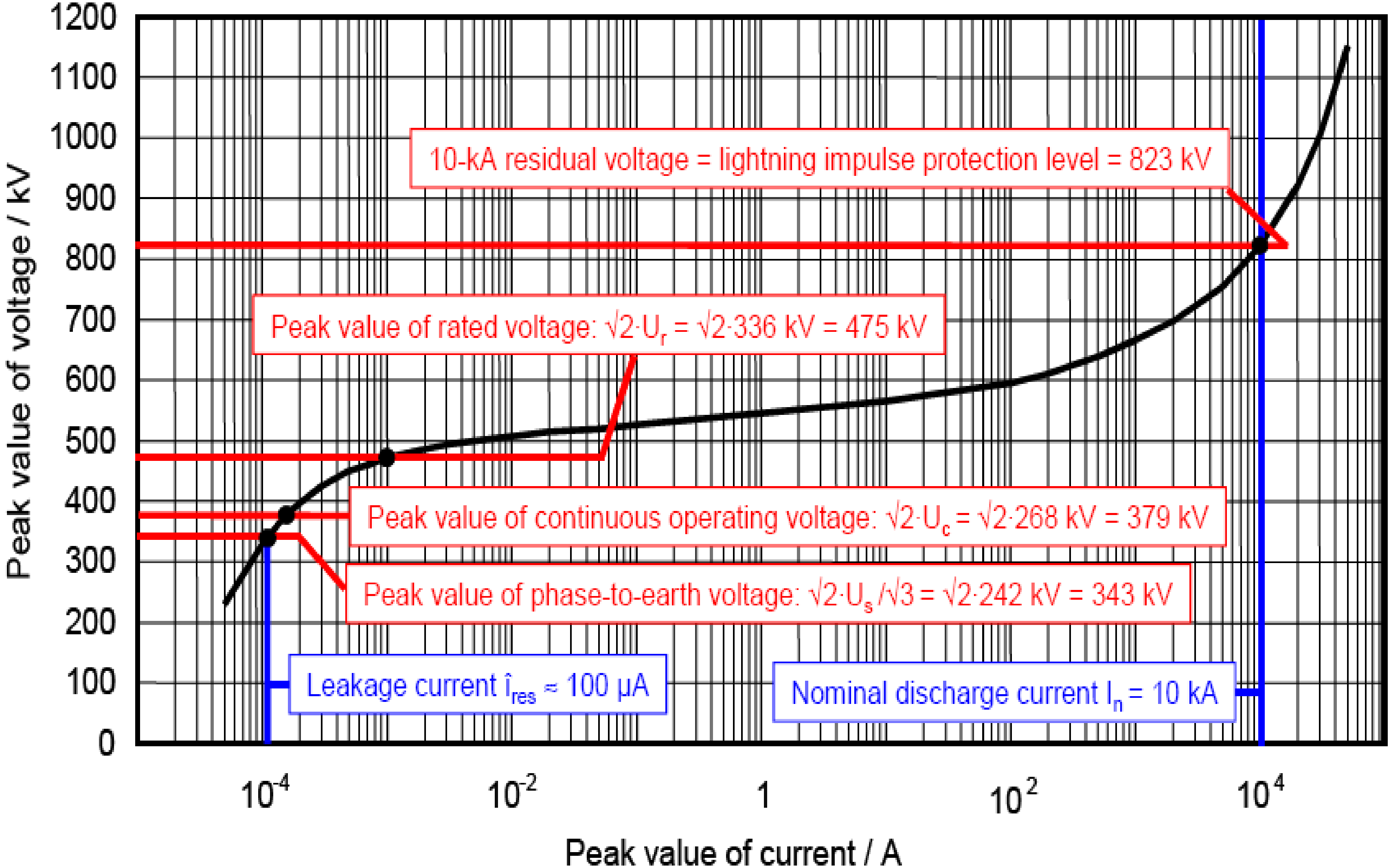


Fig. 2: U-I-characteristic of a typical MO arrester in a solidly earthed neutral 420-kV-system

Power-frequency voltage

- Leakage current is small in ZnO compared to SiC!!

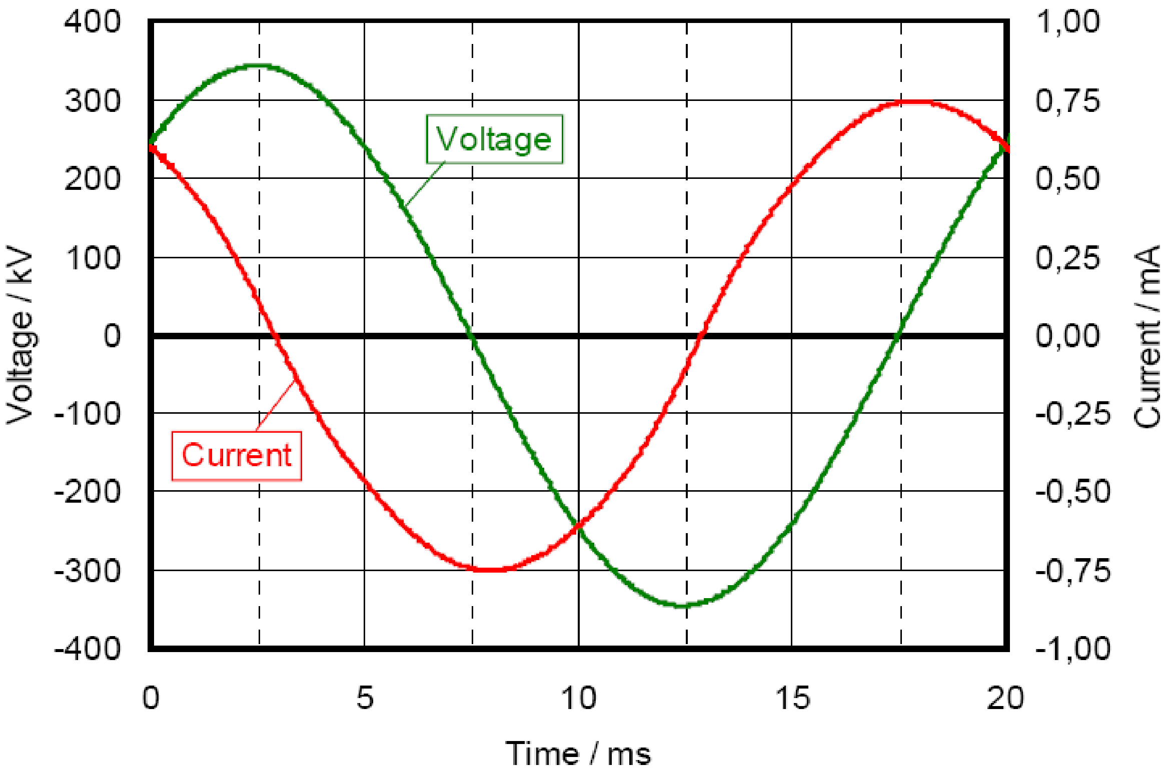


Fig. 3: Applied voltage and leakage current of the sample arrester of Fig. 2 when operated at phase-to-earth voltage (U_s = 420 kV, U_r = 336 kV)

Continuous Operating Voltage, Uc

- Also called Maximum Continuous Operating Voltage (MCOV)
- 5% above continuously occurring phase-to-earth voltage

Rated Voltage, Ur

- The name is somewhat misleading

- Voltage that can be applied temporarily without the arrester become thermally unstable
- Period of 10 seconds (or 100s for some manufacturers)
- Characterizes the capability of the arrester to deal with temporary overvoltages (not to protect against!!)

- **Ur = 1.25 . Uc**

Transient part of U-I characteristic

- Reserved for transient events (ms -switching and us - lightning)
- Applying power-frequency voltage in this area of the characteristic would destroy the arrester in a fraction of a second
- The characteristic in the region of current higher than about 100A describes the protective characteristic of the arrester
- **Lightning impulse protective level** – most important

Lightning impulse protective level

- Depicts the **voltage** which drops across the arrester terminals when the nominal discharge current flows through the arrester
- The discharge current is a lightning current impulse of a standardized shape whose amplitude is assigned to **different classes** from 1.5kA to 20kA (IEC 60099-4)
- For HV arresters (U_s >123kV), only classes in currents of 10kA and 20kA are common.

Voltage class	Voltage range
Low voltage (LV)	$V \leq 1$ kV
Medium high voltage (MHV)	1kV < V ≤70kV
High Voltage (HV)	110kV ≤ V ≤ 230 kV
Extra high voltage (EHV)	275 kV ≤ V ≤ 800 kV
Ultra high voltage (UHV)	1000 kV ≤ V

Lightning impulse protective level

- 'lightning impulse protective level = 823 kV' in Fig. 2 means: a voltage at a maximum of 823 kV drops across the terminals when impressing a lightning current impulse of 8/20us shape and a peak value of 10kA.
- Fig. 4 shows the oscillograms

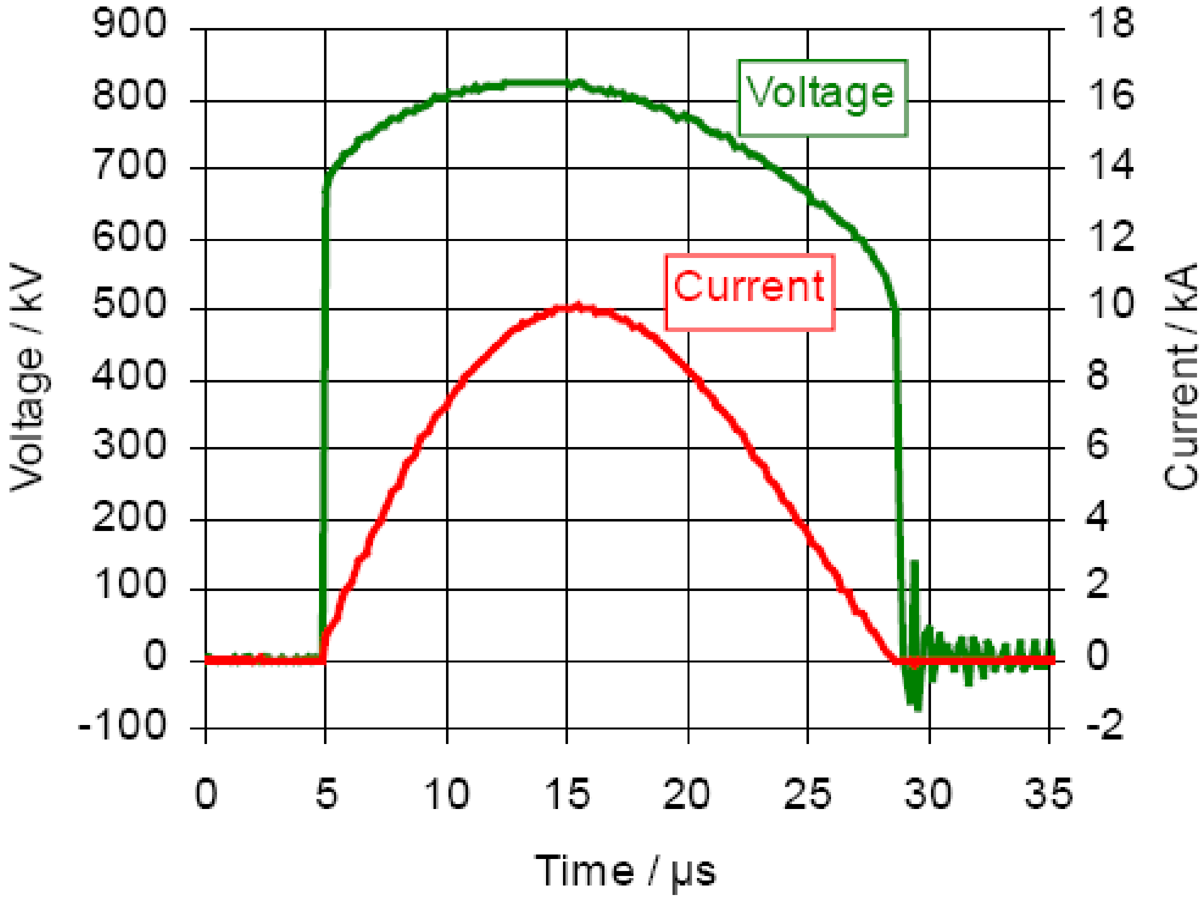


Fig. 4: Residual voltage of the sample arrester of Fig. 2 (U_r = 336 kV) at nominal discharge current (I_n = 10 kA)

Lightning impulse protective level - Example

- Normal operation:
  phase-to-earth voltage = 343 kV peak
  Current (resistive) = 100 uA peak
- During a discharge:
  V_{pr} = 823 kV peak
  Current = 10 kA peak
- Factor of increments:
  Voltage: 823/343 = 2.4
  Current: 8 decades
- Hence extreme non-linearity of voltage-current characteristic !!!

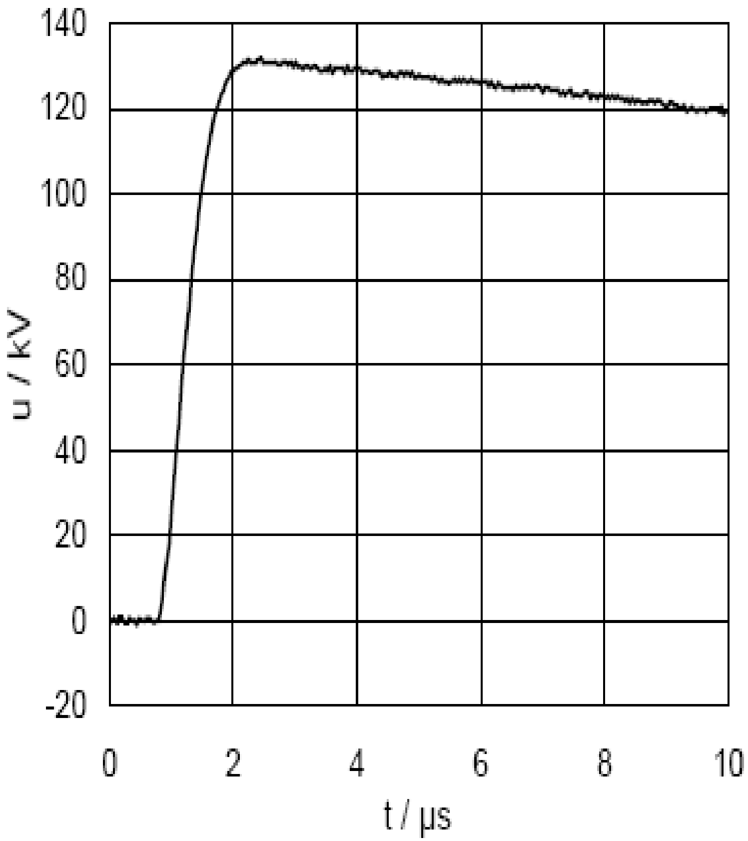
Lightning impulse protective level

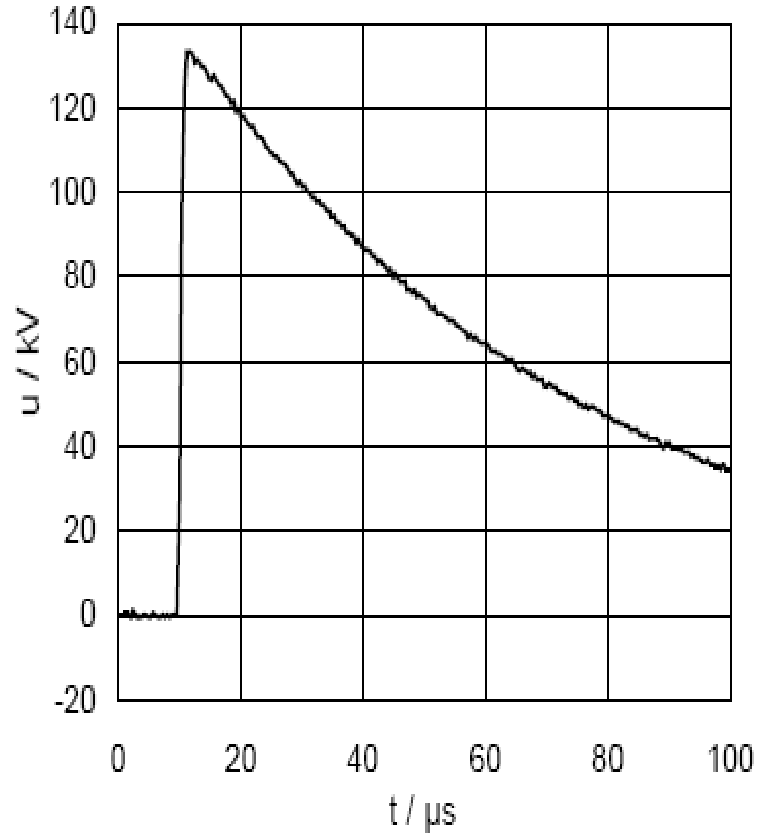
- For 420kV system, standard lightning impulse withstand voltage is 1425 kV (see Fig. on next slide)
- IEC 60071-2 (Insulation Coordination) specifies a 15% margin for non-self-restoring insulation
  1425/1.15 -> 1239kV is the highest occurring voltage allowed
- Arrester terminal voltage = 823kV (about 34% lower)
- Is this enough protection? What about equipment terminals?

Table 3 – Standard insulation levels for range II (U_m > 245 kV)

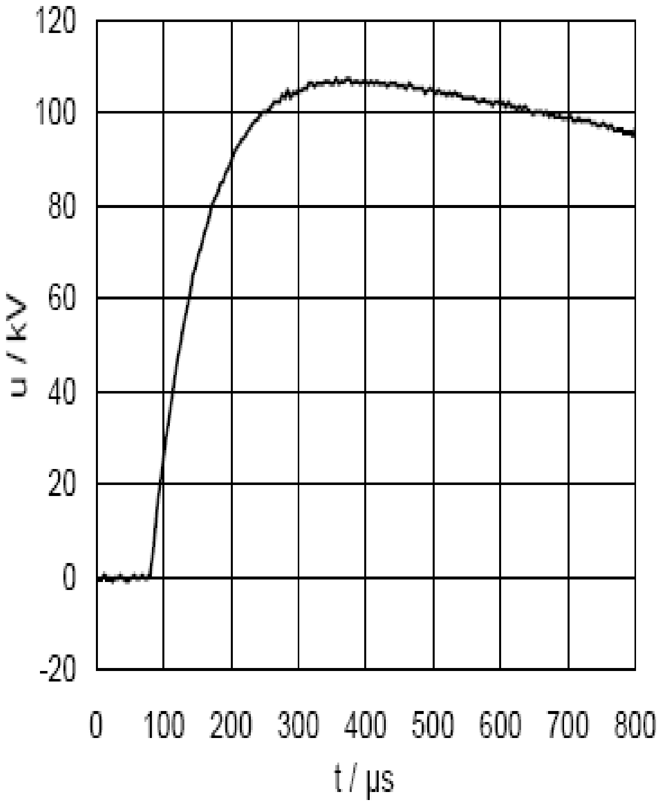
Highest voltage for equipment (U_m) kV (r.m.s. value)	Standard rated switching impulse withstand voltage			Standard rated lightning impulse withstand voltage [b] kV (peak value)
	Longitudinal insulation [a] kV (peak value)	Phase-to-earth kV (peak value)	Phase-to-phase (ratio to the phase-to-earth peak value)	
300 [c]	750	750	1,50	850
				950
	750	850	1,50	950
				1050
362	850	850	1,50	950
				1050
	850	950	1,50	1050
				1175
420	850	850	1,60	1050
				1175
	950	950	1.50	1175
				1300
	950	1050	1,50	1300
				1425

