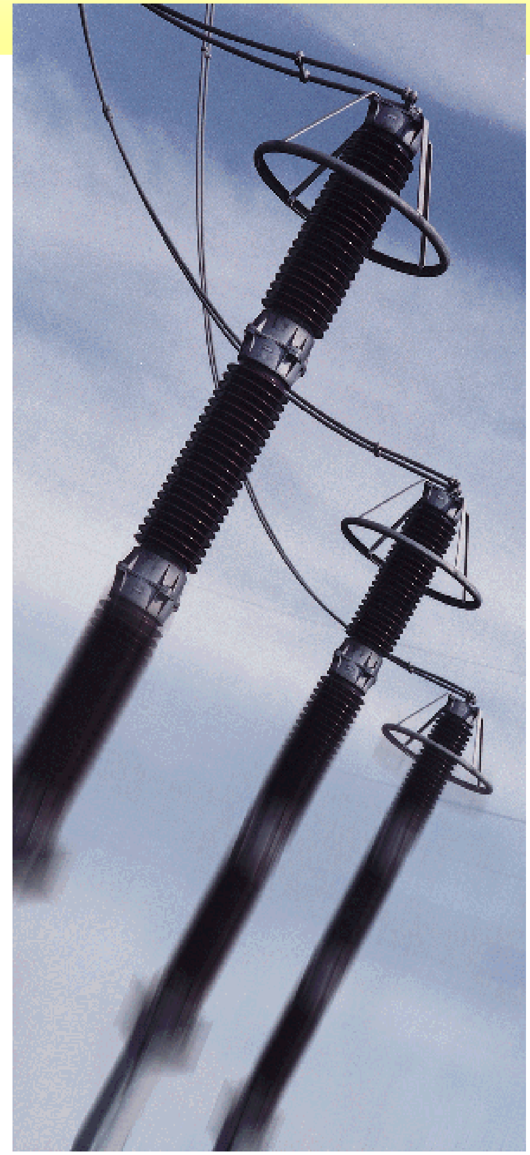
Tutorial on

Metal Oxide Surge Arresters

by

Volker Hinrichsen



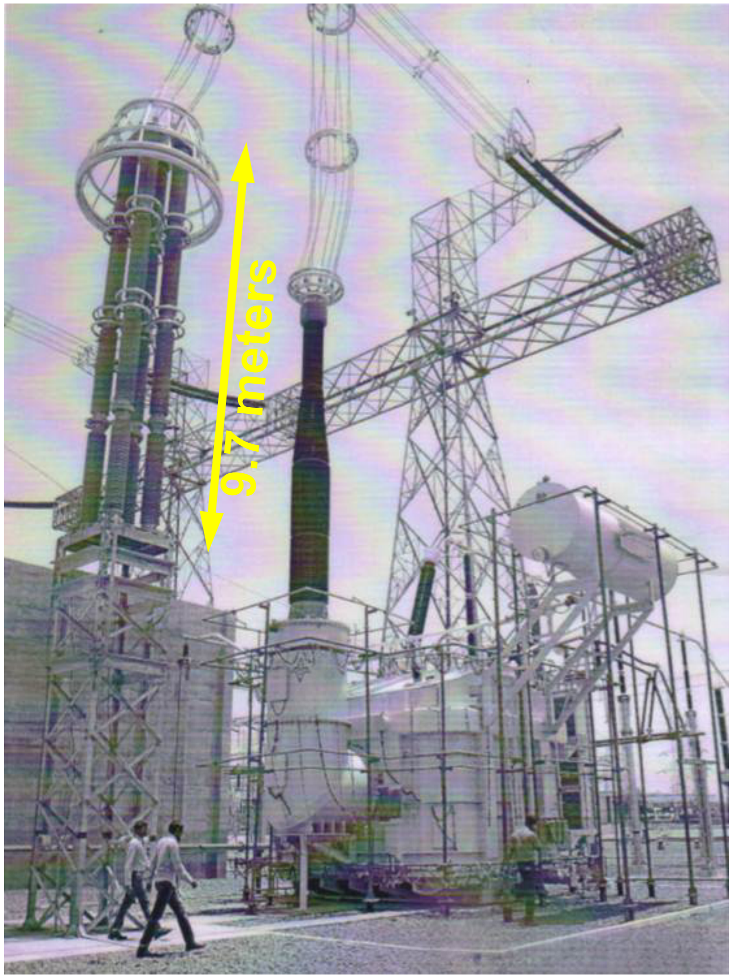
Contents

- **Part 1**
  - Arrester application in general
- **Part 2** (very short today)
  - Basic high-voltage arrester design
- **Part 3**
  - Configuring arresters
  - “Old” and “new” approaches (IEC 60099-4 Ed. 2.2 vs. Ed. 3.0)
- **Part 4** (depending on request and remaining time)
  - Special considerations on UHV arresters

Part 1: Arrester Application

Typical Arrester Application: Transformer Protection

Extreme Dimensions - 1200 kV Arresters (Examples)