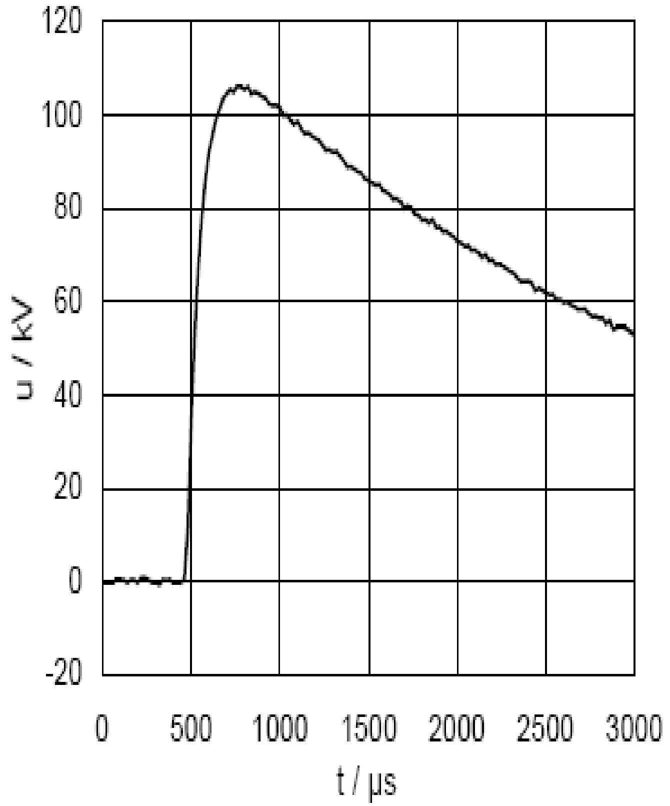
Standard lightning impulse (voltage)





Standard switching impulse (voltage)





Tasks and Operating Principles of Metal-Oxide Arresters

Lightning impulse protective level

Three significant causes/considerations:

1. Travelling wave process:
   A connected transformer appears similar to an unterminated end

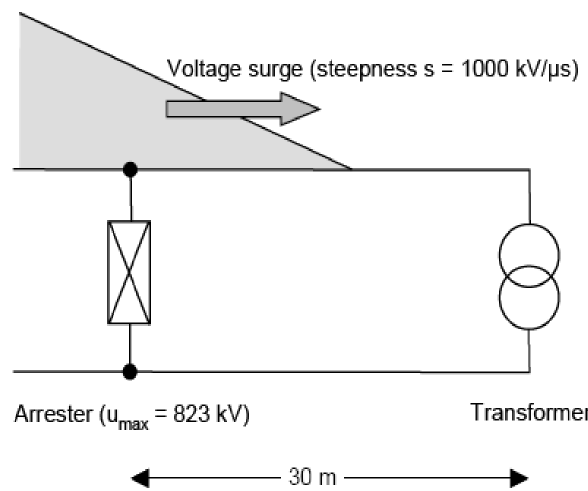


Fig. 5: Simplified arrangement to illustrate the protective zone of an arrester (explanation see text)

Notes:

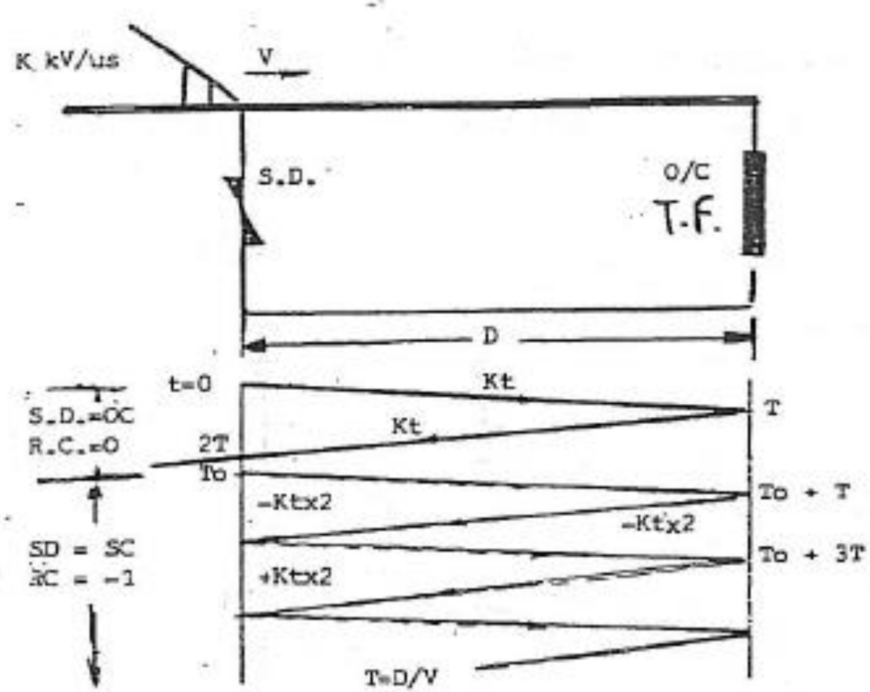
Station arresters normally are designed to divert to the ground only a **fraction** of the charge which is introduced to the overhead line conductor as a result of a direct lightning stroke (due to insulator flashovers).

The greatest part of the charge is thus diverted through the **flashover channels** towards the ground. **Only overvoltages limited to the <u>insulator flashover voltage</u>** with appropriately reduced charge content will finally reach the stations (switchyards, transformer substation), and **only these must further be limited by the arresters in the station and their contained charge further diverted to the ground**.

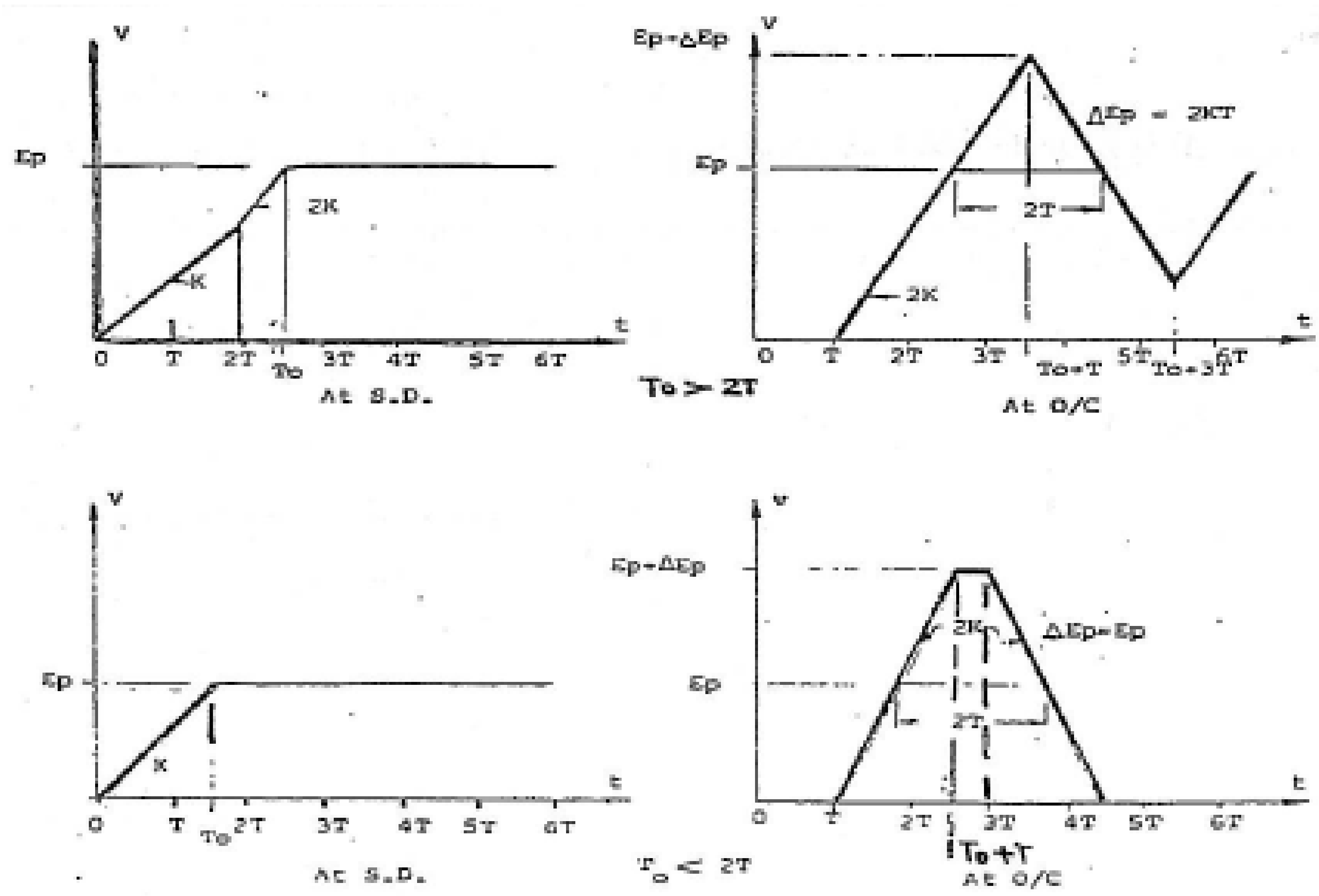
The damage due to nearby direct lightning stroke is <u>**less**</u> in <u>station-arresters</u> compared to <u>distribution</u> arresters due to <u>**extra line shielding**</u> near stations.

The effect of surge arrester location- Further Notes

- **Travelling wave effects cause voltages remote from surge arrester to exceed its protective level Ep.**
- **<u>Case 1:</u>** transformer connected at end of line d m from the arrester

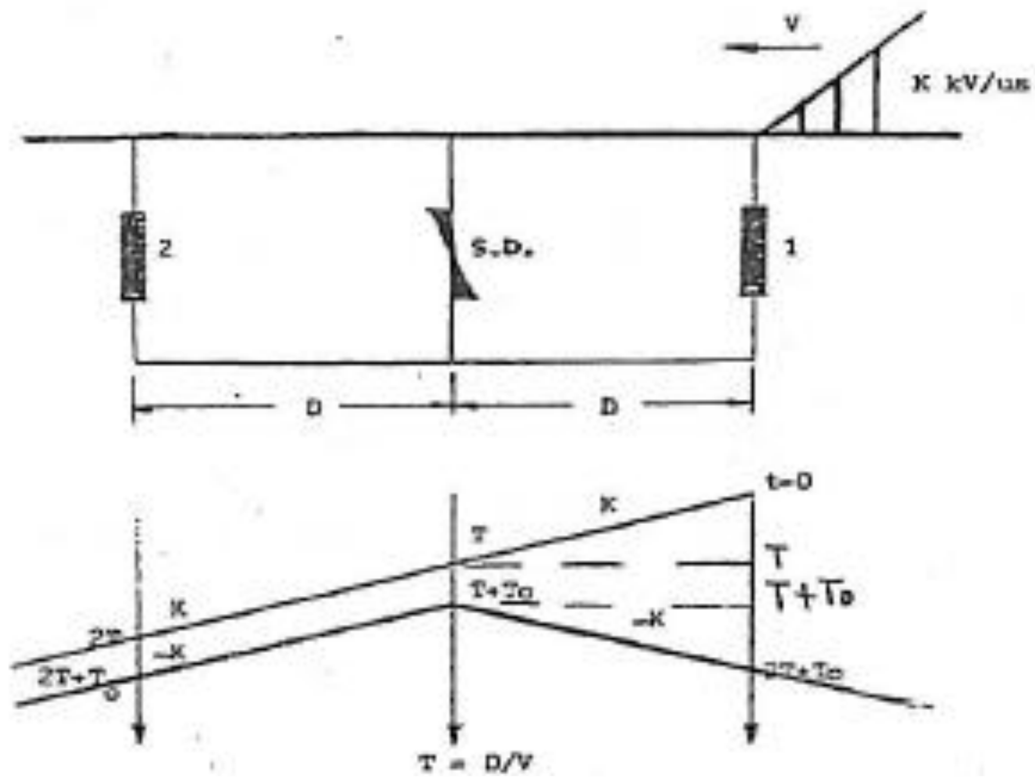


The effect of surge arrester location



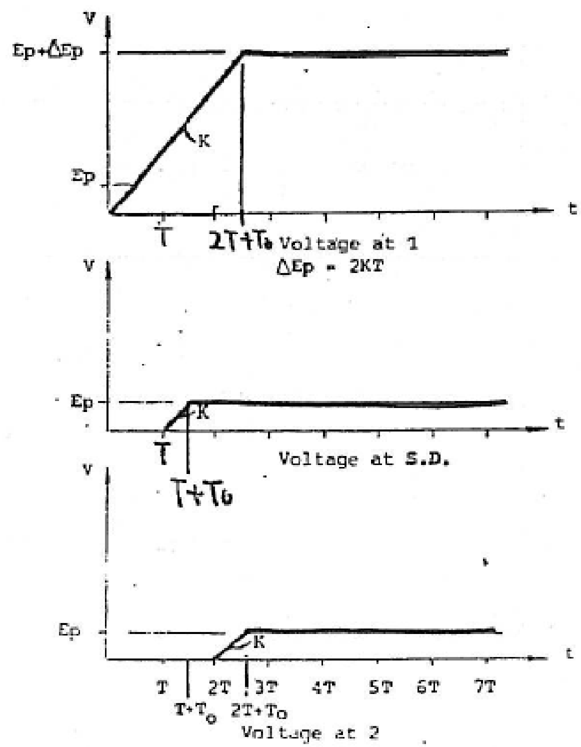
The effect of surge arrester location- Further Notes

- **Case 2:** surge arrester connected at centre of long line with apparatus connected to the line at a distance d m on either side



The effect of surge arrester location- Further Notes

- Maximum voltage occurs UP LINE of arrester and $= E_p + 2KT$



2. Inductive voltage drops:

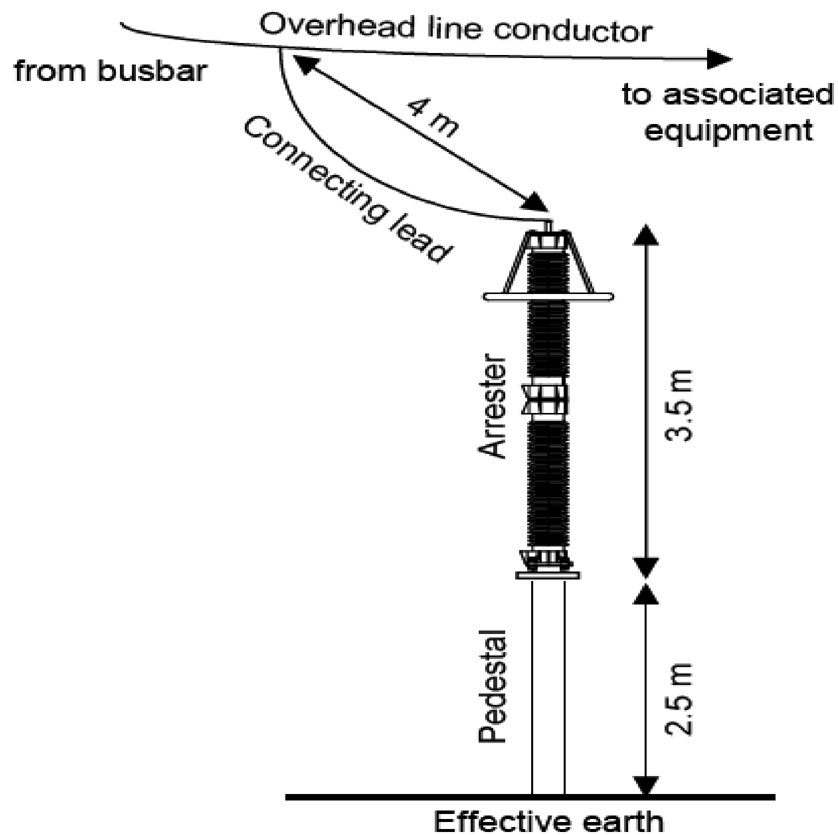


Fig. 6: Typical arrangement of an arrester in a 420-kV substation

3. Discharge currents higher than the arrester nominal discharge current:

->higher protective level

- Thus, when choosing an arrester **protective level**, certain details must be considered, such as the distance between the arrester and the device to be protected, the particular substation configuration or the typical overvoltage stress in the system.
- Normally **a factor of at least** 1.4 (between device's BIL and V_{pr}) is used to cater for fast-front overvoltages (so 1425/1.4 = 1018kV cf. 823 kV).

Apart from stable continuous operation and low protective levels, the arrester must also possess the necessary **energy absorption capability** (2 different aspects- fast and slow):

1. **Single** impulse energy absorption capability

The maximum energy which is injected within only a few micro- or milli-seconds that cause extreme, sudden temperature rises associated with excessive tensile and compressive forces acting on the MO resistor ceramic, above which, damage occurs (due to thermo-mechanically overstressed).

Damaged MO Resistor

2. **Thermal** energy absorption capability

The maximum level of energy injected into the arrester, at which it can still cool back down to its normal operating temperature.

Fig. 7 illustrates this problem.

Actual **thermal stability limit** depends on the overall design (typically 170^{o}C -200^{o}C)

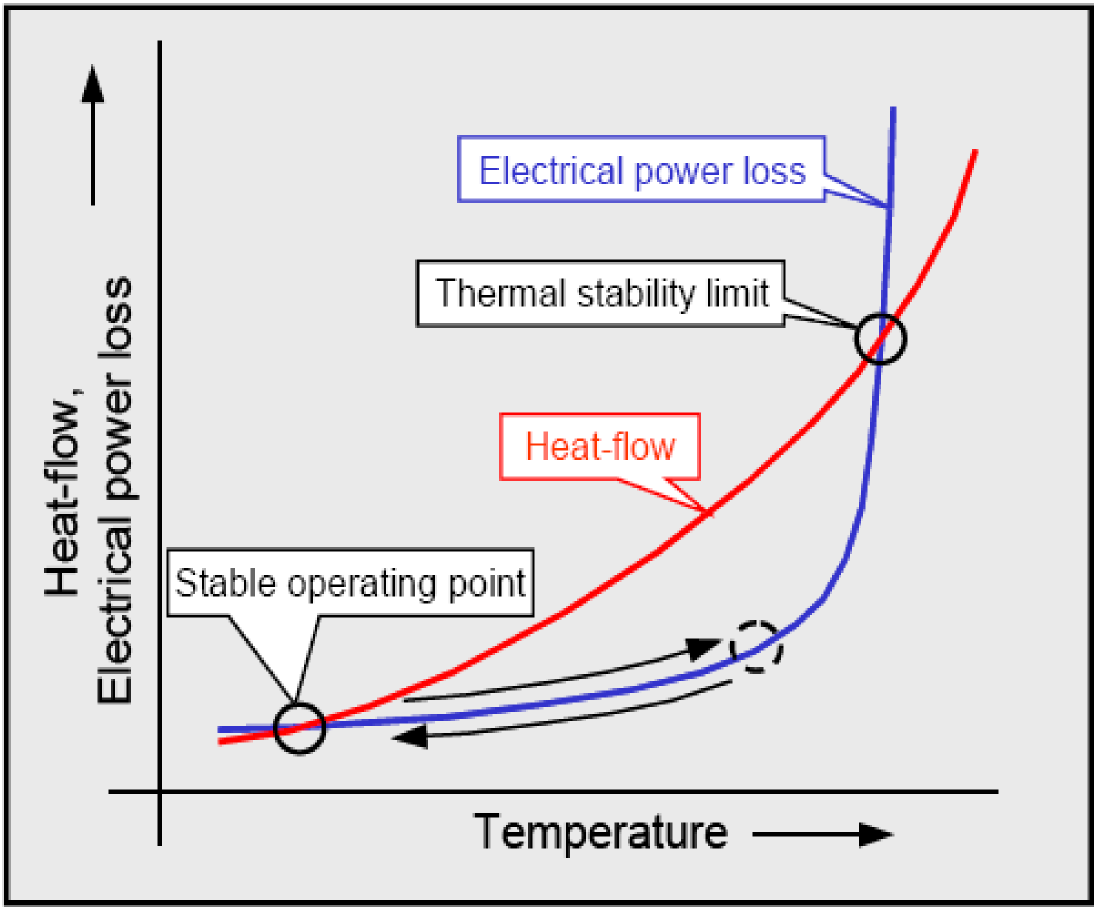


Fig. 7: Explanation of the thermal stability

Both definitions (1 and 2 above) not specified in standards.

IEC 60099-4 describe the energy by means of the **line discharge class** (see later).