OBLUM 1200 kV arrester

Siemens 1200 kV arrester

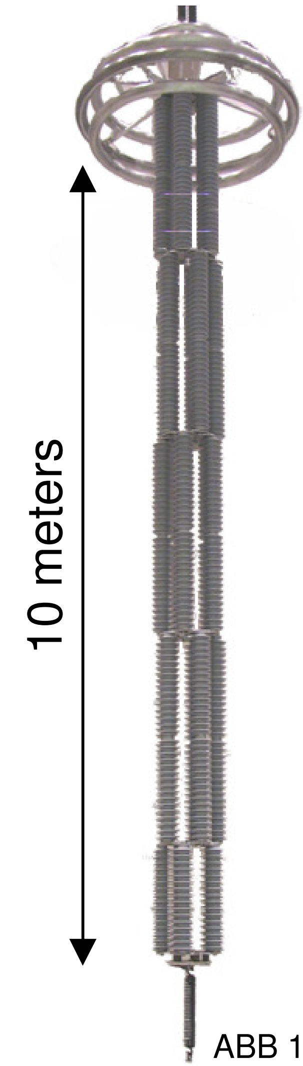
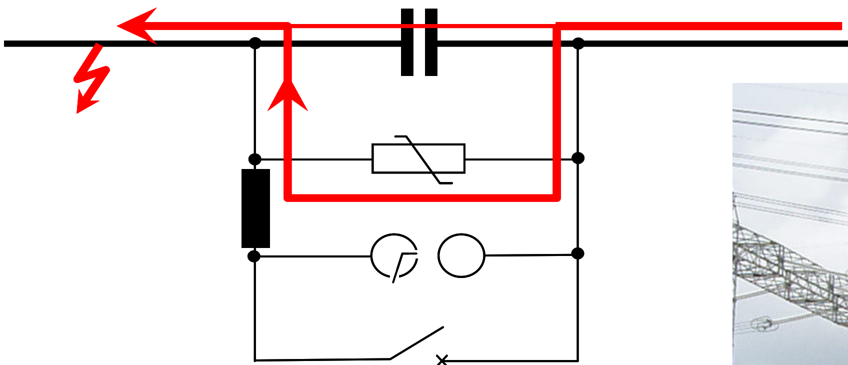


ABB 1200 kV arrester

Special Arrester Application: for FACTS

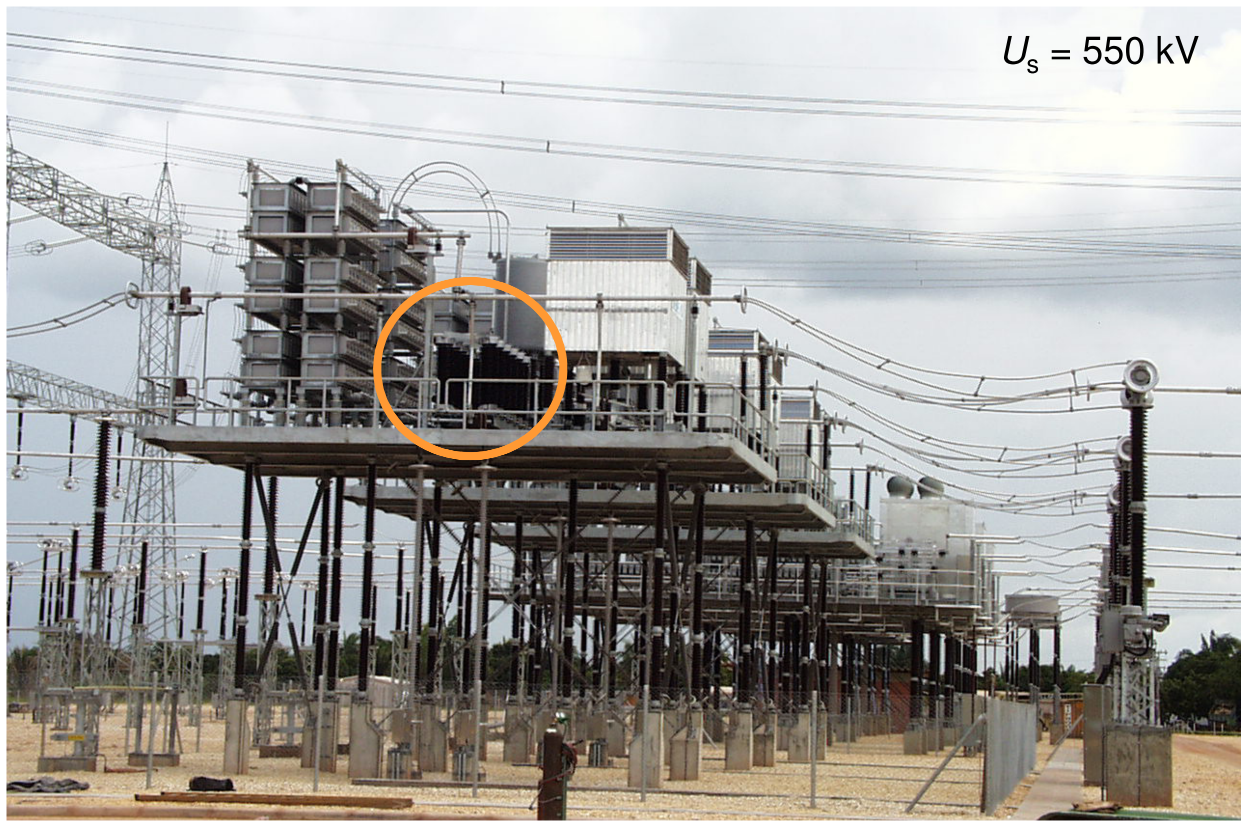
Example: **series capacitors**

Increasing application to be expected (UHV; extra long transmission lines)



Extreme energy injection in case of a line fault

Arrester **banks** (several ten or hundred MO columns in parallel)