Part II: Constructive Design of MO Arresters

Construction
MO Resistors
Porcelain Housed
Polymeric Housed
MV and HV Arresters

Constructive Design of MO Arrester

- Design made simple by the existence of MO compared to mandatory gap for SiC arresters.
- **Polymeric** housings were made possible by MO
- Many parts of gapped arresters can be done by MO single effective active element
- Fig. 8 shows a cross section of an MO arrester with porcelain housing destined for HV system

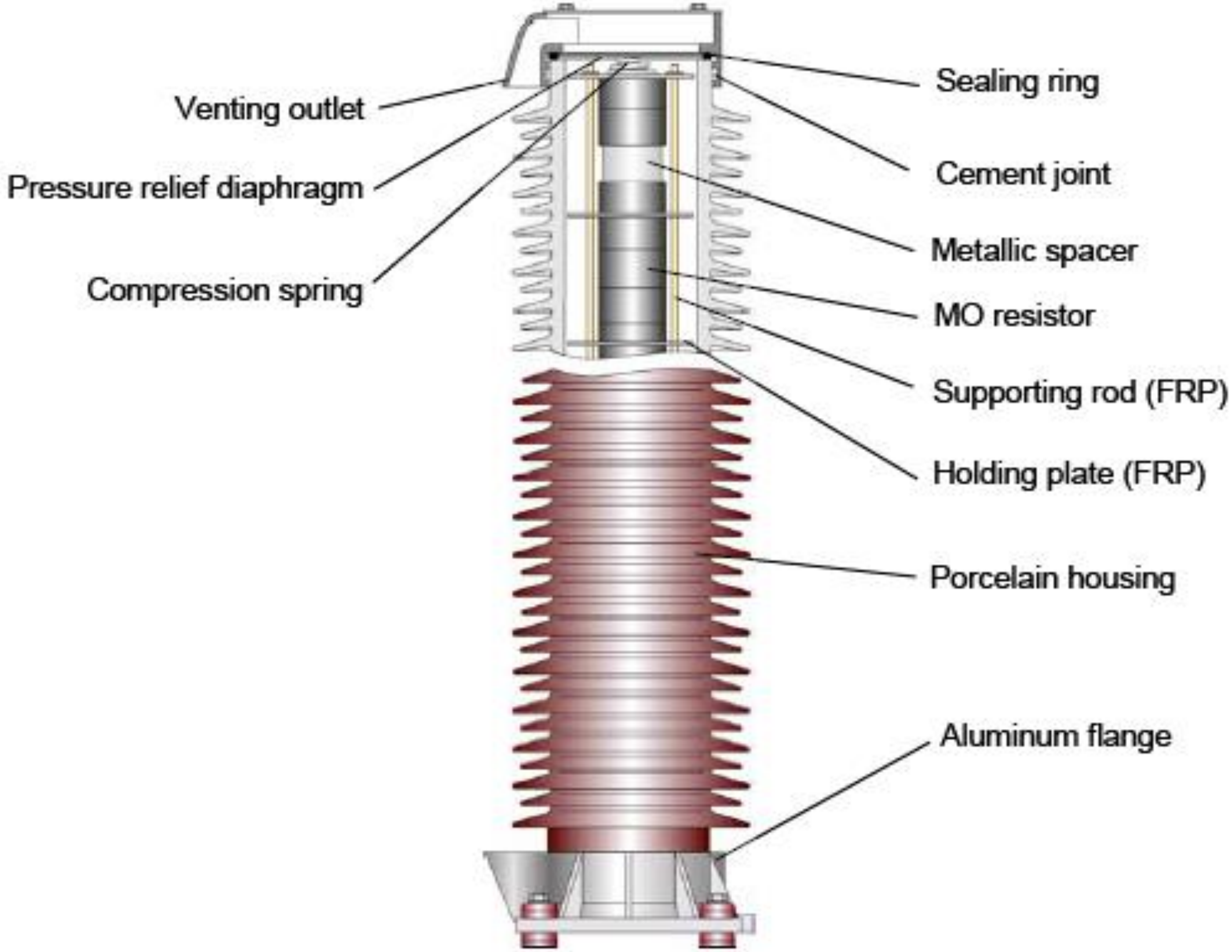


Fig. 8: Cross-sectional drawing of the unit of a porcelain housed MO arrester

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MO Resistors

- MO resistors are almost always produced in a cylindrical form.

Fig. 9: Metal-oxide resistors

MO Resistors

- The **diameter** decisively determines the energy absorption and the current carrying capability.
- It is within the range of 30mm when used for distribution systems, and up to 100mm or more for high- and extra-high voltage systems and special applications.
- For especially high demand, active parts are also realized in multi-column technique.
- Between 20mm and 45 mm height (manufacturing limitation).

MO Resistors

- Residual voltage per mm height (for 10 kA current)
  - **From 450 V/mm (32 mm diameter - Distribution arresters)**
  - **To 280 V/mm (70 mm diameter - EHV arresters)**
    - for 45mm-height cylinder block -> 12.6 kV
    - for 823 kV, 66 resistors would have to be stacked on top of each other
    - -> 3m height -> not possible for single-housing
    - Use 2 units in series

Metallic spacers

- Metallic spacers are used for fitting the active part
- Also as heat sink

Supporting rods

- Fiber-glass reinforced plastic (FRP) encircle the MO like a cage

Holding plates

- Holding plates (FRP) for extra support at intervals

Compression Spring

- Compression spring braces the active part in the housing

Whole supporting structure

- Demands on supporting construction: free of PD, high mechanical strength, high temperature resistance, high tracking and erosion resistance, flame retardant and self-extinguishing in case of fire

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Housing

- Housing – **porcelain** (IEC 60672-3) as well as polymer
- Ends of the porcelain housing are equipped with aluminum flanges which are applied with the help of cement
- Adequate creepage distance should be provided
- Shed profile design(distances, overhang, angle of inclination) (IEC 60815)
  - Alternating and normal profile (Fig. 10)

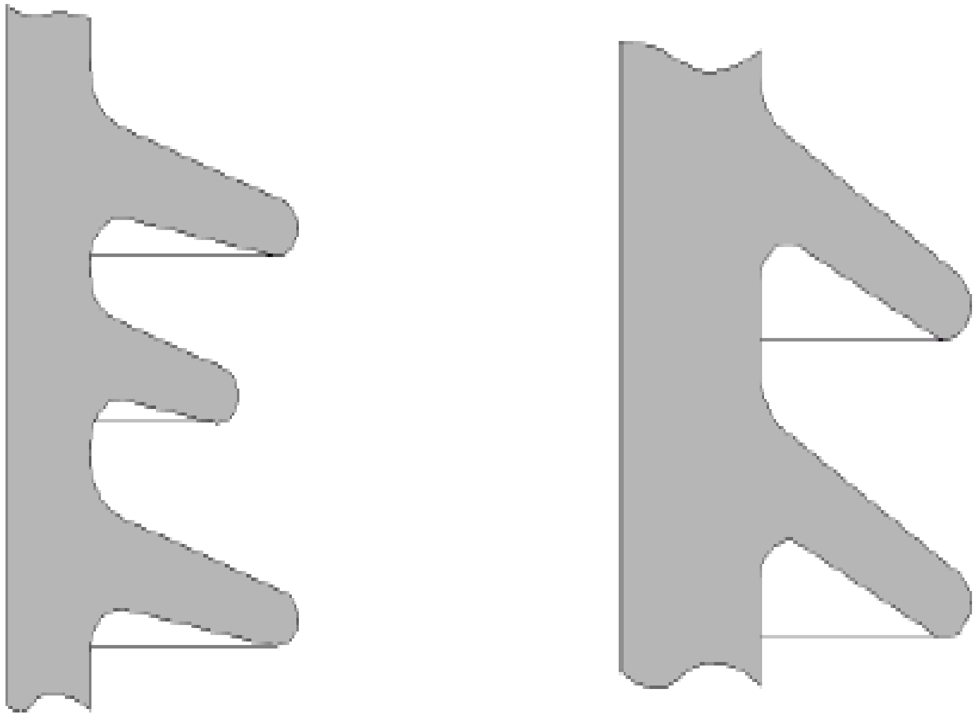

Fig. 10: Alternating shed profile (left) and normal shed profile (right)

Sealing system

- Sealing system – leakage can cause failure and hence most critical component
- Deter ingress of moisture for lifetime (25 to 30 years)
- Fast operating pressure relief device in rare event of an arrester overload (which can cause a rapid build-up of pressure in the housing, and would otherwise lead to a violent shattering of the porcelain body)

Also, a well-defined current transfer from the flange to the MO resistor column must be established

Example of a sealing system

- sealing ring & pressure relief diaphragm

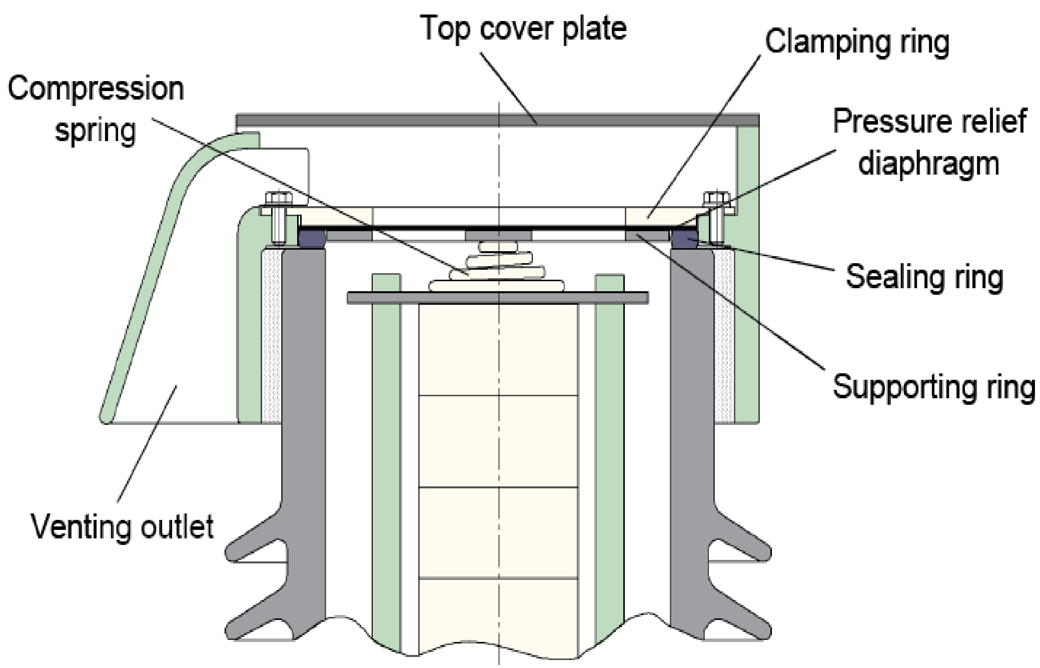

Fig. 11: Sealing system of a high-voltage porcelain housed MO arrester

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Sealing system

- Sealing ring
  - rubber not suitable
  - must be ozone resistance (synthetic)

- Pressure relief diaphragm
  - Very pure high grade steel or nickel
  - Few tenths of a millimeter thick
  - Resistance to corrosion for 30 years
  - Pressed against the sealing ring with a metal clamping ring

Pressure relief

- Short opening time when arrester overload occurs (direct lightning strikes occurring near arrester, etc.)
- A partial arc builds up, which in split seconds turns into a complete arc between the two flanges inside the housing
- The arc causes a full short-circuit current and hence an abrupt increase in pressure develops within the housing
- Within a few milliseconds, the diaphragm tears open
- Hot pressure gases escape through two venting outlets

Other construction features

- Longest porcelain housing is about 2 m (for technical and economic reasons)
- 2 m translate to a single unit for 245kV system, but more (2 to 5) for higher voltages (e.g. 420kV system- 2 units)
- Grading rings are absolutely essential for length > about 1½ m
  - Control the voltage distribution from the top to the bottom
  - Equal distribution of stress

Two unit HV arrester with grading ring

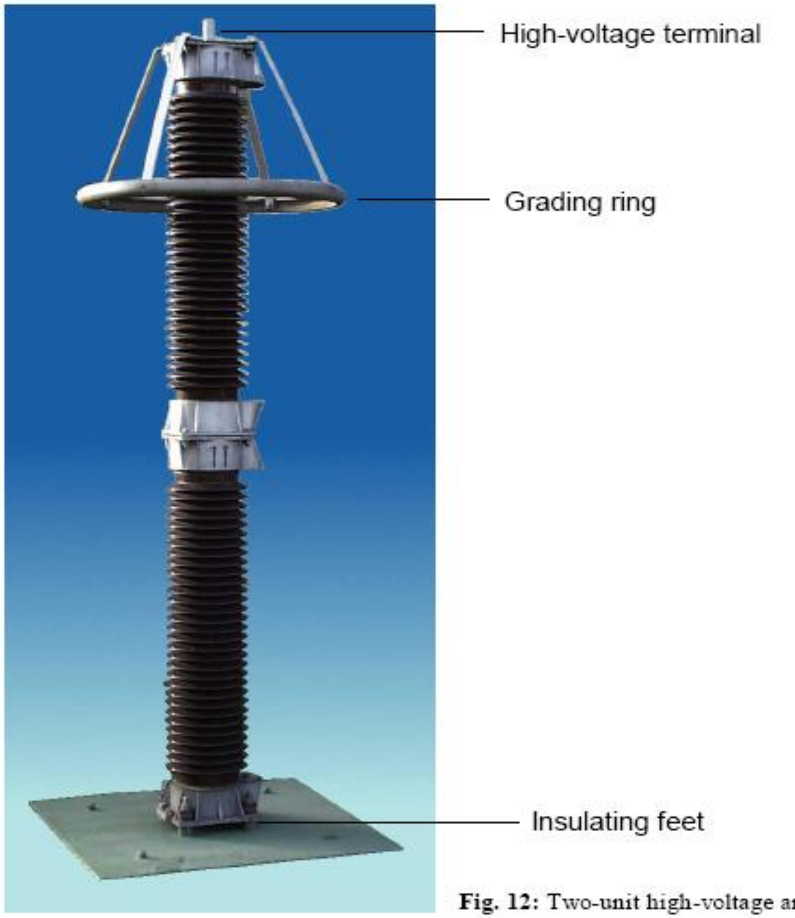


Fig. 12: Two-unit high-voltage arrester

Grading rings

- The larger the diameter, the longer the brace, the better the control effect is on the voltage distribution
- However, small sizes are preferred
  - ➢ The relevant standards on erecting electrical installations stipulate a minimum distance between conductors of the neighbouring phases
  - ➢ The housing must fulfill certain withstand voltage requirements

Connections and monitoring devices

- **Surge counters**, **monitoring spark gaps** or **leakage current indicators** are connected with the arrester in series
- Hence an insulating feet are used (arrester not directly earthed) (must be electrically and mechanically strong)
- Ground connection lead should have a cross section of at least **35mm^2** (more for mechanical and environmental resistance purposes)

Fig. 13: Bottom flange with insulating feet and monitoring spark gap

Leakage current indicator and Lightning Counter

Normally **bolts and flat terminals** are used as **high-voltage terminals**

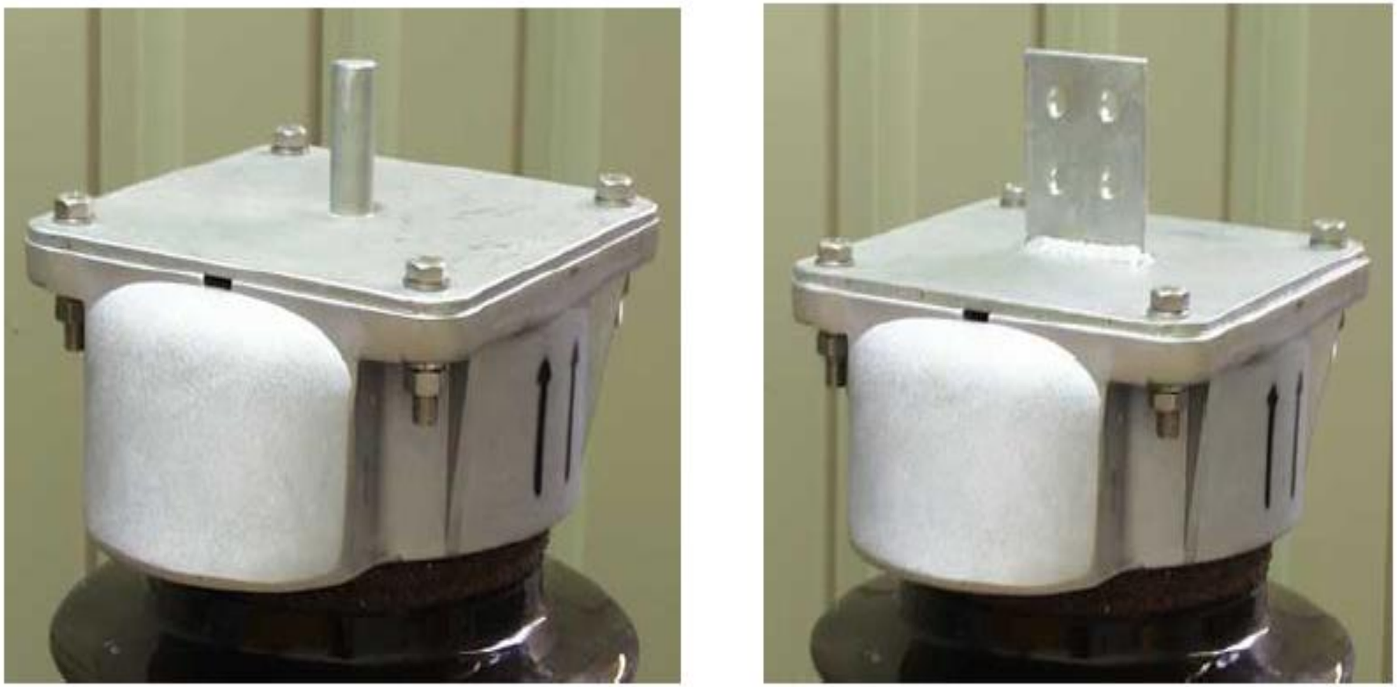


Fig. 14: Bolt terminal (left) and flat terminal (right)

Other Models of MO Arresters

1. Medium-voltage distribution arrester with porcelain housing

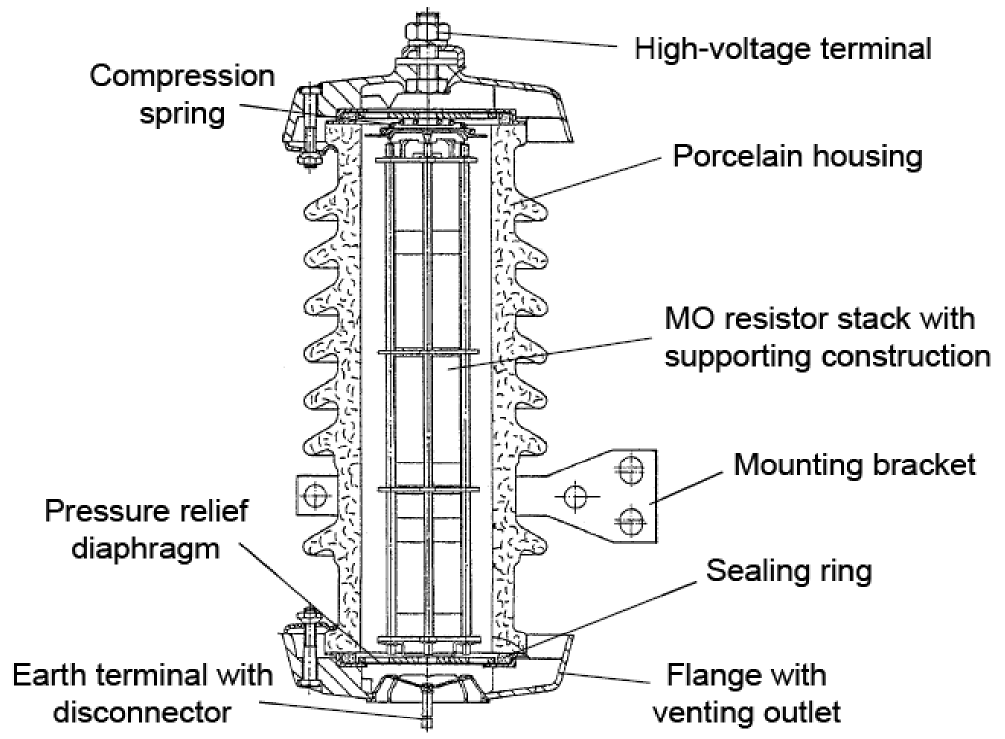


Fig. 15: Cross-sectional drawing of a porcelain housed MO distribution arrester

Medium-voltage distribution arrester with porcelain housing

- Millions are in use
- Increasingly being replaced by polymeric ones

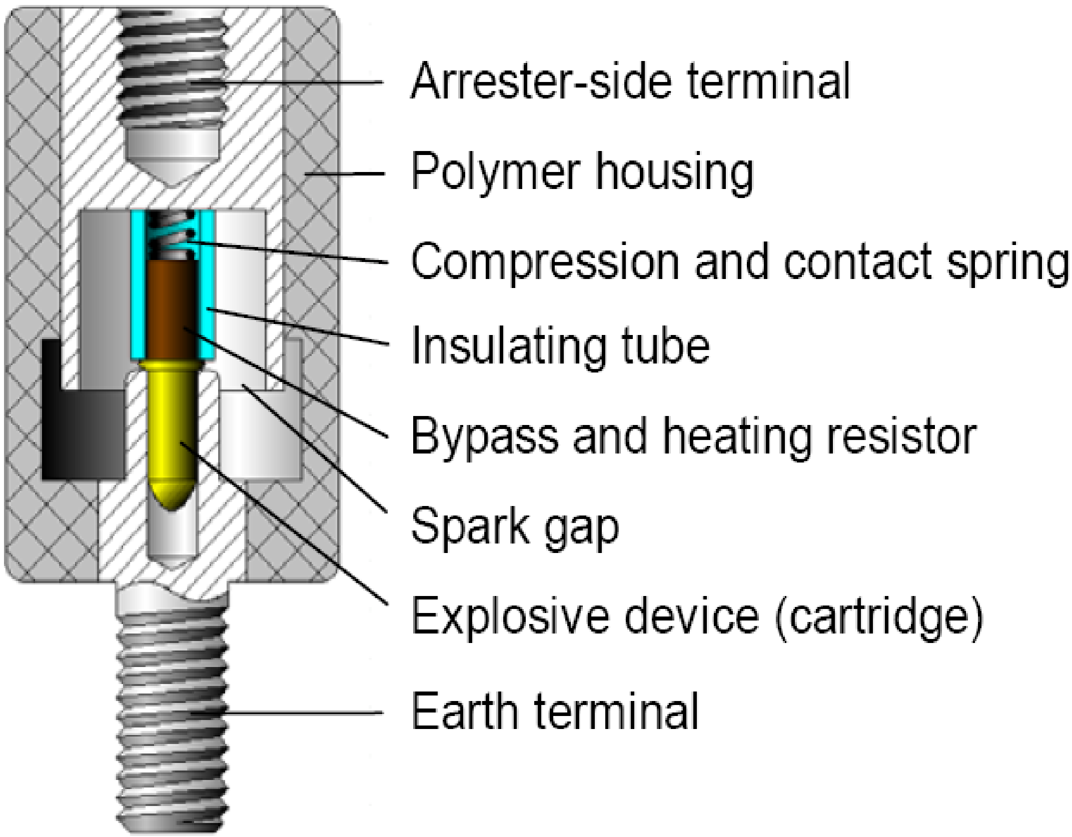
- Low production costs are essential but sealing system must be of highest possible standards
- Same sealing system as high-voltage arresters