Special Arrester Application: for FACTS

"Type A" Porcelain

Example: Siemens

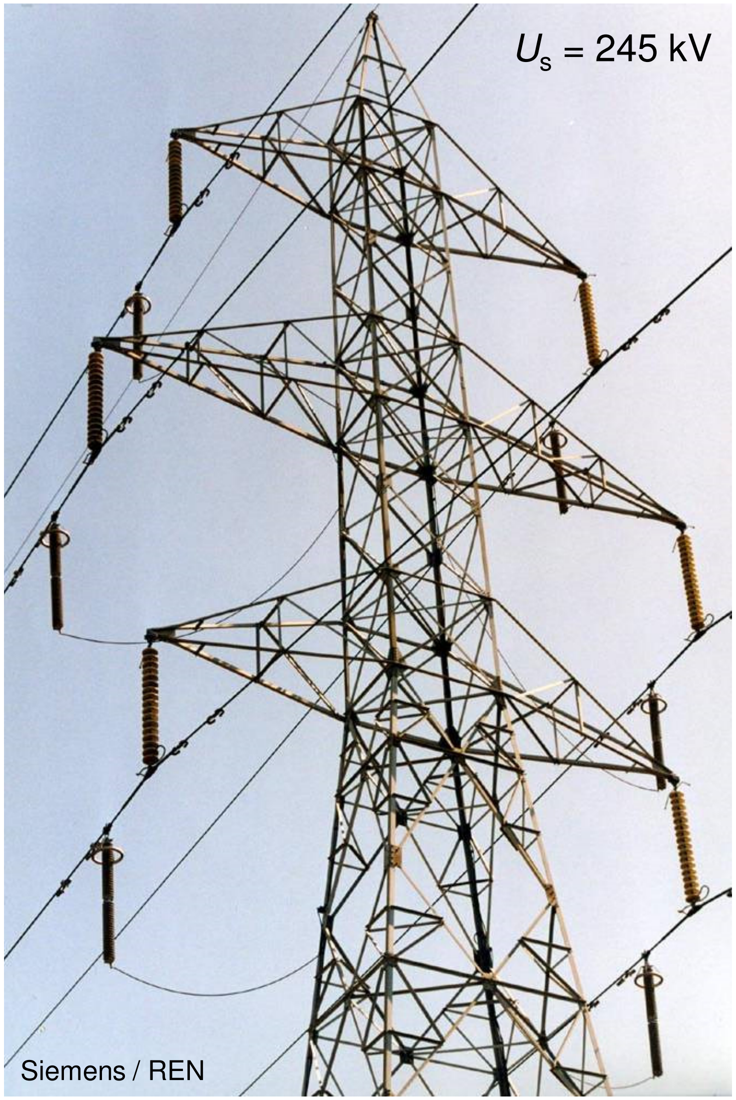
"Type A" Polymer

Example: Siemens

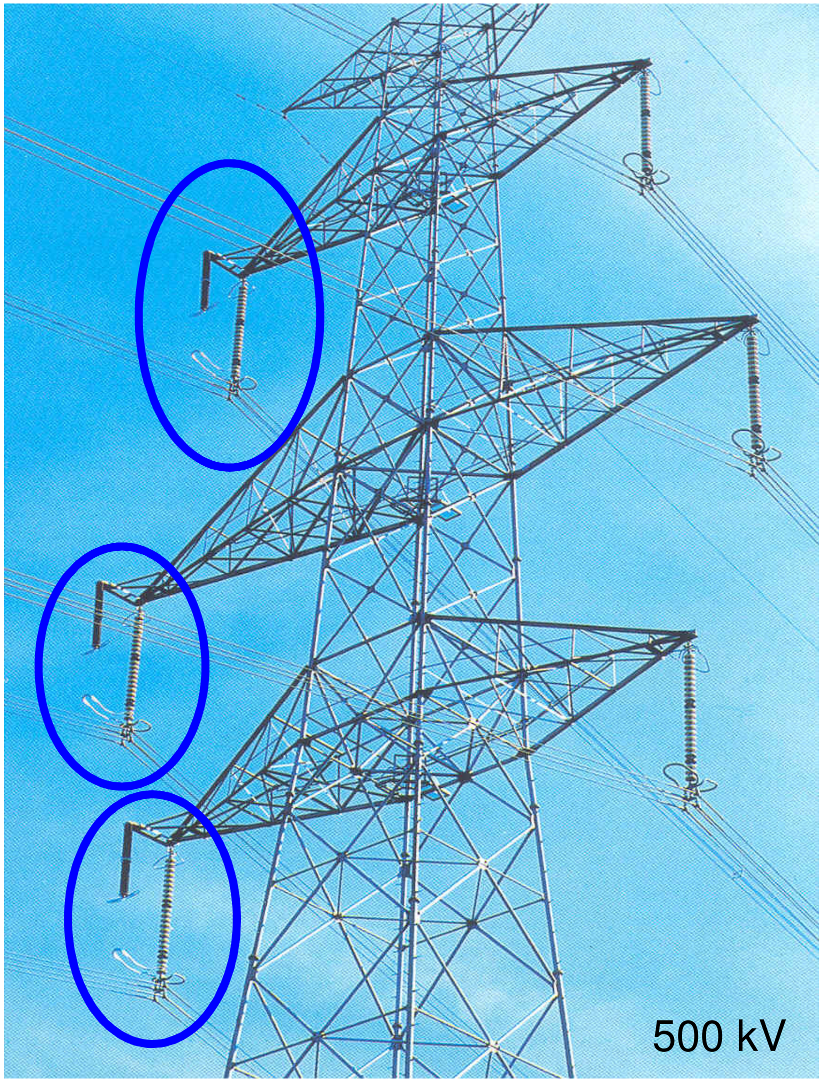
"Type B" Polymer

Example: ABB

Special Arrester Application: Line Arresters



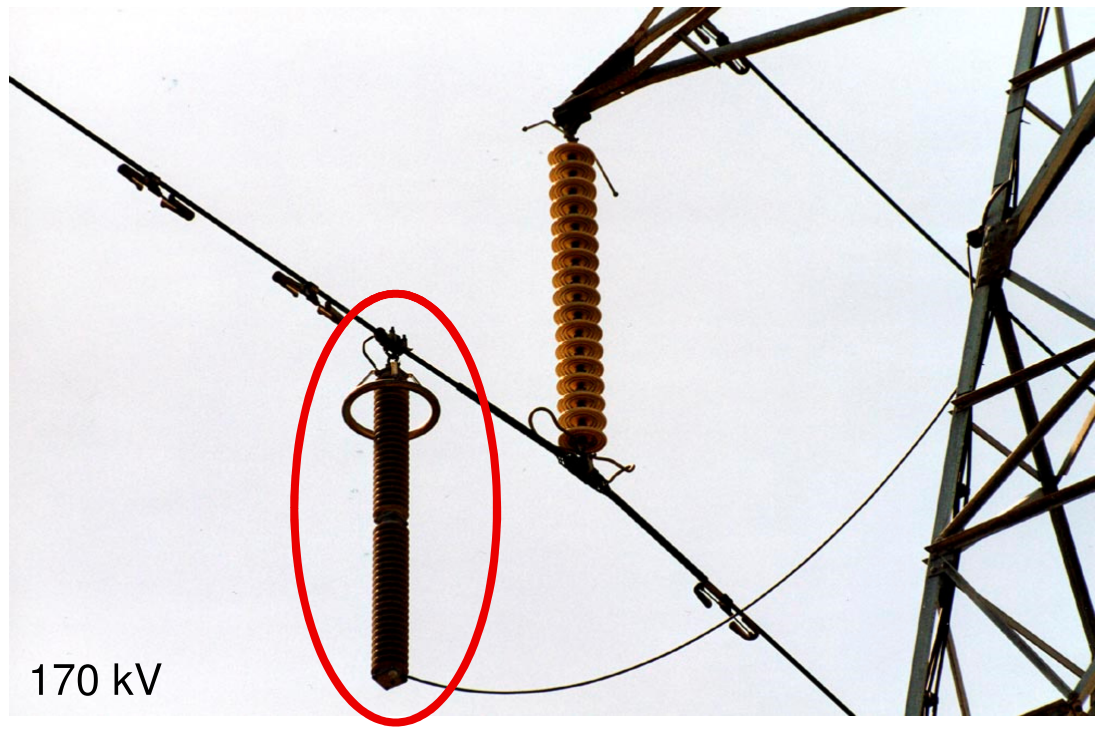
Transmission Line Arresters (TLA) – Classification



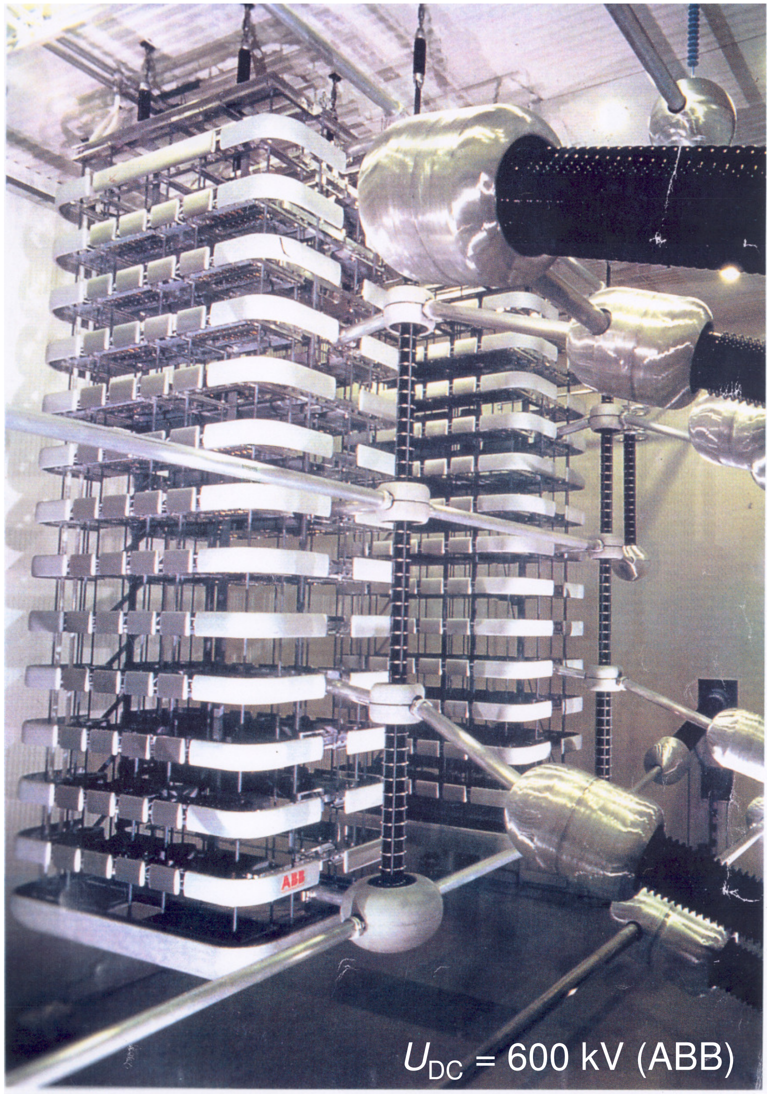
Gapped …

or

… gapless



Special Arrester Application: HVDC (Valve Protection) Arresters



U_{DC} = 600 kV (ABB)

U_{DC} = 600 kV (Siemens)

Fundamentals of Insulation Coordination – IEC 60071 Series