- Some designs in the market do not provide pressure relief device at all
- Peculiar to distribution arresters is the **disconnectors**
  - Isolate faulty arresters

Disconnectors

- A pot pressed into the bottom flange in an appropriate form
- Hot gases expel the pot together with its connected earth wire

Disconnectors- Working principle - ignition of explosive device



Other Models of MO Arresters

2. Medium-voltage distribution arrester with polymeric housing

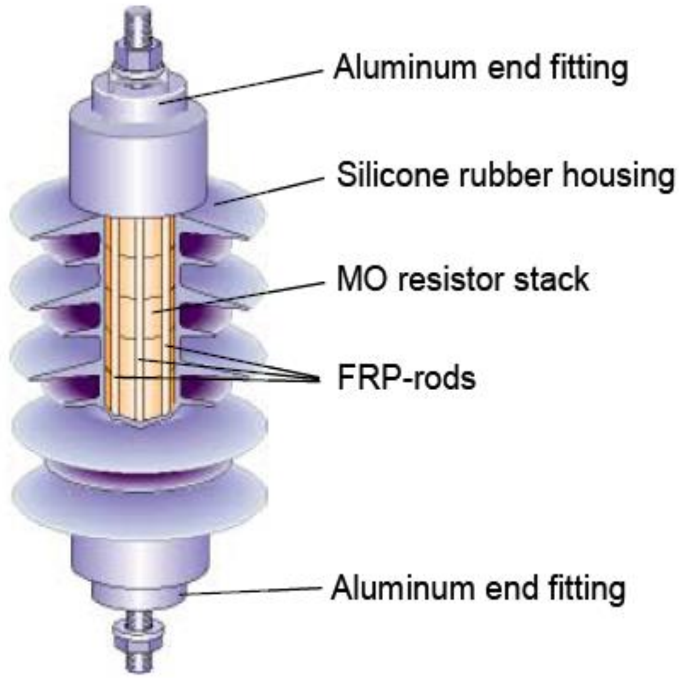


Fig. 16: Construction of a polymer housed MO distribution arrester

Medium-voltage distribution arrester with polymeric housing

- Introduced to solve leakage problems in cheap porcelain housed arresters in the late 1980's
- Most remarkable design – polymeric housing located directly on the MO resistor stack
- Hence no gas-filled gap -> **a sealing system can be completely omitted**
- In case of an overload, a pressure buildup and the related risk of housing breakage can be avoided
- The role of mechanical strength and creepage requirements achieved through two different components (unlike porcelain ones)

Medium-voltage distribution arrester with polymeric housing

- Mechanical – FRP
- Whole module is inserted in a mold, in which **silicone rubber is directly injected**
- Possible to obtain perfect bond of the silicone rubber with the other components, void-free and permanent
- Silicone rubber
  - ✓ high endurance (30 years experience)
  - ✓ hydrophobicity (even if heavily polluted)
- Risk of housing bursting and splitting in case of overload is nonexistent (the arc resulting from puncture or flashover of the MO rips the silicone rubber housing open)

Medium-voltage distribution arrester with polymeric housing

- Other advantages (cf. porcelain)
  - ✓ Weight reduction
  - ✓ Non-risky handling during transportation and installation
  - ✓ Saving in cost

- Very popular for medium-voltage
- For HV and EHV levels, electrical and mechanical demands are harder to be fulfilled by polymeric housing

Other Models of MO Arresters

3. High-voltage station arrester with polymeric housing

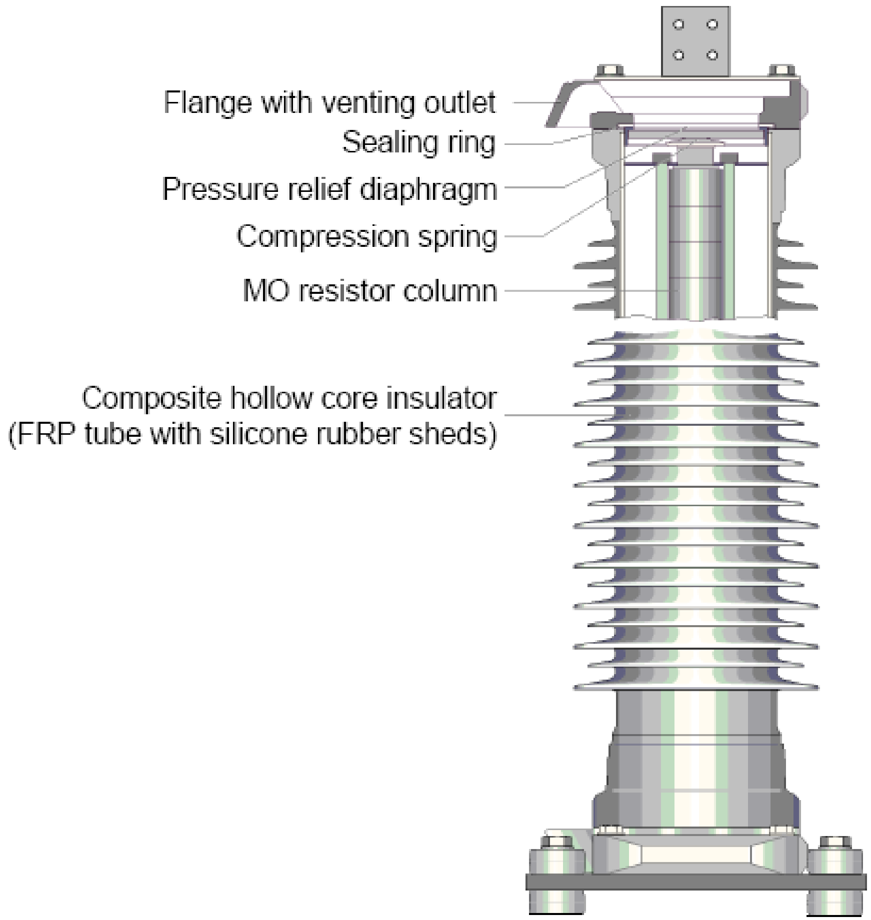


Fig. 17: Cross-sectional drawing of the unit of a polymer housed high-voltage arrester (with composite hollow core insulator housing)

High-voltage station arrester with polymeric housing

- Introduced in late 1980's
- Porcelain insulator has been replaced with a composite hollow core insulator made of FRP

- The FRP tube on which the silicone rubber sheds are directly molded on, or pushed on and vulcanized in the form of individual prepared sheds.
- Arresters can be mechanically strong due to FRP

- Breakage will never occur
- However, the cost is higher in comparison to porcelain

Part III: Configuring MO Arresters

Choosing the Continuous Operating Voltage and the Rated Voltage
Selecting the Nominal Discharge Current
Selecting the Line Discharge Class
Selection and Review of the Protective Levels
Selecting the Housing
Service Conditions

Configuring MO Arresters

- How to configure an arrester?
- Need to understand how different requirements and parameters affect the operational performance
- e.g. for U_s = 24kV (distr.) and U_s = 550kV (transm.)

- Two basic requirements:

1. **Provide adequate protection**
   - Reduce voltage to below withstand level with safety margin
2. Laid out for **stable continuous operation**
   - Electrically and thermally stable under all stresses

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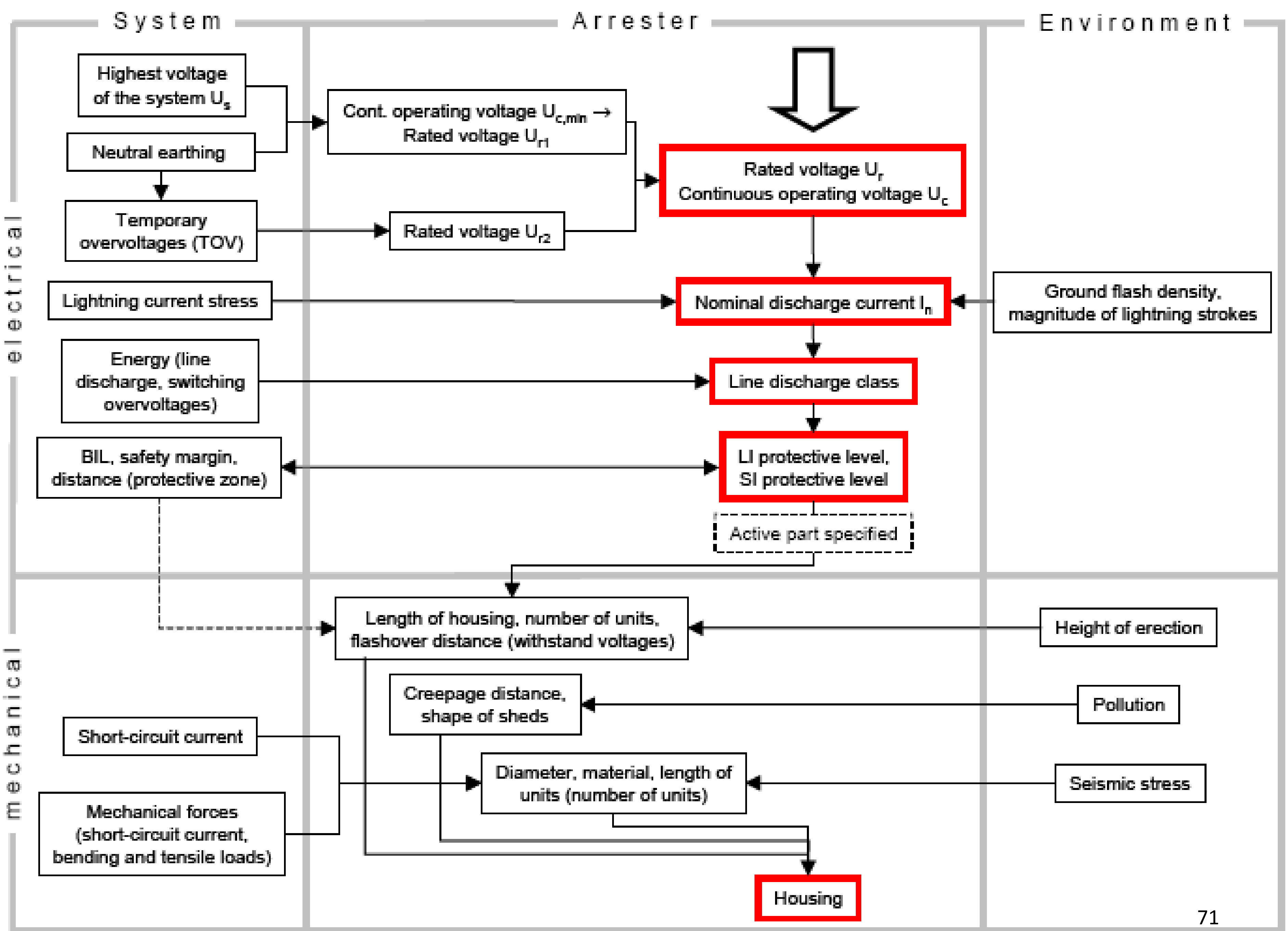
Configuring MO Arresters

- Both requirements cannot be fulfilled independently
- **Increasing c.o.v. increases V_{pr} as well**

- Additional electrical characteristics requirements:
  - should not change during its life span
  - Insensitive to environmental influences (pollution, solar radiation or mechanical strain)

- Fig. 18 – Procedure for configuring an MO arrester


System
Arrester
Environment
electrical
mechanical
Highest voltage of the system U_s
Neutral earthing
Cont. operating voltage $U_{c,min}$ → Rated voltage U_{r1}
Rated voltage U_r
Continuous operating voltage U_c
Temporary overvoltages (TOV)
Rated voltage U_{r2}
Lightning current stress
Nominal discharge current I_n
Ground flash density, magnitude of lightning strokes
Energy (line discharge, switching overvoltages)
Line discharge class
BIL, safety margin, distance (protective zone)
LI protective level, SI protective level
Active part specified
Length of housing, number of units, flashover distance (withstand voltages)
Height of erection
Creepage distance, shape of sheds
Pollution
Short-circuit current
Diameter, material, length of units (number of units)
Seismic stress
Mechanical forces (short-circuit current, bending and tensile loads)
Housing

1. Choosing the Continuous Operating Voltage and Rated Voltage

- **First** step – establish U_c, min (5% above phase-to-earth voltage of the system, harmonics effects)

Solidly earthed neutral system:	Isolated or resonant earthed neutral system:
$U_{c,\,min} \geq 1.05 \cdot U_s/\sqrt{3}$	$U_{c,\,min} \geq U_s$

- Use 1.25 factor to get the rated voltage

Solidly earthed neutral system:	Isolated or resonant earthed neutral system:
$U_{r1} \geq 1.25 \cdot 1.05 \cdot U_s/\sqrt{3}$	$U_{r1} \geq 1.25 \cdot U_s$

- **Second** step – establish U_r by examining the temporary overvoltages which **may occur** in the system

Solidly earthed neutral system:

$$U_{r2} = U_{tov} / k_{tov}$$

- If no info. available, use an earth-fault factor of 1.4 and 10s (**solidly earthed neutral**)

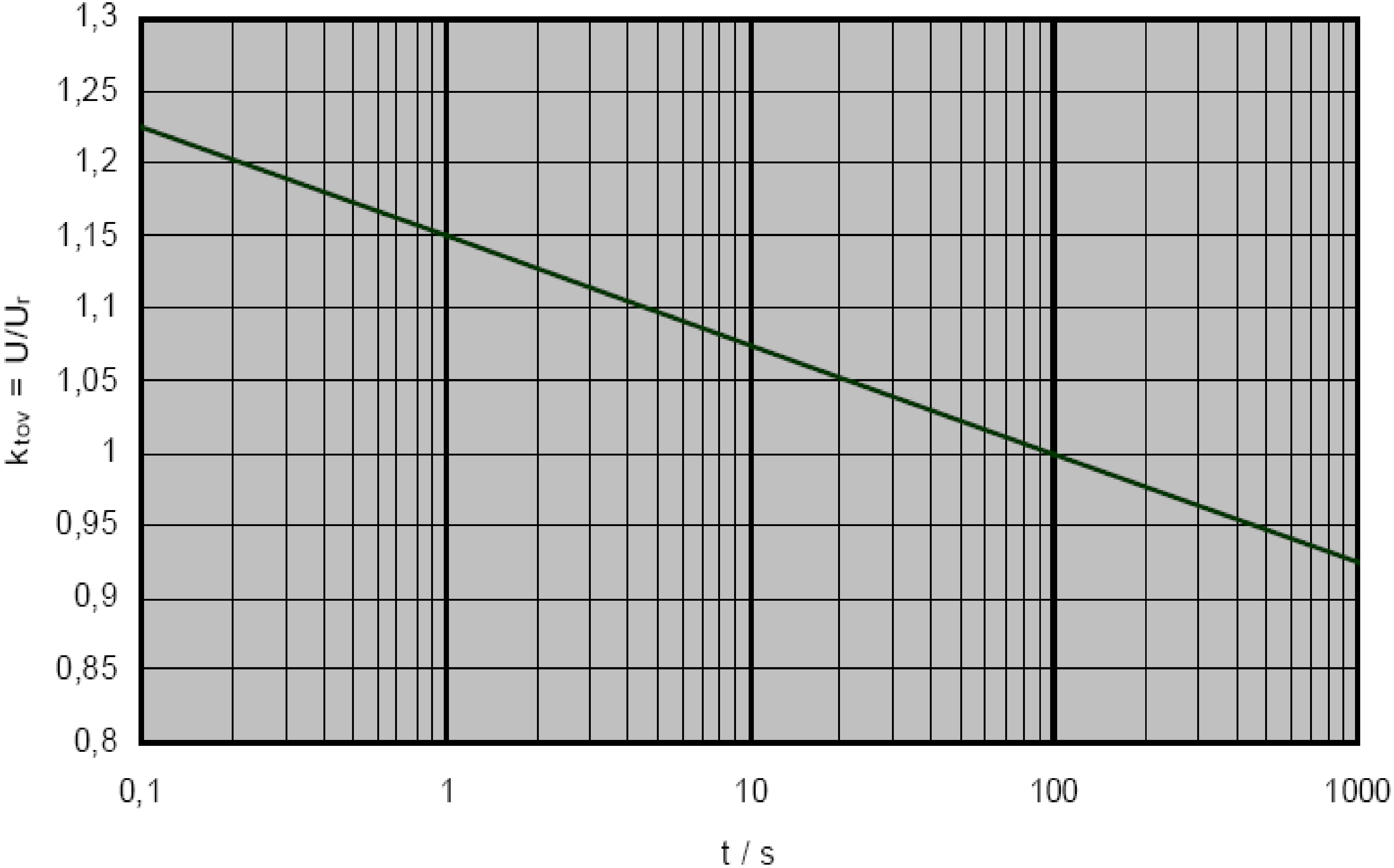


Fig. 19: Example of a power-frequency voltage versus time (U-t-) characteristic

- Choose a higher U_r

$$U_r = \max\{U_{r1}, U_{r2}\}$$

rounded up to a value divisible by three

- A higher value of U_r is recommended to be chosen for unforeseen problems (pollution etc.)

2. Selecting the Nominal Discharge Current

- The nominal discharge current serves to classify an MO arrester

- IEC 60099-4 specifies 5 different values

1 500 A	2 500 A	5 000 A	10 000 A	20 000 A
under consideration	$U_r \leq 36$ kV	$U_r \leq 132$ kV	3 kV $\leq U_r \leq$ 360 kV	360 kV $< U_r \leq$ 756 kV

- Current class functions to specify further demands and test requirements

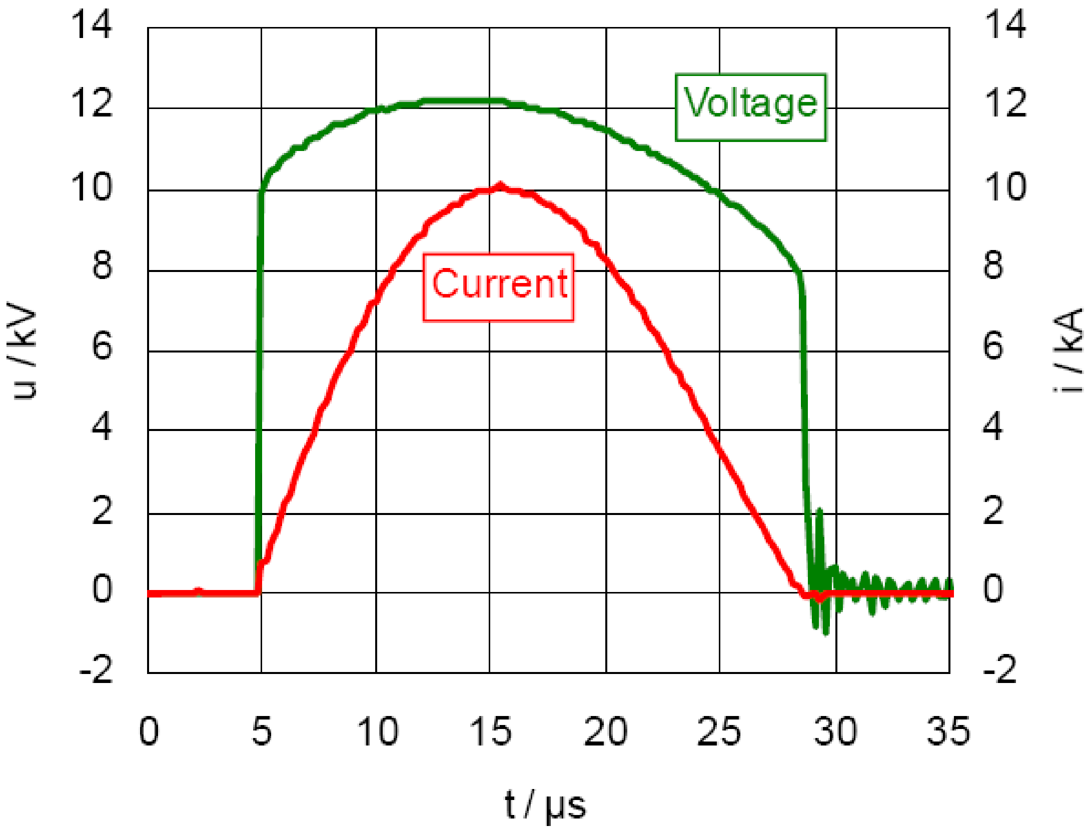
<u>Distribution arresters</u>

- Operating duty test:

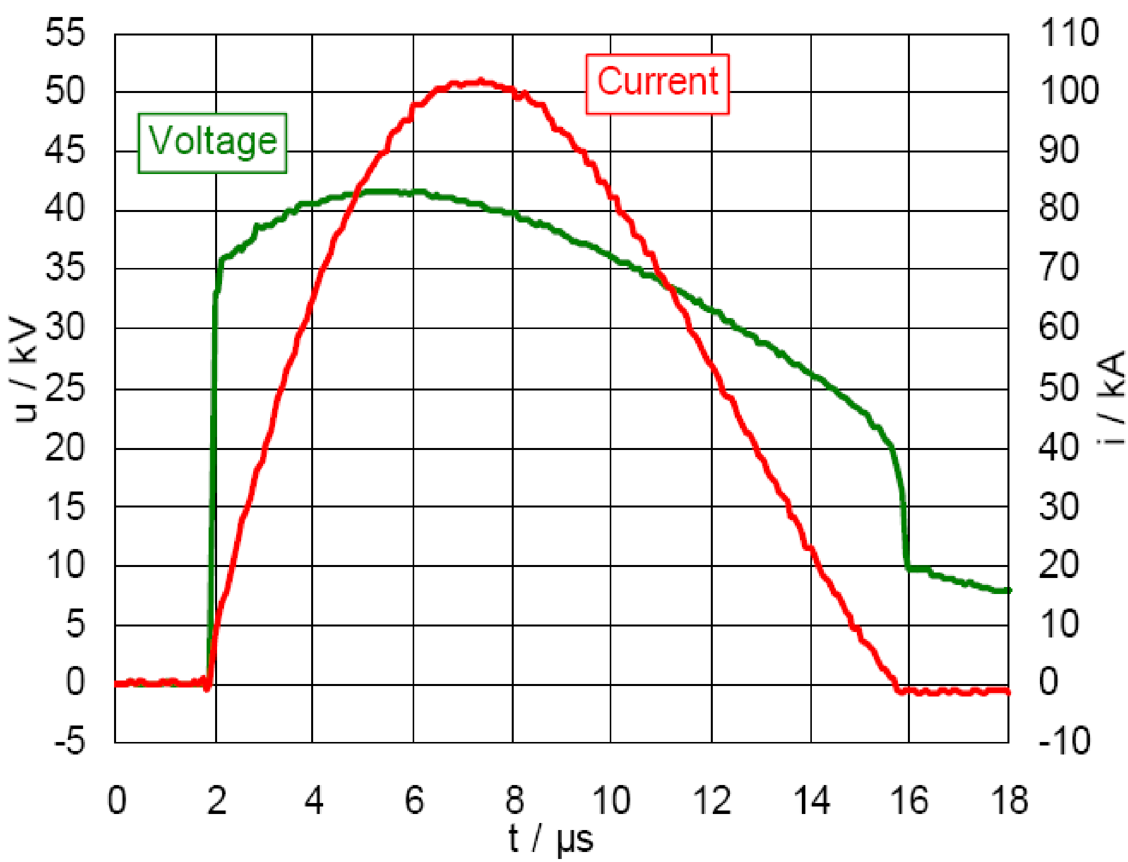
  - 5kA class- 20 x 5kA impulses then 2 x 65kA impulses
  - 10kA class- 20 x 10kA impulses then 2 x 100kA impulses

- 5kA usually sufficient for distribution in European systems

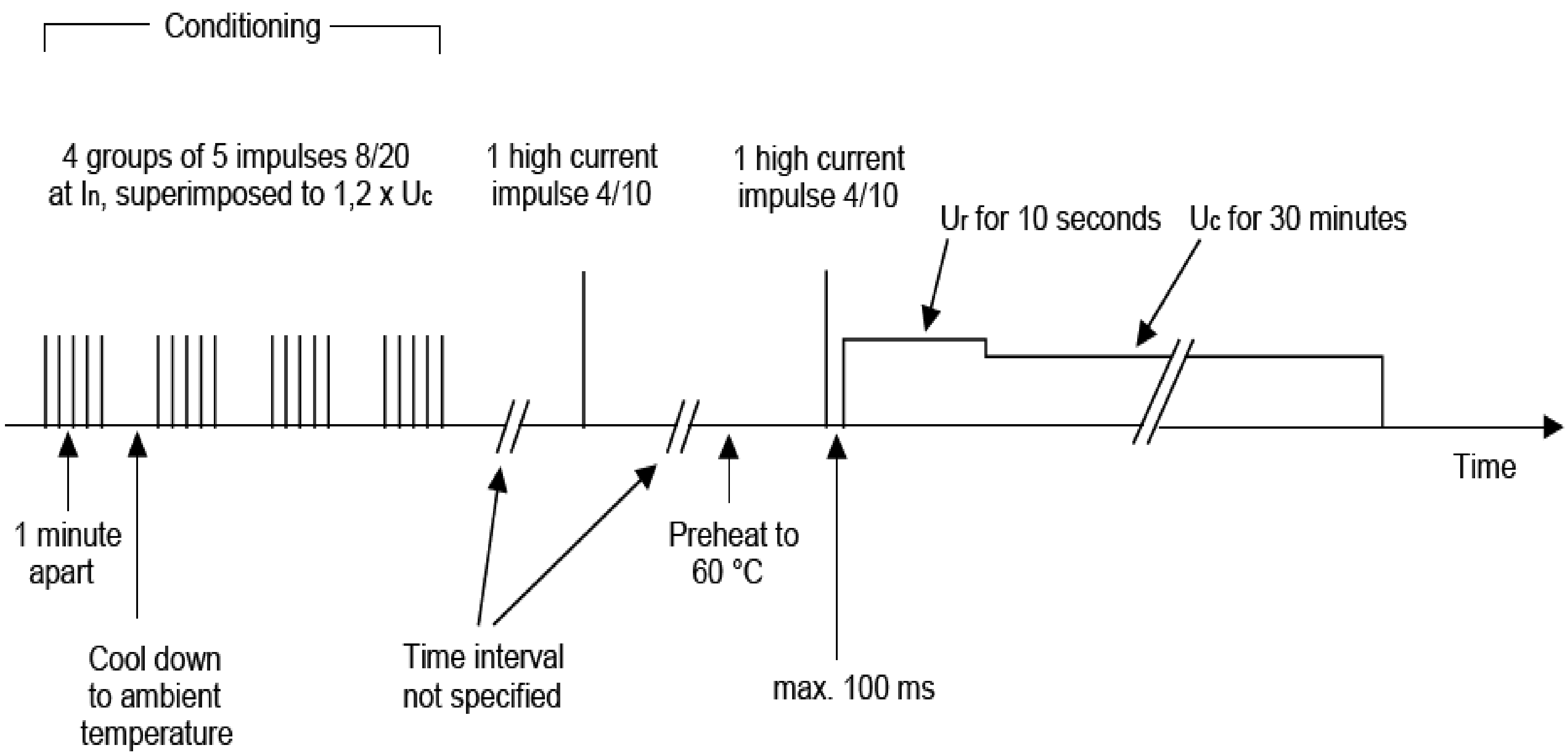
Lightning current impulse



High current impulse



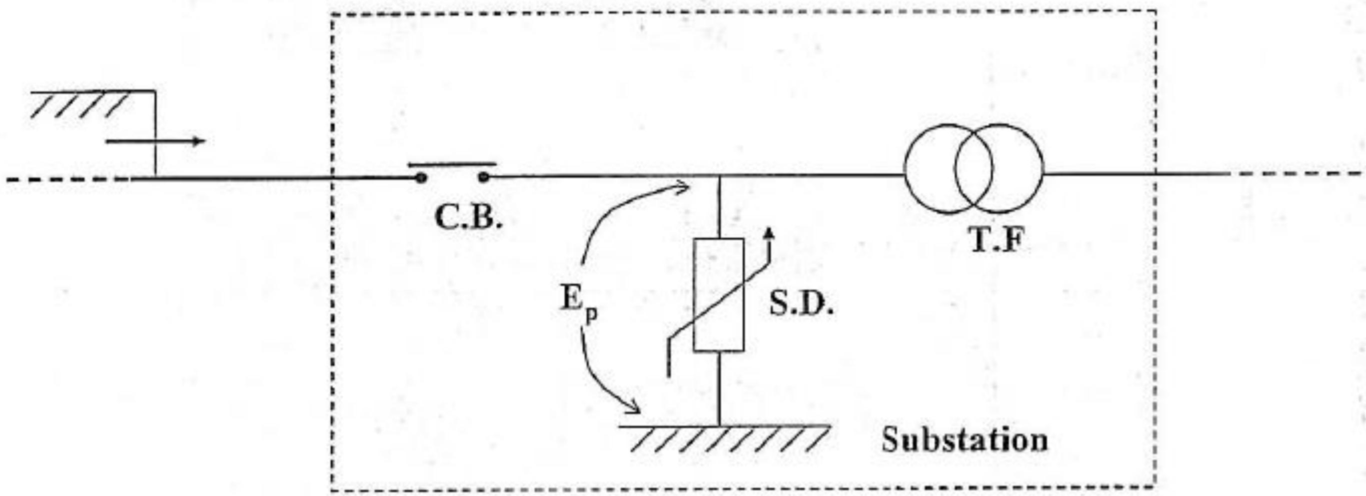
High current impulse operating duty test



HV arresters

- Use 10kA and 20kA classes
- Uncommon to use 5kA class although the above table allows (IEC 600099-5 recommends 5kA class for U_s=72.5kV or lower)
- Main difference:
  - 10kA arresters – line discharge class 1 to 3
  - 20kA arresters – line discharge class 4 and 5

Estimation of incoming surge magnitude into a substation



Surge Arrester Application-Distance Effect

- The BIL (basic lightning insulation level) is often determined by simply adding a MARGIN of, say 25% to 30% to the protective level of the surge arrester and then selecting the next higher BIL from the list of standard values.
- For large and important stations, it is necessary to allow for the 'DISTANCE EFFECT' more accurately

Surge Arrester Application-Example 1 (SIMPLIFIED)

A backflashover on the phase A of a transmission line insulator causes a surge of 1100-kV magnitude to travel to a surge arrester protected transformer in a substation. The surge impedance of the conductor is 350 Ω. The characteristics of the arrester is given below:

I (kA)	1.0	2.0	4.0	6.0	9.0	12.0
V (kV)	500	650	750	800	825	850

If no attenuation of the surge during travel is assumed, determine

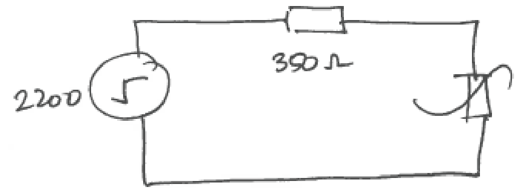
- The discharge current and the residual voltage of the arrester if no other circuit conductors are connected to the transformer.
- The discharge current and the residual voltage of the arrester if two other circuit conductors are connected to the transformer.
- The discharge current and the residual voltage of the arrester if another circuit conductor is also connected to the transformer with exactly the same backflashover voltage traveling towards the transformer.
- The discharge current and the residual voltage of the arrester if two other circuit condcutors are also connected to the transformer with exactly the same backflashover voltage traveling towards the transformer.
- The discharge current and the residual voltage of the arrester if two other circuit condcutors are also connected to the transformer with exactly the same backflashover voltage traveling towards the transformer, AND two other circuit conductors are also connected to the transformer,

Note: Neglect the effects of surge attenuation and earthing factors.

Q3 (a) BIL insulator 1100-kV

$Z_L = 350\Omega$.

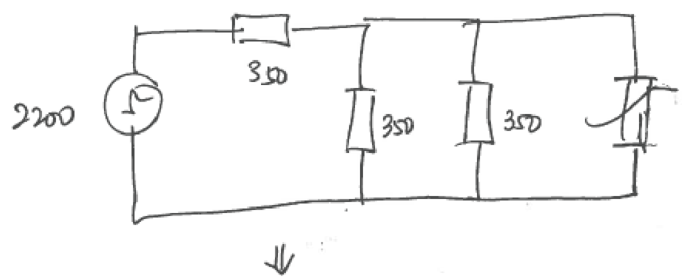
(i) Equivalent circuit :

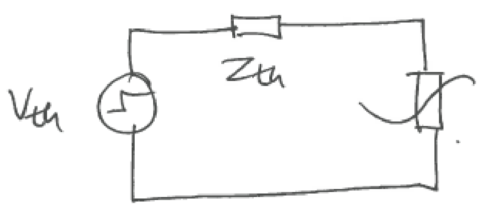


From the graph, the discharge current is 4.15 kA ; V_{res} = 750 kV

(4)

(ii)





(6)

$$V_{th} = \frac{175}{175+350} \times 2200 = 733.3 \text{ kV}.$$

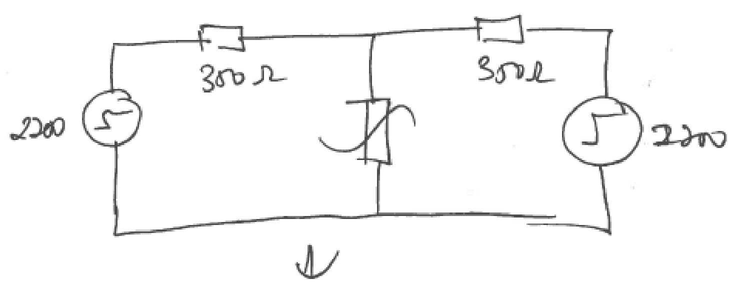
$$Z_{th} = \frac{350}{3} = 116.7\ \Omega$$

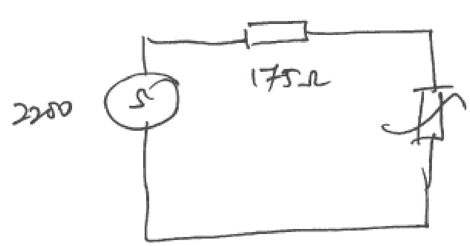
From the graph, the discharge current

$= 1.4$ kA.

$V_{res} \simeq 575$ kV

(iii) Equivalent circuit:



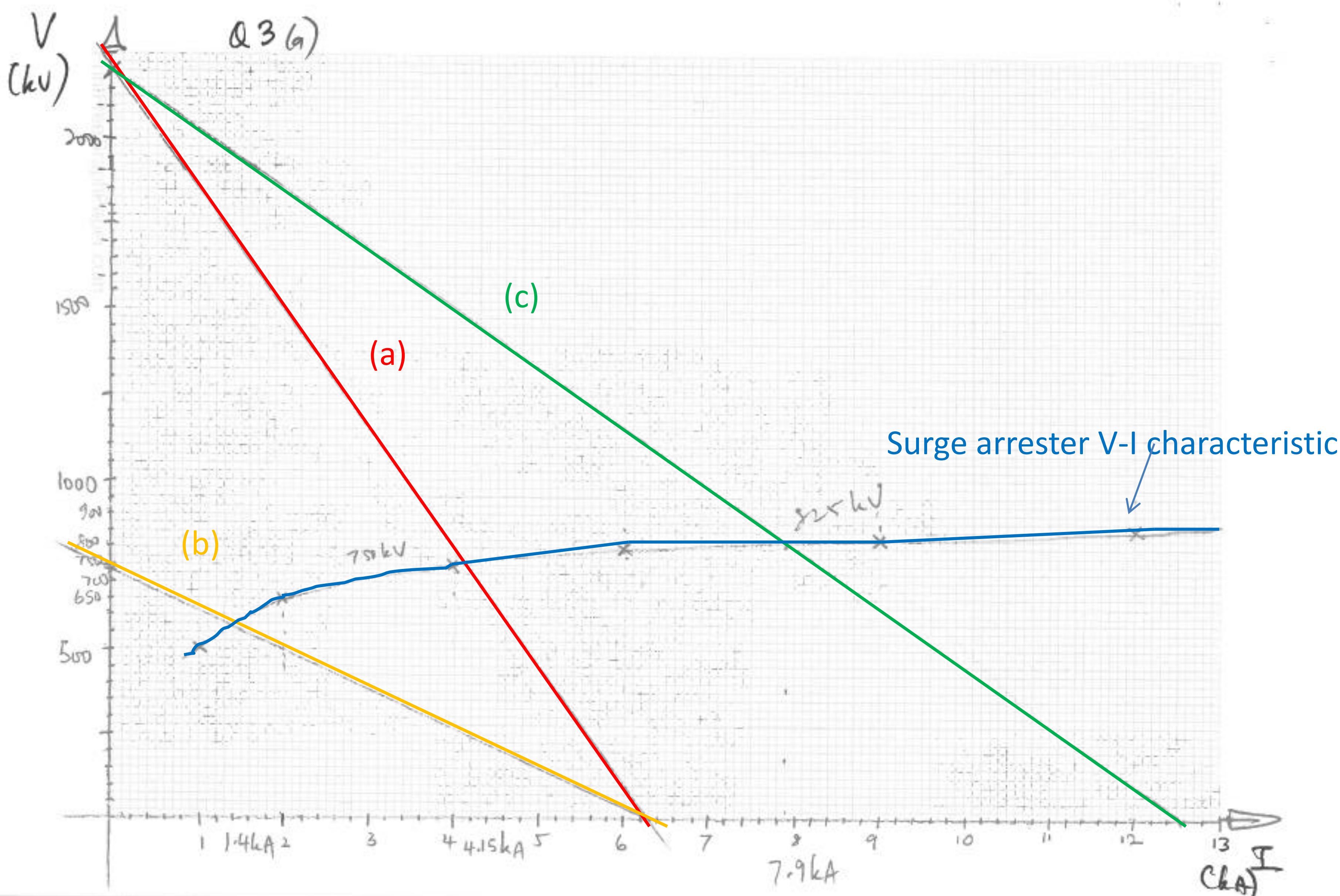


From the graph

$I = 7.9\ kA$

$V_{res} = 825\ kV$ #

5



Q3(a)
V (kV)
I (kA)
2000
1500
1000
900
800
750
700
650
500
(a)
(b)
(c)
Surge arrester V-I characteristic
750kV
825kV
1.4kA
4.15kA
7.9kA
1
2
3
4
5
6
7
8
9
10
11
12
13