NORME INTERNATIONALE
INTERNATIONAL STANDARD

CEI
IEC
71-1

Septième édition
Seventh edition
1993-12

Coordination de l'isolement

Partie 1:
Définitions, principes et règles

Insulation co-ordination

Part 1:
Definitions, principles and rules

IEC

Numéro de référence
Reference number
CEI/IEC 71-1: 1993

NORME INTERNATIONALE
INTERNATIONAL STANDARD

CEI
IEC
71-2

Troisième édition
Third edition
1996-12

Coordination de l'isolement –

Partie 2:
Guide d'application

Insulation co-ordination –

Part 2:
Application guide

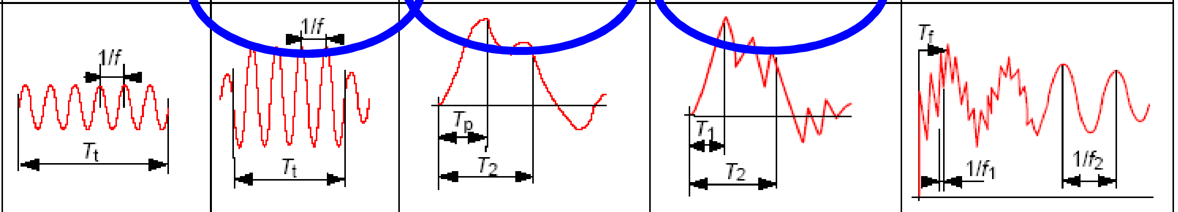
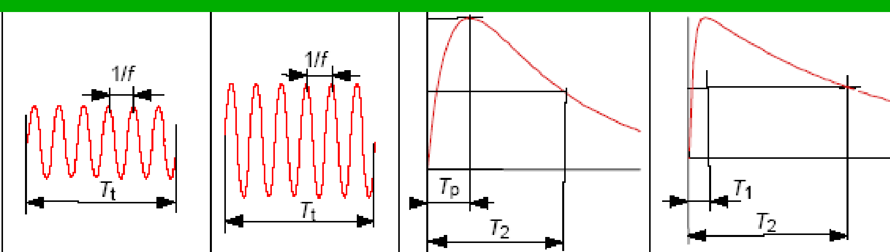
IEC