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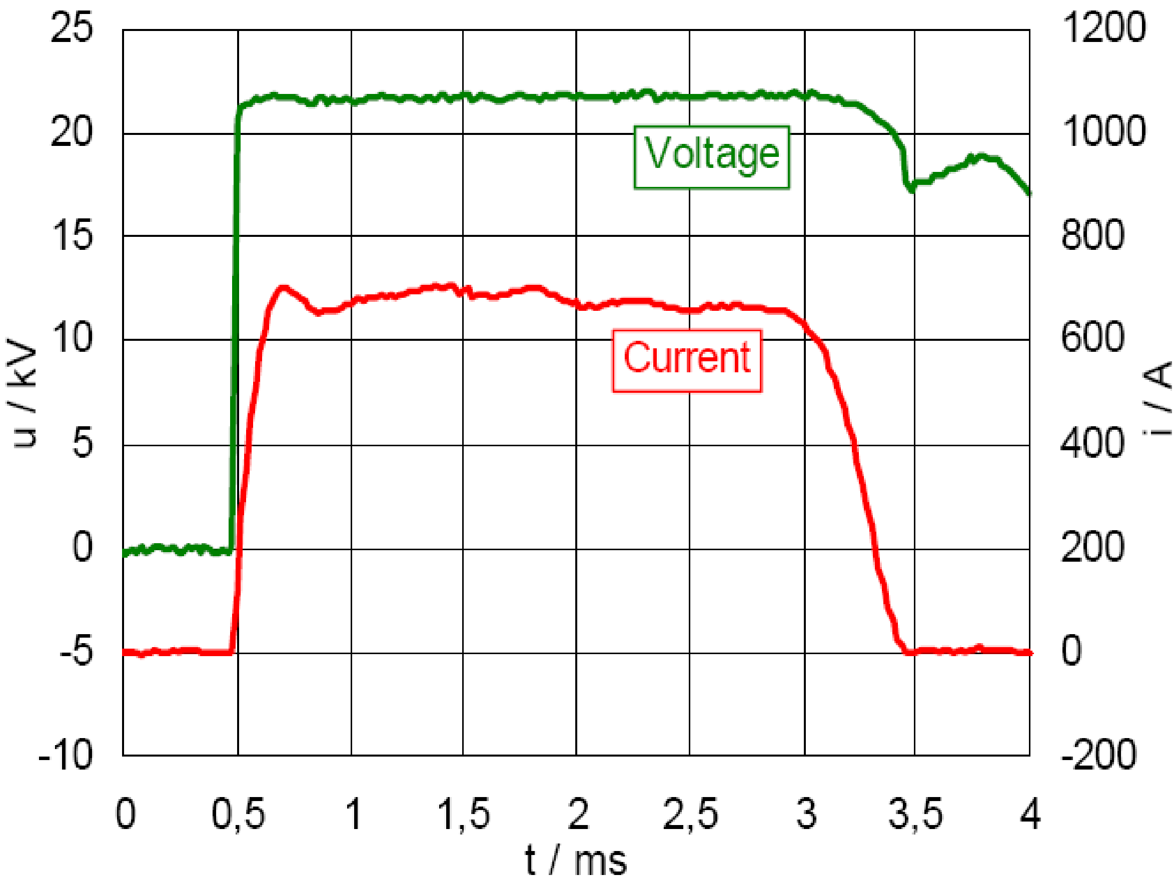
3. Selecting the Line Discharge Class (for HV - 10kA and 20 kA - arresters)

- The only way to differentiate energy absorption capability (IEC 60099-4)
- Based on the line discharge test whereby a long transmission line, charged to a certain overvoltage during a switching operation, will discharge into a connected arrester in the form of a travelling wave process
- Test using a distributed constant impulse generator (20 to 30 π-elements (series L's and shunt C's))

Line Discharge Test Oscillograms



Line discharge class	Surge impedance of the line Z in Ω	Virtual duration of peak T in µs	Charging voltage U_L in kV (d.c.)
1	$4.9 \cdot U_r$	2000	$3.2 \cdot U_r$
2	$2.4 \cdot U_r$	2000	$3.2 \cdot U_r$
3	$1.3 \cdot U_r$	2400	$2.8 \cdot U_r$
4	$0.8 \cdot U_r$	2800	$2.6 \cdot U_r$
5	$0.5 \cdot U_r$	3200	$2.4 \cdot U_r$

U_r = rated voltage of the test sample as an r.m.s. value in kV

Relating Line Discharge Class and Energy

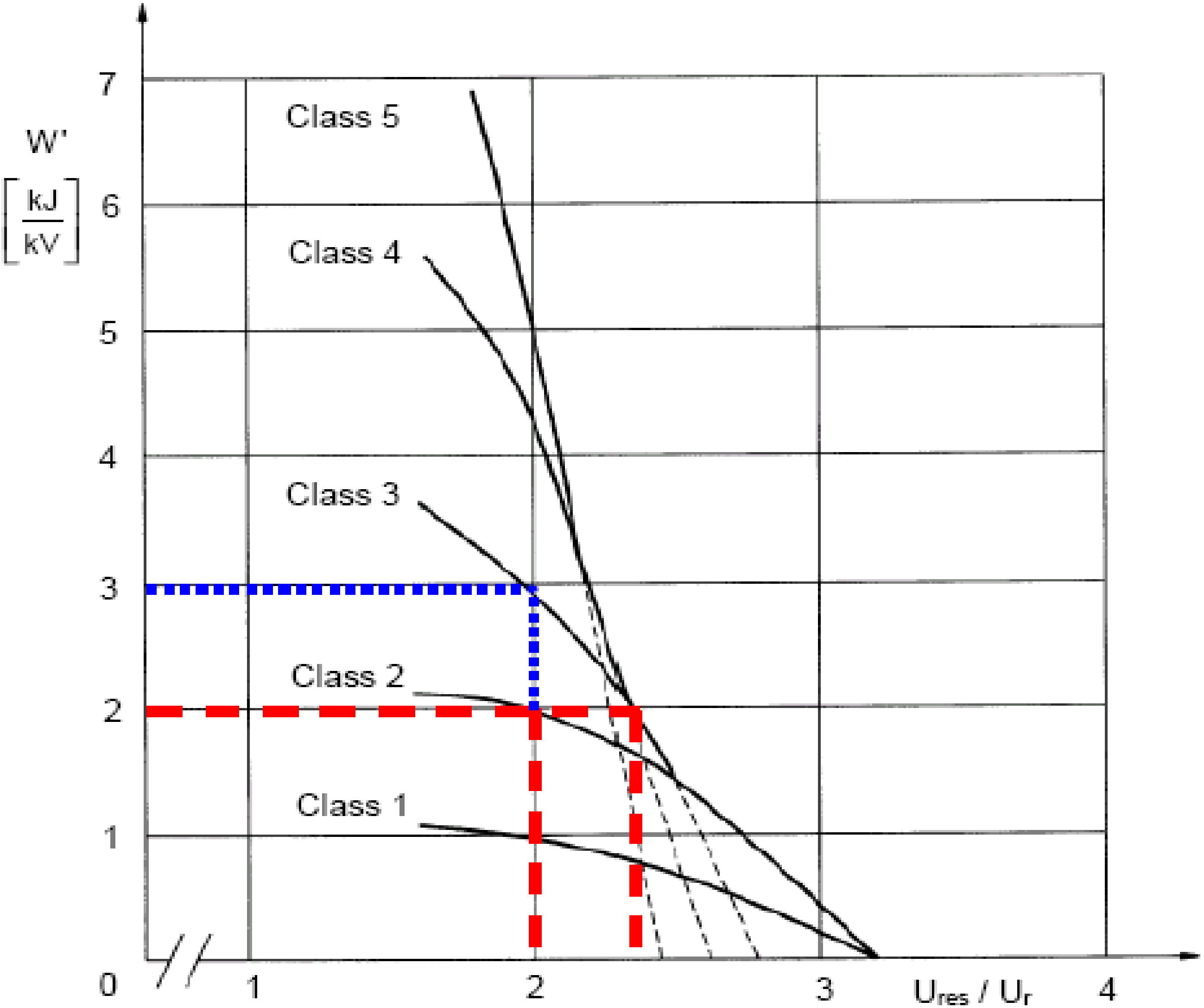


Fig. 20: Specific energy in kJ/kV of rated voltage dependent on the ratio of switching impulse residual voltage U_{res} to the r.m.s. value of the rated voltage U_r of the arrester (from IEC 60099-4)

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Selecting the Line Discharge Class

- Dependent on U_{res}

The dependence of the specific energy on the switching impulse residual voltage is shown in Figure 20.

The selection of the line discharge class is done in the following sequence:

a) Determine the energy which is generated in the metal-oxide arrester in service, taking into account possible events caused by lightning and/or switching.

b) **Determine the specific energy by dividing the energy by the r.m.s. value of the rated voltage.**

c) Compare this specific energy with the specific energy generated in the test using Figure 20 and select the next higher line discharge class.

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Example:

- Using an MO resistor capable of absorbing 2kJ/kV of energy per line discharge, the arrester has a line discharge class of 2 at a ratio of U_{res}/U_r = **2**.
- It can also be assigned as class 3 but at a higher risk ratio of U_{res}/U_r = **2.35**
- To maintain U_{res}/U_r = 2.0 but specified as class 3, we need resistors that can absorb about 3 kJ/kV per discharge, and hence those with greater diameters

- The following line discharge classes are recommended:

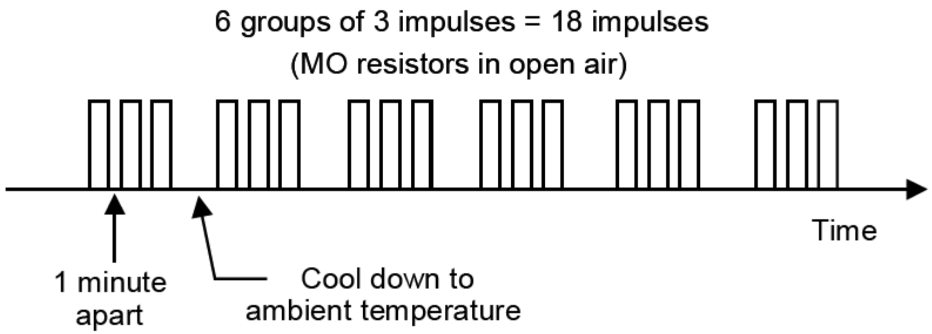
Line discharge class	U_s (kV)
1	≤ 245
2	≤ 300
3	≤ 420
4	≤ 550
5	≤ 800

- In practice, one tends to select the next higher line discharge class
- When deciding on a definite line discharge class and thereby indirectly on a definite energy absorption capability, the required MO resistor diameter has also automatically been selected

MO resistor diameter (mm)	Line discharge class
50	1 and 2
60	2 and 3
70	3 and 4
80	4 and 5
100 (or 2 · 70 in parallel)	5 and higher

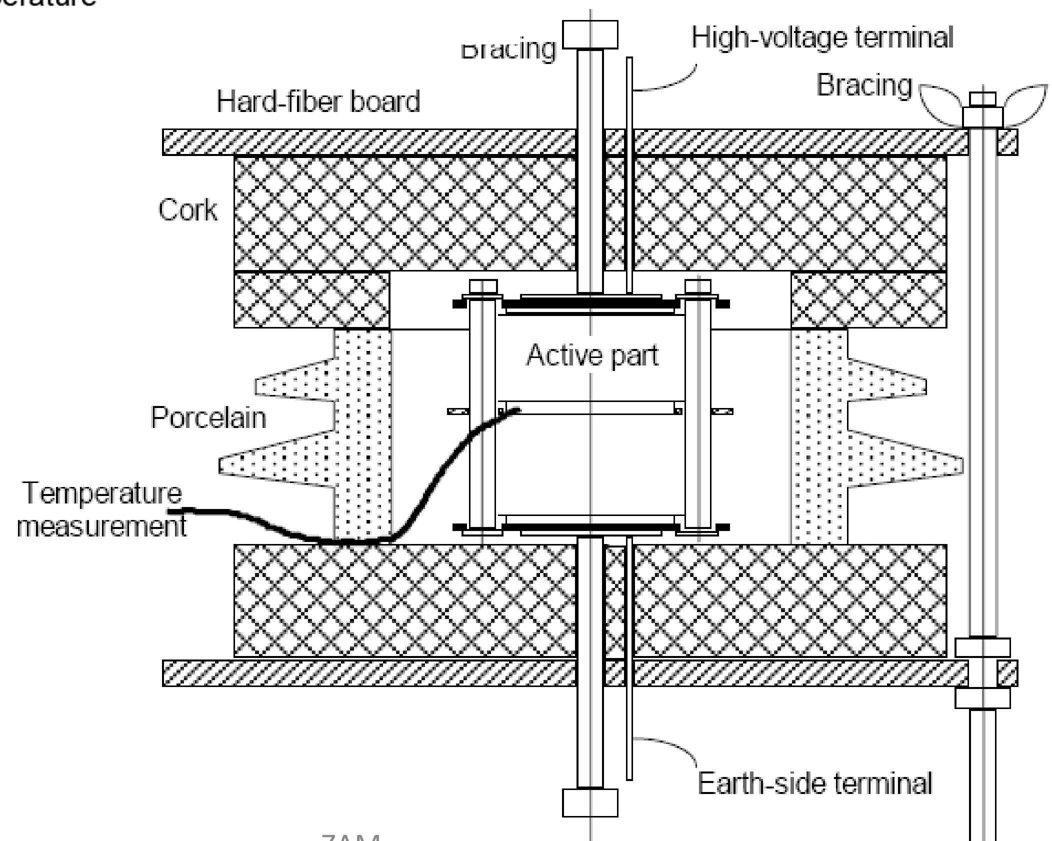
Other related tests

- Long duration current impulse withstand test



Other tests

- Thermally equivalent prorated section



4. Selection and Review of the Protective Levels

- In the previous exercise of determining the rated voltage and subsequently choosing the MO resistor diameter, the protective characteristic of the arrester has been completely established.

- Next step is to check adequacy of the protective characteristic.

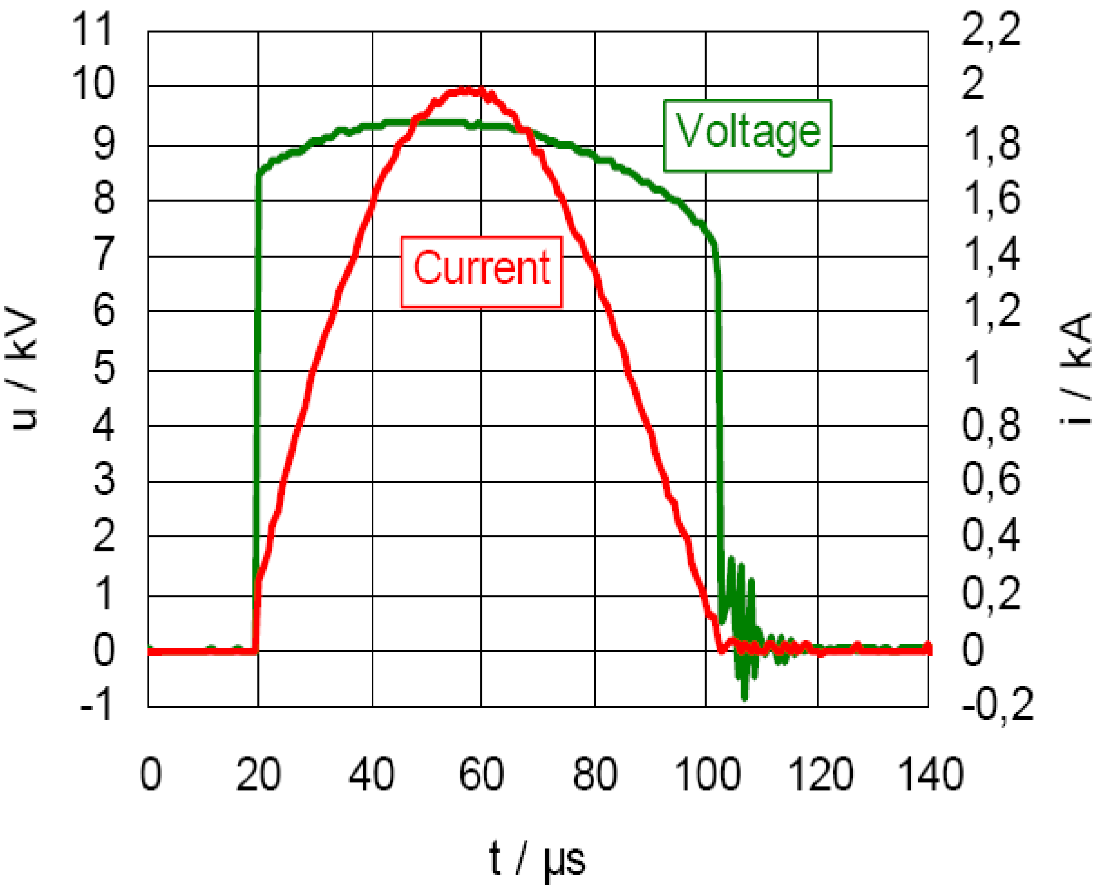
- IEC 60071-2 specifies a safety factor of 1.15 between BIL (standard lightning impulse withstand voltage) of the device to be protected with a non-self-restoring insulation, and the highest lightning overvoltage which is expected to occur at its terminals.

Residual voltage selection

- Protective zone (a few m's for distribution and up to 60m for HV and EHV systems) and distance effect (a factor of **1.4**)
- EHV – switching impulse residual voltage is normally the determining characteristic

Arrester class	Switching current impulses (A)
20 kA, LD-classes 4 and 5	500 and 2000
10 kA, LD-class 3	250 and 1000
10 kA, LD-class 1 and 2	125 and 500

Switching current impulse (T_f 30-100us, T_t~$2T_f$)



Selection and Review of the Protective Levels

Residual voltage selection

- Safety factors (1.4 for LI,
  1.15 (no travelling wave and inductive effects) for SI for non-self-restoring insulation)

- Special application: Steep current impulse
  -> protective level (5% higher)

  (Front times within the range < 1us, hence any inductance is important)

Selection and Review of the Protective Levels

- Once all requirements are fulfilled, the choice for the electrical characteristic of the arrester is then finished
- For a given type of MO resistor, all the residual voltage values, as well as the continuous operating and rated voltage, comprise **a fixed ratio** – thus none of these can be decreased alone (e.g. to obtain a lower switching impulse protective level, we choose a lower U_{res}, but then the whole characteristic would have to be shifted downwards)

Selection and Review of the Protective Levels

- However, one can select MO resistors with larger cross sections!
  - Either by choosing a larger diameter or by connecting several resistors in parallel
  - The ratio U_{res}/U_r is smaller for bigger MO cross section (U-I characteristic is flatter)

- Therefore, for a given c.o.v. and U_r, a larger resistor cross section will result in a lower protective level
  - 10kA distribution arrester: U_{res}/U_r ~ 3 or more
  - 10kA heavy-multi-column HV: U_{res}/U_r ~ 2

Selection and Review of the Protective Levels

- Larger resistors and greater numbers of them are more usually used due to low residual voltage requirements rather than would actually be needed for the required energy absorption capability

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5. Selecting the Housing

- Dielectric and mechanical requirements

- **Length** (minimal length dependent on MO's length), **creepage distance**, **shed profile**, **diameter** and the **material**

- Withstand voltage requirements (IEC 60099-4)

Housing Dielectric Withstand

	I_n = 10 kA and 20 kA		$I_n \leq 5$ kA and High Lightning Duty Arresters (1 kV $\leq U_s \leq$ 52 kV)
	$U_r \geq$ 200 kV	$U_r <$ 200 kV	
Test with lightning impulse voltage	1.3 · lightning impulse protective level		
Test with switching impulse voltage	1.25 · switching impulse protective level	–	–
Test with power-frequency voltage (û; duration 1 min)	–	1.06 · switching impulse protective level	0.88 · lightning impulse protective level

Withstand Voltage of the Housing

- e.g. 420-kV system (BIL = 1425kV)

  -> U_{res} = 823kV
  -> $V_{lightning\ impulse}$ = 1.3 x 823 = 1070 kV

  -> 1070 kV lower than normal system BIL! (75%)
  -> OK because the housing is the best-protected insulation (next to MO!)

  -> not necessary to request housing with system's BIL (housing can be longer and more expensive!)

Housing Length

- Creepage requirement
  - Pollution dependent -> pollution levels (UEC 60815, Table 1)
    - Level I – 16mm/kV
    - Level II – 20mm/kV
    - Level III – 25mm/kV
    - Level IV – 31mm/kV
  - Central European – I and II sufficient

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Mechanical Criteria of Housing

- Last step
- "Normal operation conditions" (see later)
- Stress -> **static** head loads (strain relieving conductor loops and a wind velocity of 34m/s(~120km/h):

  F_{stat} = 400N for $U_s \leq 420$ kV
  F_{stat} = 600N for $U_s = 550$ kV
  F_{stat} = 800N for $U_s = 800$ kV

- Stress -> **dynamic** head loads (short-circuit currents, gusting winds): see table

Mechanical Criteria of Housing

Highest system voltage U_s (kV)	$F_{min, static}$ (N)	$F_{min, dynamic}$ (N)	Minimum breaking value (N)
≤ 420	400	1000	1200
550	600	1500	1800
800	800	2000	2400

Mechanical Criteria of Housing

- Seismic requirements

Fig. 21: Polymer housed arrester for a 550-kV-system during seismic testing on a shaking table

Mechanical Criteria of Housing

- Short-circuit withstand capability
- pressure relief behaviour-> short-circuit tests

Fig. 22: Porcelain housed arrester after pressure relief test with rated short-circuit current (63 kA, 200 ms). With the exception of some sheds which were broken the housing remained intact.

Old (according to IEC 60099-1, 1991-5):

Pressure relief class	r.m.s. value of the symmetrical short-circuit current (A)
80	80 000
63	63 000
50	50 000
40 (A)	40 000
20 (B)	20 000
10 (C)	10 000
16 (D)	16 000
5 (E)	5 000

New (according to IEC 60099-1, Ed. 3.1, 1999-12):

Rated short-circuit current (A)	r.m.s. value of the symmetrical short-circuit current (A)[1]
80 000	80 000
63 000	63 000
50 000	50 000
40 000	40 000
31 500	31 500
20 000	20 000
16 000	16 000
10 000	10 000
5 000	5 000

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Mechanical Criteria of Housing

- For the short-circuit withstand capability, the porcelain housing is influenced by:
  - ✓ Housing diameter: greater diameters bring about higher strength (also applicable to polymer ones)
  - ✓ Housing length: the greater the length, the lower the strength at a given diameter (also applicable to polymer housing)
  - ✓ Wall thickness: strength increases with increasing wall thickness
  - ✓ Housing material: the porcelain quality “C 120” results in greater strength than quality “C 110”

Mechanical Criteria of Housing

- In summary, the mechanical requirements are:
  - ❑ **Required head loads**
  - ❑ **Seismic demand**
  - ❑ **Short-circuit withstand capability**

  -> **housing** material, diameter and length
  (2 m length max)

- **Selection is now complete**!!

Normal Service Conditions (Cls. 4.4.1 IEC 60099-4)

- Ambient air temperature within the range of -40^{o}C to + 40^{o}C
- Solar radiation 1.1 kW/m^2
- Altitude not exceeding 1000 m above sea level
- Frequency of the a.c. power supply not less than 48 Hz and not exceeding 62 Hz
- Power-frequency voltage applied continuously between the terminals of the arrester's continuous operating voltage
- (wind velocity = 34 m/s)
- (vertical mounting)

Example 1: "Solidly earthed neutral 66-kV-system"

(All the information which is asterisked (*) are typical. Individually, however, these are manufacturer-dependent values.)

Tacitly assumed, if no further information is given and no special requests are made:

- $U_s = U_m = 72.5$ kV {based on IEC 60071 standard voltage for the given system}
- standard lightning impulse withstand voltage (BIL) of equipment = 325 kV {IEC 60071}
- earth fault factor k = 1.4 {based on system analysis}
- maximum duration of temporary overvoltage: 10 s {based on system TOV clearance scheme}
- required nominal discharge current $I_n = 10$ kA {based on station worst case condition}
- required line discharge class: 2 {based on integral of arrester v(t).i(t)}
- pollution level I {not so polluted area}
- maximum short-circuit current: 40 kA {based on system analysis}

Determining the minimally required continuous operating and rated voltage

- $U_{c,\,min} = 1.05 \cdot U_s/\sqrt{3} = 1.05 \cdot 72.5/\sqrt{3}$ kV = 44 kV
- $U_{r1,\,min} = 1.25^* \cdot U_{c,\,min} = 1.25^* \cdot 44$ kV = 55 kV
- $U_{r2,\,min} = 1.4 \cdot (U_s/\sqrt{3}) / k_{tov,\,10\,s} = 1.4 \cdot (72.5/\sqrt{3}) / 1.075^*$ kV = 55 kV

  ($k_{tov,\,10\,s}$ from Figure 19) {TOV - applicable for solidly grounded neutral}

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Table 2 – Standard insulation levels for range I (1kV < U_m ≤ 245 kV)

Highest voltage for equipment (U_m) kV (r.m.s. value)	Standard rated short-duration power-frequency withstand voltage kV (r.m.s. value)	Standard rated lightning impulse withstand voltage kV (peak value)
3,6	10	20 40
7,2	20	40 60
12	28	60 75 95
17,5 [a]	38	75 95
24	50	95 125 145
36	70	145 170
52 [a]	95	250

52 [a]	95	250
72,5	140	325
100 [b]	(150)	(380)
	185	450
123	(185)	(450)
	230	550
145	(185)	(450)
	230	550
	275	650
170 [a]	(230)	(550)
	275	650
	325	750
245	(275)	(650)
	(325)	(750)
	360	850
	395	950
	460	1050

NOTE If values in brackets are considered insufficient to prove that the required phase-to-phase withstand voltages are met, additional phase-to-phase withstand voltage tests are needed.

[a] These U_m are non preferred values in IEC 60038 and thus no most frequently combinations standardized in apparatus standards are given.

[b] This U_m value is not mentioned in IEC 60038 but it has been introduced in range I in some apparatus standards.

Establishing the actual continuous operating and rated voltage:

- $U_r = U_{r1,\,min}$ rounded up to the next value divisible by 3 = 57 kV
  Normally an arrester with a rated voltage of at least 60 kV is used in this system. This leads to a more stable layout, and nevertheless offers a sufficiently low protective level.
- U_r = 60 kV
- $U_c = U_r/1.25^* = 60\ kV/1.25^* = 48\ kV$

Selecting an MO resistor suitable for I_n = 10 kA and LD-class 2

- MO diameter: 50* mm {diameter chosen based on availability and safety}
- $\hat{u}_{10\,kA}/U_r = 2.8^*$ (This factor is characteristic for the MO resistor used when configuring it for the line discharge class 2.)

{for the 50 mm arrester, $U_{10kA,8/20}/U_r = 2.8$, **$U_{0.5kA,30/60}/U_r = 2.18$**, and $U_{10kA,1/2}/U_r = 2.97$}

The resulting protective characteristics*:

- lightning impulse protective level ($\hat{u}_{10\,kA,\,8/20\,\mu s}$): 168 kV
- switching impulse protective level ($\hat{u}_{0,5\,kA,\,30/60\,\mu s}$): 131 kV
- steep current impulse protective level ($\hat{u}_{10\,kA,\,1/2\,\mu s}$): 178 kV

Checking the protective values:

- $BIL/\hat{u}_{10\,kA,\,8/20\,\mu s} = 325\,kV/168\,kV = 1.93 \rightarrow$ definitely sufficient

Height of the MO resistor column:

- $h_{MO} = 600^*$ mm

Selecting a Housing

Since in this case no further information is available, a housing would be chosen which fulfills the following minimal requirements:

- lightning impulse withstand voltage = $1.3 \cdot$ lightning impulse protective level $= 1.3 \cdot 168\,kV = 219\,kV$
- power-frequency withstand voltage 1 min, wet = $1.06/\sqrt{2} \cdot$ switching impulse protective level $= 1.06/\sqrt{2} \cdot 131\,kV = 98\,kV$
- creepage distance: $16\,mm/kV \cdot 72.5\,kV = 1160\,mm$
- permissible head load static: 400 N
- permissible head load dynamic: 1000 N
- rated short-circuit current: 40 kA
- possible length of the active part: 600 mm
- number of units: 1
- grading ring: no

MO Resistors

- Residual voltage per mm height (for 10 kA current)
  - From 450 V/mm (32 mm diameter - Distribution arresters)
  - To 280 V/mm (70 mm diameter - EHV arresters)
    - for 45mm-height cylinder block -> 12.6 kV
    - for 823 kV, 66 resistors would have to be stacked on top of each other
    - -> 3m height -> not possible for single-housing
    - Use 2 units in series

Example 2: "Resonant earthed neutral 110-kV-system"

(All the information which is asterisked (*) are typical. Individually, however, these are manufacturer-dependent values.)

Tacitly assumed, if no further information is given and no special requests are made:

- $U_s = U_m = 123$ kV
- standard lightning impulse withstand voltage (BIL) of equipment = 550 kV
- operation under earth fault conditions for > 30 min.
- required nominal discharge current $I_n = 10$ kA
- required line discharge class: 2
- pollution level I
- maximum short-circuit current: 40 kA

Determining the minimally required continuous operating and rated voltage

- $U_{c,\,min} = U_s = 123$ kV
- $U_{r,\,min} = 1.25^* \cdot U_{c,\,min} = 1.25^* \cdot 123\text{ kV} = 154$ kV

  (The rated voltage, however, has no technical significance in a resonant earthed system.) {no need TOV computation and resultant Ur has no technical significance because the arrester is connected to ground and Varr=Vp??????}

Establishing the actual continuous operating and rated voltage:

- $U_r = U_{r,\,min}$ rounded up to the next value divisible by 3 = 156 kV
- $U_c = U_r/1.25^* = 156\ kV/1.25^* = 124\ kV$[1]

Selecting an MO resistor suitable for I_n = 10 kA and LD-class 2

- MO diameter: 60* mm {diameter chosen based on availability and safety}
- $\hat{u}_{10\,kA}/U_r = 2.35^*$ (This factor is characteristic for the MO resistor used when configuring it for the line discharge class 2.)

  Note: Compared with example 1, an MO resistor diameter of 60 mm was chosen here in order to achieve a lower lightning impulse protection level. This is usually a concern in resonant earthed and isolated neutral systems because of the required high continuous operating voltage. Also see example 6, compared with example 7.

{ratios = 2.35 $_{8/20}$, 1.88 $_{30/60}$, and 2.49 $_{1/2}$}

The resulting protective characteristics*:

- lightning impulse protective level ($\hat{u}_{10\,kA,\,8/20\,\mu s}$): 367 kV[1] { Ratio= 2.35 }
  (in accordance with the German application guide DIN EN 60099-5/VDE 0675, Part 5: lightning impulse protective level ≤ 370 kV)
- switching impulse protective level ($\hat{u}_{0{,}5\,kA,\,30/60\,\mu s}$): 294 kV { Ratio= 1.88 }
- steep current impulse protective level ($\hat{u}_{10\,kA,\,1/2\,\mu s}$): 389 kV { Ratio= 2.49 }

Checking the protective values:

- $BIL/\hat{u}_{10\,kA,\,8/20\,\mu s}$ = 550 kV/367 kV = 1.5 → generally sufficient

Height of the MO resistor column:

- h_{MO} = 1260* mm

Selecting a Housing

Minimal requirements:

- lightning impulse withstand voltage =
  1.3 · lightning impulse protective level = 1.3 · 367 kV = 447 kV
- power-frequency withstand voltage 1 min, wet =
  $1.06/\sqrt{2}$ · switching impulse protective level = $1.06/\sqrt{2}$ · 294 kV = 221 kV
- creepage distance: 16 mm/kV · 123 kV = 1968 mm
- permissible head load static: 400 N
- permissible head load dynamic: 1000 N
- rated short-circuit current: 40 kA
- possible length of the active part: 1260 mm
- number of units: 1
- grading ring: no

Example 3: "Solidly earthed neutral 220-kV-system"

(All the information which is asterisked (*) are typical. Individually, however, these are manufacturer-dependent values.)

Tacitly assumed, if no further information is given and no special requests are made:

- $U_s = U_m = 245$ kV {standard Us}
- standard lightning impulse withstand voltage (BIL) of equipment = 950 kV {standard BIL}
- earth fault factor k = 1.4 {system analysis}
- maximum duration of temporary overvoltage: 10 s {system analysis}
- required nominal discharge current $I_n = 10$ kA {lightning overvoltage analysis}
- required line discharge class: 3 {lightning overvoltage and v(t).i(t) integral analysis}
- pollution level I {not so polluted}
- maximum short-circuit current: 50 kA

Determining the minimally required continuous operating and rated voltage

- $U_{c,\,min} = 1.05 \cdot U_s/\sqrt{3} = 1.05 \cdot 245/\sqrt{3}$ kV = 149 kV
- $U_{r1,\,min} = 1.25^* \cdot U_{c,\,min} = 1.25^* \cdot 149$ kV = 187 kV
- $U_{r2,\,min} = 1.4 \cdot (U_s/\sqrt{3}) / k_{tov,\,10\,s} = 1.4 \cdot (245/\sqrt{3}) / 1.075^*$ kV = 185 kV

  ($k_{tov,\,10\,s}$ from Figure 19)

Establishing the actual continuous operating and rated voltage:

- $U_r = U_{r1,\,min}$ rounded up to the next value divisible by 3 = 189 kV
  Normally an arrester with a rated voltage of at least 198 kV is used in this system. This leads to a considerably more stable layout, and nevertheless offers a sufficiently low protective level.
- U_r = 198 kV
- $U_c = U_r/1.25^* = 198\ kV/1.25^* = 158\ kV$

Selecting an MO resistor suitable for I_n = 10 kA and LD-class 3

- MO diameter: 60* mm {ratio = 2.45 for class 3, and = 2.35 for class 2}
- $\hat{u}_{10\,kA}/U_r$ = 2.45* (This factor is characteristic for the MO resistor used when configuring it for the line discharge class 3. Compare with example 2!)

{ratios = 2.45 $_{8/20}$, 2.03 $_{30/60}$, and 2.6 $_{1/2}$}

The resulting protective characteristics*:

- lightning impulse protective level ($\hat{u}_{10\,kA,\ 8/20\,\mu s}$): 485 kV
- switching impulse protective level ($\hat{u}_{1\,kA,\ 30/60\,\mu s}$): 402 kV
- steep current impulse protective level ($\hat{u}_{10\,kA,\ 1/2\,\mu s}$): 514 kV

Checking the protective values:

- BIL/$\hat{u}_{10\,kA,\,8/20\,\mu s}$ = 950 kV/485 kV = 1.96 → definitely sufficient

Height of the MO resistor column:

- h_{MO} = 1670* mm

Selecting a Housing

Minimal requirements:

- lightning impulse withstand voltage = 1.3 · lightning impulse protective level = 1.3 · 485 kV = 631 kV
- power-frequency withstand voltage 1 min, wet = $1.06/\sqrt{2}$ · switching impulse protective level = $1.06/\sqrt{2}$ · 402 kV = 302 kV
- creepage distance: 16 mm/kV · 245 kV = 3920 mm
- permissible head load static: 400 N
- permissible head load dynamic: 1000 N
- rated short-circuit current: 50 kA
- possible length of the active part: 1670 mm
- number of units: 1 (Borderline case when using a porcelain housing!)
- grading ring: no (Borderline case! If this arrester – for example, because of higher creepage distance requirements – were designed in two parts, a grading ring would indeed be required.)

Example 4: "Solidly earthed neutral 380-kV-system; industrial pollution"

(All the information which is asterisked (*) are typical. Individually, however, these are manufacturer-dependent values.)

Tacitly assumed, if no further information is given and no special requests are made:

- $U_s = U_m = 420$ kV
- standard lightning impulse withstand voltage (BIL) of equipment = 1425 kV
- earth fault factor k = 1.4
- maximum duration of temporary overvoltage: 10 s
- required nominal discharge current $I_n = 10$ kA
- required line discharge class: 3
- pollution level III
- maximum short-circuit current: 50 kA

{for the 60 mm arrester, $U_{10kA,8/20}/U_r = 2.45$, **$U_{0.5kA,30/60}/U_r = 2.03$**, and $U_{10kA,1/2}/U_r = 2.6$}

Determining the minimally required continuous operating and rated voltage

- $U_{c,\,min} = 1.05 \cdot U_s/\sqrt{3} = 1.05 \cdot 420/\sqrt{3}$ kV = 255 kV
- $U_{r1,\,min} = 1.25^* \cdot U_{c,\,min} = 1.25^* \cdot 255$ kV = 319 kV
- $U_{r2,\,min} = 1.4 \cdot (U_s/\sqrt{3}) / k_{tov,\,10\,s} = 1.4 \cdot (420/\sqrt{3}) / 1.075^*$ kV = 316 kV

  ($k_{tov,\,10\,s}$ from Figure 19)

(U_m) kV (r.m.s. value)	Longitudinal insulation [a] kV (peak value)	kV (peak value)	(ratio to the phase-to-earth peak value)	withstand voltage [b] kV (peak value)
300 [c]	750	750	1,50	850
				950
	750	850	1,50	950
				1050
362	850	850	1,50	950
				1050
	850	950	1,50	1050
				1175
420	850	850	1,60	1050
				1175
	950	950	1.50	1175
				1300
	950	1050	1,50	1300
				1425
550	950	950	1,70	1175
				1300
	950	1050	1,60	1300
				1425
	950 1050	1175	1,50	1425
				1550
				1675

Establishing the actual continuous operating and rated voltage:

- $U_r = U_{rl,\,min}$ rounded up to the next value divisible by 3 = 321 kV
  Normally an arrester with a rated voltage of at least 336 kV is used in this system. This leads to a considerably more stable layout and nevertheless offers a sufficiently low protective level.
- U_r = 336 kV
- $U_c = U_r/1.25^*$ = 336 kV/1.25* = 268 kV

Selecting an MO resistor suitable for I_n = 10 kA and LD-class 3

- MO diameter: 60* mm
- $\hat{u}_{10\,kA}/U_r$ = 2.45* (This factor is characteristic for the MO resistor used when configuring it for the line discharge class 3. Compare with example 2!)

The resulting protective characteristics*:

- lightning impulse protective level ($\hat{u}_{10\,kA,\,8/20\,\mu s}$): 823 kV
- switching impulse protective level ($\hat{u}_{1\,kA,\,30/60\,\mu s}$): 683 kV
- steep current impulse protective level ($\hat{u}_{10\,kA,\,1/2\,\mu s}$): 872 kV

Checking the protective values:

- $BIL/\hat{u}_{10\,kA,\,8/20\,\mu s}$ = 1425 kV/823 kV = 1.73 → definitely sufficient

Height of the MO resistor column:

- h_{MO} = 2820* mm

Selecting a Housing

Minimal requirements:

- lightning impulse withstand voltage =
  1.3 · lightning impulse protective level = 1.3 · 823 kV = 1070 kV
- switching impulse withstand voltage =
  1.25 · switching impulse protective level = 1.25 · 683 kV = 854 kV
- creepage distance: 25 mm/kV · 420 kV = 10500 mm
- permissible head load static: 400 N
- permissible head load dynamic: 1000 N
- rated short-circuit current: 50 kA
- possible length of the active part : 2820 mm (2 · 1410 mm)*
- number of units: 2*
- grading ring: yes

Example 5: "Solidly earthed neutral 500-kV-system; special requirements"

(All the information which is asterisked (*) are typical. Individually, however, these are manufacturer-dependent values.)