Numéro de référence
Reference number
CEI/IEC 71-2: 1996

Arresters are indispensable for insulation coordination in power systems; related IEC standards: 60071-1, 60071-2

Fundamentals of Insulation Coordination

IEC 60071-1
"Table 1 – Classes and shapes of overvoltages, Standard voltage shapes and Standard withstand voltages"

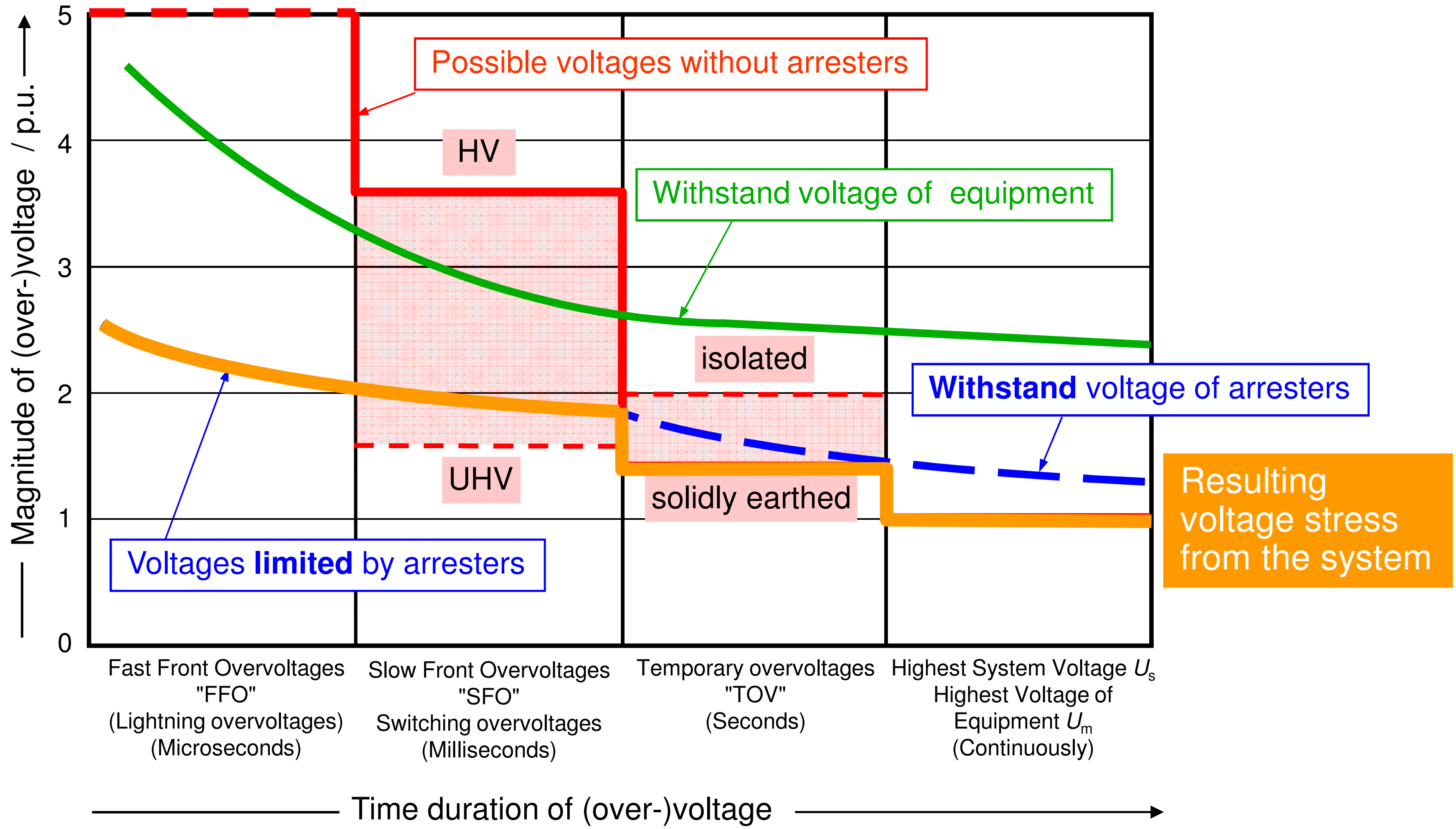
Class	Low frequency		Transient		
	Continuous	Temporary	Slow-front	Fast-front	Very-fast-front
Voltage or over-voltage shapes					
Range of voltage or over-voltage shapes	f = 50 Hz or 60 Hz $T_t \geq 3\,600$ s	10 Hz < f < 500 Hz 0,02 s ≤ T_t ≤ 3 600 s	20 µs < T_p ≤ 5 000 µs T_2 ≤ 20 ms	0,1 µs < T_1 ≤ 20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

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

System

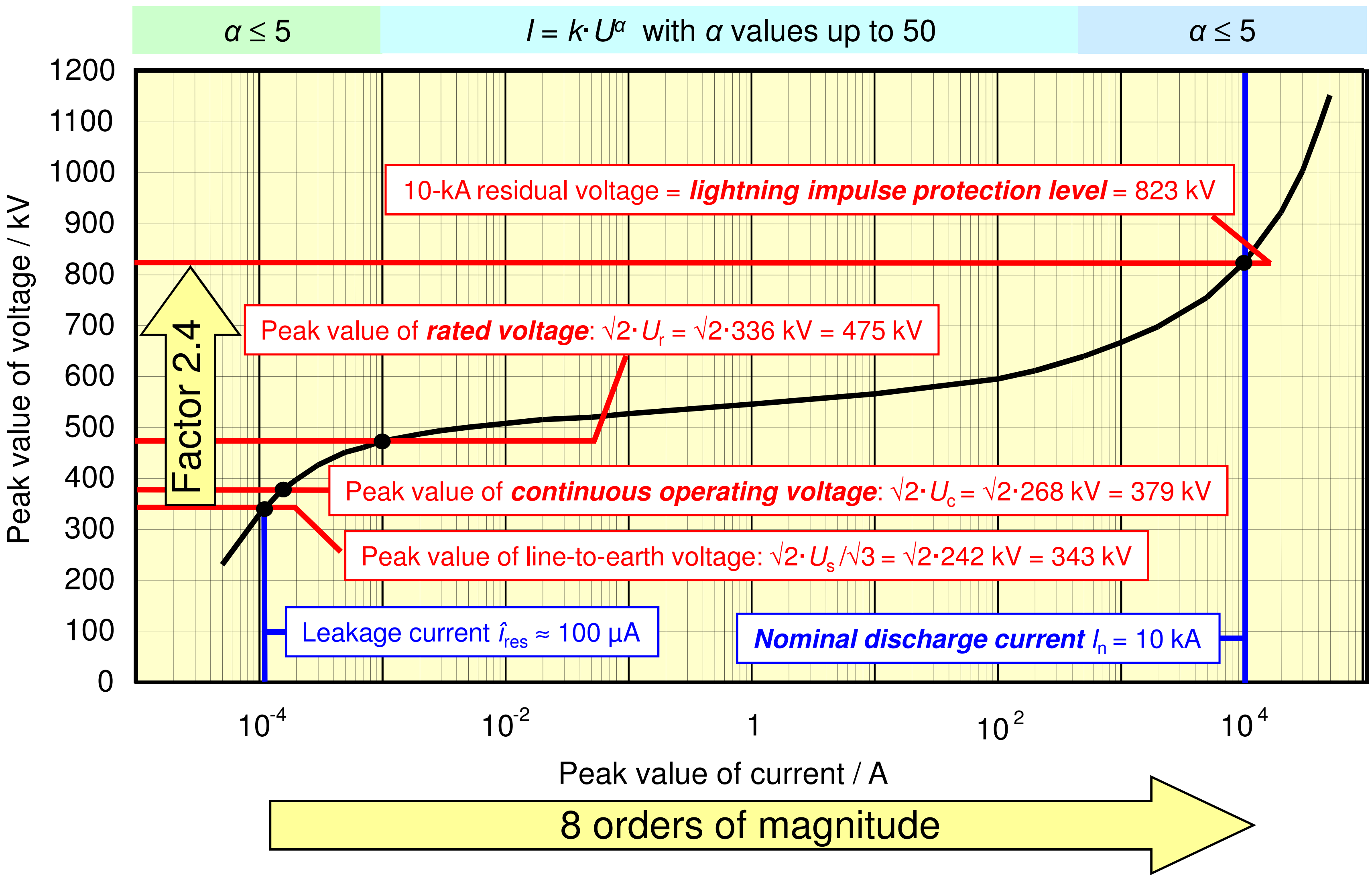
Laboratory

Insulation Coordination with the Help of Surge Arresters



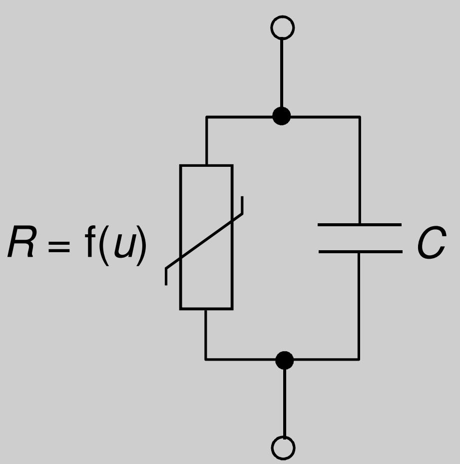
(Full red line: Example of a solidly earthed system, lower transmission voltage)

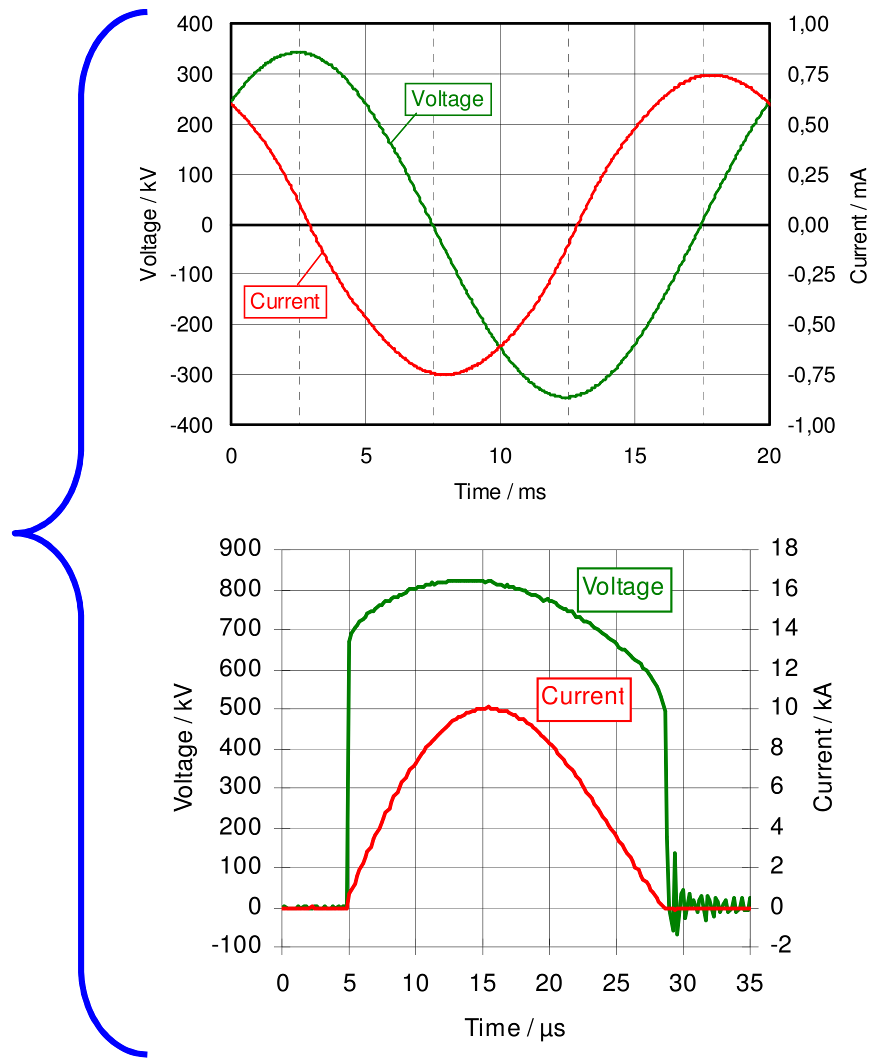
Voltage-Current Characteristic of an MO Arrester (U_s = 420 kV)