Tacitly assumed, if no further information is given and no special requests are made:

- $U_s = U_m = 550$ kV
- standard lightning impulse withstand voltage (BIL) of equipment = 1550 kV
- earth fault factor k = 1.4
- maximum duration of temporary overvoltage: 10 s
- required nominal discharge current $I_n = 20$ kA
- required line discharge class: 5
- pollution level I
- maximum short-circuit current: 50 kA

Special information and requirements:

- $U_s = 525$ kV
- switching impulse protective level ($\hat{u}_{2\,kA,\,30/60\,\mu s}$): 760 kV[1]
- energy absorption capability ≥ 5 MJ
- creepage distance 25 mm/kV
- seismic withstand capability: ground acceleration 0.5·g acc. to US standard IEEE 693 (→ arrester base acceleration 1·g)[2]

Determining the minimally required continuous operating and rated voltage

- $U_{c,\,min} = 1.05 \cdot U_s/\sqrt{3} = 1.05 \cdot 525/\sqrt{3}\,kV = 318\,kV$
- $U_{r1,\,min} = 1.25^* \cdot U_{c,\,min} = 1.25^* \cdot 318\,kV = 398\,kV$
- $U_{r2,\,min} = 1.4 \cdot (U_s/\sqrt{3}) / k_{tov,\,10\,s} = 1.4 \cdot (525/\sqrt{3}) / 1.075^*\,kV = 395\,kV$

  ($k_{tov,\,10\,s}$ from Figure 19)

Establishing the actual continuous operating and rated voltage:

- $U_r = U_{r1,\,min}$ rounded up to the next value divisible by 3 = 399 kV
- $U_c = U_{c,\,min} = 318$ kV

  In contrast to the previous examples, the minimum possible continuous operating and rated voltage are actually established here. Otherwise the required extremely low switching impulse protective level could not be attained.

Selecting an MO resistor suitable for I_n = 20 kA and LD-class 5

- MO diameter: 100* mm (alternatively: 2 · 70* mm, connected in parallel)
- $\hat{u}_{20\,kA}/U_r = 2.32^*$ (This factor is characteristic for the MO resistor(s) used.)

The resulting protective characteristics*:

- lightning impulse protective level ($\hat{u}_{20\,kA,\,8/20\,\mu s}$): 927 kV
- switching impulse protective level ($\hat{u}_{2\,kA,\,30/60\,\mu s}$): 760 kV
- energy absorption capability (thermal): 18 kJ/kV of U_r → 7.2 MJ total

Checking the protective values:

- $BIL/\hat{u}_{20\,kA,\,8/20\,\mu s}$ = 1550 kV/927 kV = 1.67 → definitely sufficient
- switching impulse protective level requirement fulfilled
- energy absorption capability requirement fulfilled

Height of the MO resistor column(s):

- h_{MO} = 3700* mm

Selecting a Housing (composite hollow core insulator* in order to fulfill the seismic requirements)

Minimal requirements:

- lightning impulse withstand voltage =
  1.3 · lightning impulse protective level = 1.3 · 927 kV = 1205 kV
- switching impulse withstand voltage =
  1.25 · switching impulse protective level = 1.25 · 760 kV = 950 kV
- creepage distance: 25 mm/kV · 525 kV = 13125 mm
- permissible head load dynamic: 16400 N (due to seismic requirements!)
- permissible head load static: 11500 N (= 70 % of the dynamic value)
- rated short-circuit current: 50 kA
- possible length of the active part : 3700 mm (2 · 1850 mm)*
- number of units: 2* (in porcelain 3* units would be necessary)
- grading ring: yes

Example 6: "Resonant earthed or isolated neutral 20-kV-system"

(All the information which is asterisked (*) are typical. Individually however, these are manufacturer-dependent values.)

Tacitly assumed, if no further information is given and no special requests are made:

- $U_s = U_m = 24$ kV
- standard lightning impulse withstand voltage (BIL) of equipment = 125 kV
- operation under earth fault conditions for > 30 min.
- required nominal discharge current $I_n = 10$ kA
- pollution level I
- maximum short-circuit current: 20 kA

{for the 50 mm arrester, $U_{10kA,8/20}/U_r = 2.667$, and $U_{10kA,1/2}/U_r = 2.83$}

Determining the minimally required continuous operating and rated voltage

- $U_{c,\,min} = U_s = 24$ kV
- $U_{r,\,min} = 1.25^* \cdot U_{c,\,min} = 1.25^* \cdot 24\text{ kV} = 30$ kV

  (The rated voltage, however, has no technical significance in a resonant earthed or isolated system.)

Establishing the actual continuous operating and rated voltage:

- $U_r = U_{r,\,min}$ rounded up to the next value divisible by 3 = 30 kV
- $U_c = U_r/1.25^* = 30\ kV/1.25^* = 24\ kV$

Selecting an MO resistor suitable for I_n = 10 kA

- MO diameter: 40* mm
- $\hat{u}_{10\,kA}/U_r = 2.667^*$ (This factor is characteristic for the MO resistor used if the protective level requirements of central European distribution systems must be met.)

The resulting protective characteristics*:

- lightning impulse protective level ($\hat{u}_{10\,kA,\ 8/20\,\mu s}$): 80 kV
  (in accordance with the German application guide DIN EN 60099-5/VDE 0675, Part 5: lightning impulse protective level ≤ 80 kV)
- steep current impulse protective level ($\hat{u}_{0,5\,kA,\ 30/60\,\mu s}$): 85 kV

Checking the protective values:

- $BIL/\hat{u}_{10\,kA,\ 8/20\,\mu s} = 125\ kV/80\ kV = 1.56 \rightarrow$ sufficient

Height of the MO resistor column:

- $h_{MO} = 200^*$ mm

Selecting a Housing (polymeric type)

Minimal requirements:

- lightning impulse withstand voltage =
  $1.3 \cdot$ lightning impulse protective level $= 1.3 \cdot 80$ kV $= 104$ kV
- power-frequency withstand voltage 1 min, wet =
  $0.88/\sqrt{2} \cdot$ lightning impulse protective level $= 0.88/\sqrt{2} \cdot 80$ kV $= 50$ kV
- creepage distance: 16 mm/kV $\cdot$ 24 kV = 384 mm
- permissible head load static: 400 N
- permissible head load dynamic: 600 N
- short circuit withstand capability: 20 kA
- possible length of the active part: 200 mm
- number of units: 1 (in medium voltage this is generally the case)
- grading ring: for medium voltage arresters this is generally not necessary

Example 7: "Solidly earthed neutral 20-kV-system"

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(All the information which is asterisked (*) are typical. Individually however, these are manufacturer-dependent values.)

Tacitly assumed, if no further information is given and no special requests are made:

- $U_s = U_m = 24$ kV
- standard lightning impulse withstand voltage (BIL) of equipment = 125 kV
- earth fault factor k = 1.4
- maximum duration of temporary overvoltage: 10 s
- required nominal discharge current $I_n = 10$ kA
- pollution level I
- maximum short-circuit current: 20 kA

Determining the minimally required continuous operating and rated voltage

- $U_{c,\,min} = 1.05 \cdot U_s/\sqrt{3} = 1.05 \cdot 24/\sqrt{3}$ kV = 14.6 kV
- $U_{r1,\,min} = 1.25^* \cdot U_{c,\,min} = 1.25^* \cdot 14.5$ kV = 18.2 kV
- $U_{r2,\,min} = 1.4 \cdot (U_s/\sqrt{3}) / k_{tov,\,10\,s} = 1.4 \cdot (24/\sqrt{3}) / 1.0^*$ kV = 19.4 kV

  ($k_{tov,\,10\,s}$ is different from that of Figure 19 for the distribution arrester under consid-eration!)

Establishing the actual continuous operating and rated voltage:

- $U_r = U_{r2,\,min}$ rounded up to the next value divisible by 3 = 21 kV
- $U_c = U_r/1.25^* = 21\ kV/1.25^* = 16.8\ kV$

Selecting an MO resistor suitable for I_n = 10 kA

- MO diameter: 40* mm
- $\hat{u}_{10\,kA}/U_r = 2.76^*$ (This factor is characteristic for the MO resistor used if there are no particular protective level requirements.)

The resulting protective characteristics*:

- lightning impulse protective level ($\hat{u}_{10\,kA,\ 8/20\,\mu s}$): 58 kV
- steep current impulse protective level ($\hat{u}_{0{,}5\,kA,\ 30/60\,\mu s}$): 62 kV

Checking the protective values:

- $BIL/\hat{u}_{10\,kA,\ 8/20\,\mu s} = 125\ kV/58\ kV = 2.15 \rightarrow$ definitely sufficient

Height of the MO resistor column:

- h_{MO} = 135* mm

Selecting a Housing (polymeric type)

Minimal requirements:

- lightning impulse withstand voltage =
  1.3 · lightning impulse protective level = 1.3 · 58 kV ≈ 76 kV
- power-frequency withstand voltage 1 min, wet =
  $0.88/\sqrt{2}$ · lightning impulse protective level = $0.88/\sqrt{2}$ · 58 kV ≈ 37 kV
- creepage distance: 16 mm/kV · 24 kV = 384 mm
- permissible head load static: 400 N
- permissible head load dynamic: 600 N
- short circuit withstand capability: 20 kA
- possible length of the active part: 135 mm
- number of units: 1 (in medium voltage this is generally the case)
- grading ring: for medium voltage arresters this is generally not necessary

Standards

a) IEC arrester standards and draft documents

IEC 60099-1, Edition 3.1, 1999-12

(Edition 3: 1991 consolidated with amendment 1: 1999)

Surge arresters – Part 1: Non-linear resistor type gapped surge arresters for a.c. systems

IEC 60099-4, Edition 1.1, 1998-08

(Edition 1: 1991 consolidated with amendment 1: 1998)

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

Note: Amendment 1 is "Annex F (normative): Artificial pollution test with respect to the thermal stress on porcelain-housed multi-unit metal-oxide surge arresters".

IEC 37/268/FDIS, July 13, 2001 [1]

Amendment 2 to IEC 60099-4 Ed1

IEC 60099-5, Edition 1.1, 2000-03

(Edition 1: 1996 consolidated with amendment 1: 1999)

Surge arresters – Part 5: Selection and application recommendations

Note: Amendment 1 is the new Section 6 "Diagnostic indicators of metal-oxide surge arresters in service".

IEC 37/261/CDV, November 17, 2000

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

b) IEC standards and draft documents on insulation coordination

IEC 60071-1, Seventh Edition, 1993-12

Insulation co-ordination – Part 1: Definitions, principles and rules

IEC 60071-2, Third Edition, 1996-12

Insulation co-ordination – Part 2: Application guide

IEC 28/138/CD, February 9, 2001

(IEC 60071-4, Ed. 1: Insulation co-ordination – Part 4: Computational Guide to Insulation Co-ordination & Modelling of Electrical Networks)

IEC 28/139/CDV, February 9, 2001

(IEC 60071-5: Insulation co-ordination – Part 5: Procedures for HVDC Converter Stations)

IEC 60060-1, Second Edition, 1989-11

High-voltage test techniques. Part 1: General definitions and test requirements

IEC 60507, Second edition 1991-04

Artificial pollution tests on high-voltage insulators to be used in a.c. systems

IEC 60672-3, Second Edition, 1997-10

Ceramic and glass-insulating materials – Part 3: Specifications for individual materials

IEC 60694, Second Edition, 1996-05

Common specifications for high-voltage switchgear and control standards

IEC/TR 60815, First edition, 1986-05

Guide for the selection of insulators in respect of polluted conditions

IEC 61166, First Edition, 1993-03

High-voltage alternating current circuit-breakers – Guide for seismic qualification of high-voltage alternating current circuit-breakers

IEEE Std 693 – 1997

Recommended Practice for Seismic Design of Substations

IEC 36/166/CD, January 28, 2001

(IEC 62073: Guide to the measurement of wettability of insulator surfaces)

HD 637 S1:1999

Power installations exceeding AC 1 kV

IEC 99/35/CD, 1998

Project IEC 61936-1 Ed. 1.0: Power installations exceeding 1 kV a.c. – Part 1: Common rules

DIN 48 113, September 1973

Stützisolatoren für Schaltgeräte und Schaltanlagen für Spannungen über 1 kV – Zuordnung der Begriffe für Biegefestigkeit *d) American standards on arresters and insulation coordination*

IEEE C62.11-1999

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

Note: This standard, in contrast to IEC 60099-4, applies to both MO arresters with and without gaps.

IEEE Std. C62.22-1997

IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems

IEEE Standard 1313.1-1996

IEEE Standard for Insulation Coordination – Definitions, Principles, and Rules

IEEE Standard 1313.2-1999

IEEE Guide for the Application of Insulation Coordination

Literature

Consult the following literature for further information on the fundamentals of MO arresters:

E. C. Sakshaug, J. S. Kresge, S. A. Miske

A new Concept in Station Arrester Design

IEEE Transactions on Power Apparatus and Systems, Vol. PAS-96, no. 2, March/April 1977, pp. 647 – 656

CIGRÉ Working Group 33.06

Metal-oxide surge arresters in AC systems

Part 1: General properties of the metal-oxide surge arrester

Part 2: Performance of metal-oxide surge arresters under operating voltage

Part 3: Temporary overvoltages and their stresses on metal-oxide surge arresters

ELECTRA 128, pp. 99-125

CIGRÉ Working Group 33.06

Metal-oxide surge arresters in AC systems

Part 4: Stresses in metal-oxide surge arresters due to temporary harmonic overvoltages

ELECTRA 130, pp. 78-115

CIGRÉ Working Group 33.06

Metal-oxide surge arresters in AC systems

Part 5: Protection performance of metal-oxide surge arresters

Part 6: Selection of metal-oxide surge arrester characteristics from the standards

ELECTRA 133, pp. 133-165

Examples:

Q.1 a) Briefly discuss the various factors that need to be considered when designing a gapless
surge arrester for a substation transformer protection.

(7 marks)

b) A 300 kV substation transformer in an isolated neutral system need to be protected by a surge arrester with a current rating of at least 20 kA and energy class 5 (corresponding to Ures 10kA, 8/20/Ur = 2.0, Ures 0.5kA, 30/60/Ur = 1.5). The transformer basic
lightning impulse withstand level is 1050 kV peak. The following information is available:

ZnO residual voltage/length = 280 V/mm, Level II Creepage length/voltage = 20 mm/kV, Switching impulse withstand voltage = 1.25 Ures 0.5kA, 30/60 (peak).

Design a suitable arrester for this transformer. Your design should include a suitable rated voltage of the arrester, corresponding protection level and margin of protection, length of the ZnO blocks required, lightning impulse withstand of the housing, power frequency withstand, creepage length (pollution level II is specified), number of housing unit required, and the requirement of a grading ring.

(10 marks)

Examples:

Q. Figure Q.1 (c) shows the applied voltage and leakage current of an MO arrester in a solidly earthed neutral 50 Hz system. Draw the equivalent circuit of the surge arrester, then determine:

i. the 3-phase system rated voltage

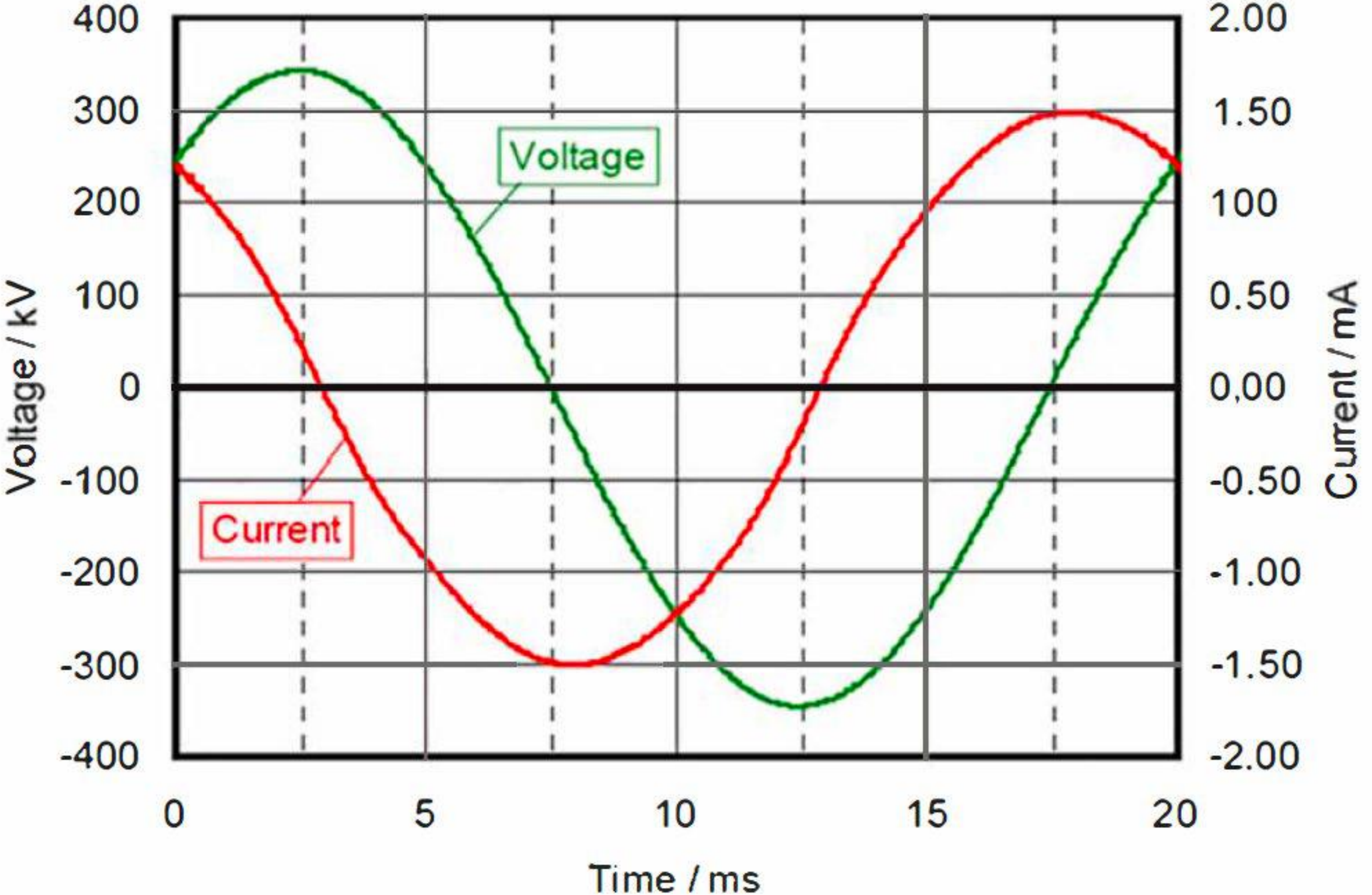
ii. the rms value of surge arrester resistive leakage current,

iii. the rms value of surge arrester capacitive leakage current,

iv. the equivalent capacitance of the ZnO surge arrester

Neglect all harmonic components.

(8 marks)


Voltage / kV
400
300
200
100
0
-100
-200
-300
-400
2.00
1.50
100
0.50
0,00
-0.50
-1.00
-1.50
-2.00
Current / mA
Voltage
Current
0
5
10
15
20
Time / ms

The following factors need to be considered:
i) the system voltage and neutral connection
system voltage and neutral connection influence maximum continuous voltage
ii) the maximum TOV level
Both of the above will determine the rated voltage of the arrester
iii) the nominal lightning current
is dependent on the circuits, surge magnitude level, and lightning probability
iv) the line discharge level or the switching overvoltage level
higher switching level means higher energy class is needed
v) the factors affecting the housing
-pollution level, short circuit level, static and dynamic force level, length of housing (must be less than 2m), requirement of grading rings (if longer than 1.5m)

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Q4 (b) $U_s = 300$ kV

isolated neutral → $U_c = 300$ kV

$U_{r_1} = 1.25 \times 300 = 375$ kV.

⇒ $U_r = 375$ kV #.

$U_c = 300$ kV

$U_{res} = 2 \times 375 = 750$ kV

margin of protection $= \frac{1050}{750} = 1.4$

∴ sufficient (just)

Block length $= \frac{750\text{k}}{280} = 2.6786$ m.

LIW for housing $= 1.3 \times 750 = 975$ kV

SIW for housing $= 1.25 \times 1.5 \times 375$

$= 703$ kV

Creepage length $= 300 \times 20$

$= 6000$ mm.

Number of units $= 2$ (> 2 m)

Grading ring ⇒ required (≥ 1.5 m).

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the 3-phase system rated voltage

Vp = 350kV -> Vrms = 247.5 kV -> V3p= 429 kV

ii. the rms value of surge arrester resistive leakage current,

Ip@Vp =0.15 mA -> Irms = 0.106 mA

4

MKEP 1543

iii. the rms value of surge arrester capacitive leakage current,

Ip =1.5 mA -> Irms = 1.061mA

iv. the equivalent capacitance of the ZnO surge arrester

Ic =Vc wC

C = Ic/(Vc . w) = 1.061m/(247.5k . 100.pi) = 13.65 pF