Voltage-Current Characteristic of an MO Arrester (U_s = 420 kV)

Simplified circuit diagram

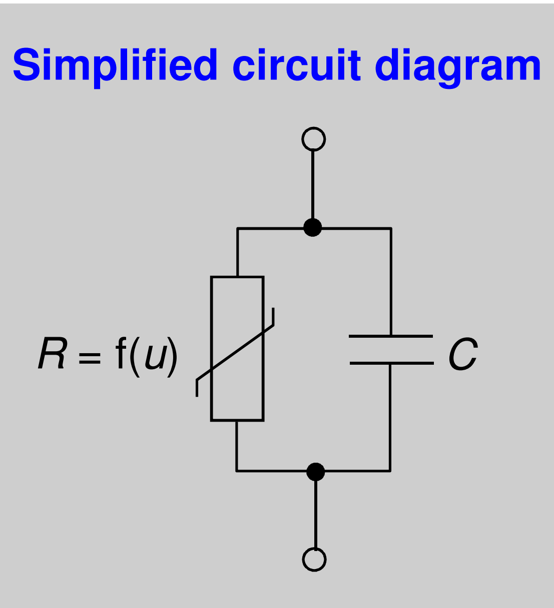


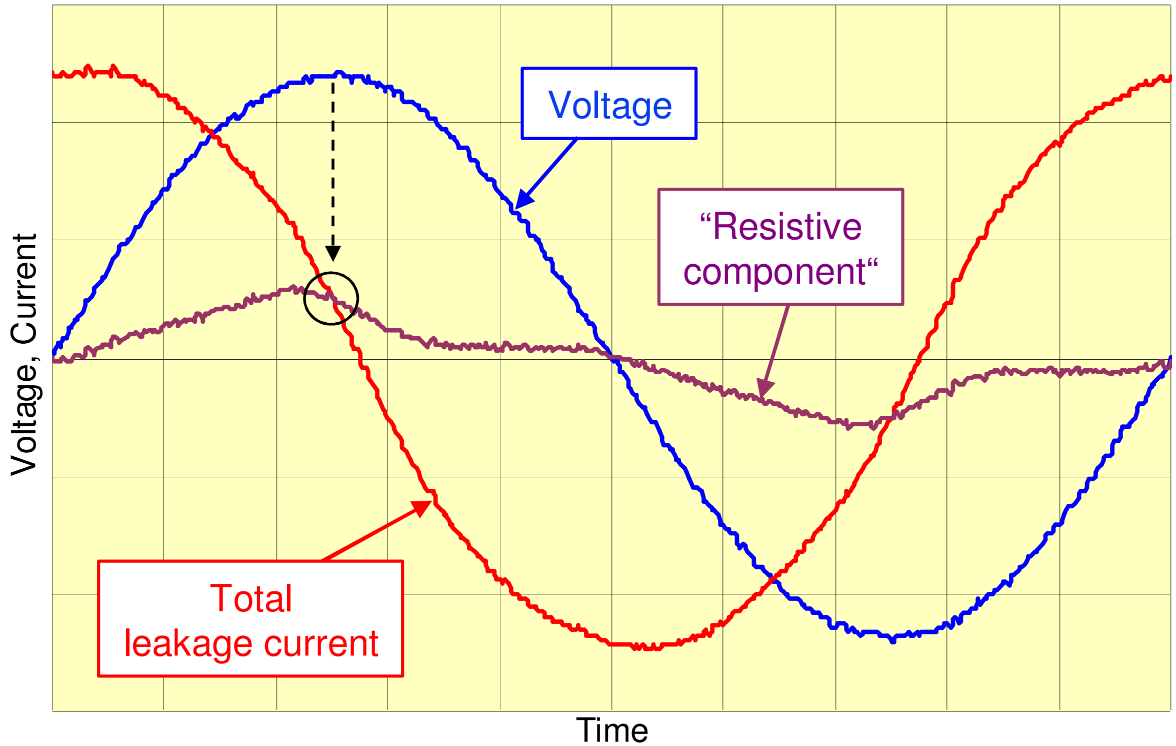


at $U = U_c$:
$I_{total} \approx 1$ mA

at $\hat{i} = I_n$:
$\hat{u} \approx 825$ kV

Voltage-Current Characteristic of an MO Arrester





at $U = U_c$:

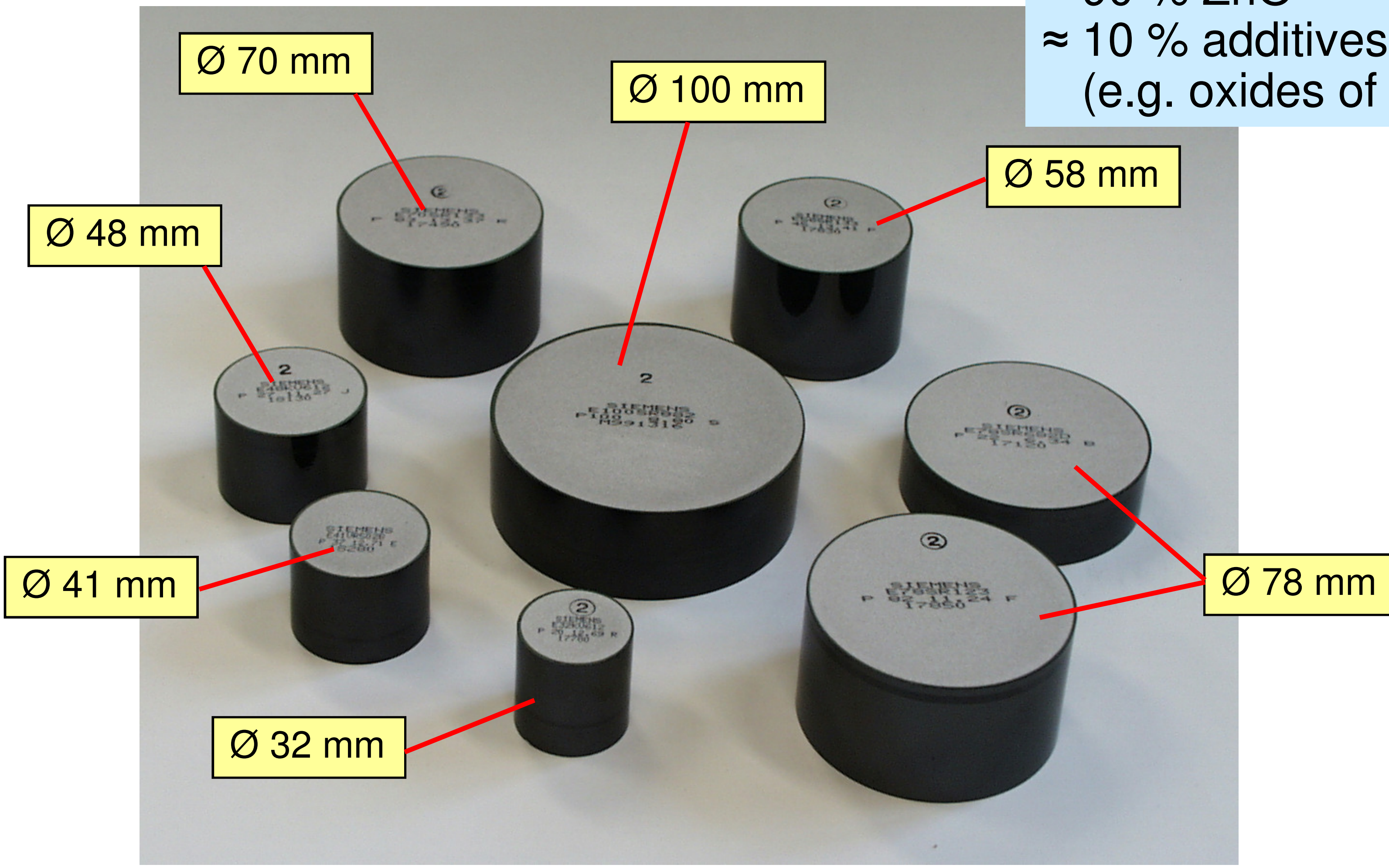
$I_{total} \approx 1$ mA

$I_{capacitive} \approx 1$ mA

$\hat{\imath}_{resistive} \approx 10\ \mu A \ldots 100\ \mu A$

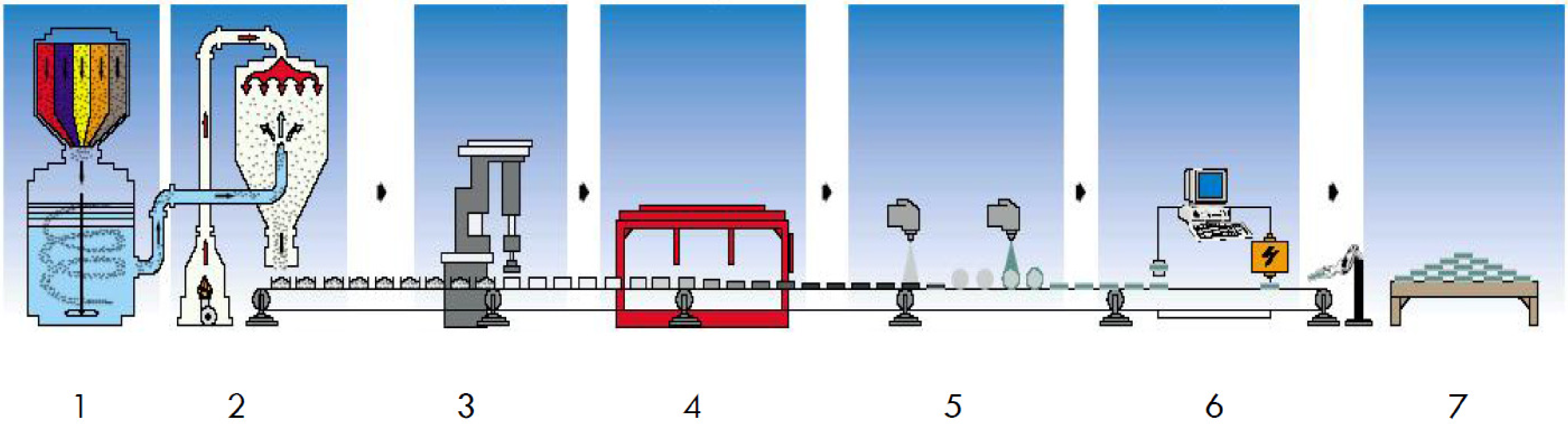
The Heart of an Arrester: MO Resistors

"MO"
≈ 90 % ZnO
≈ 10 % additives
(e.g. oxides of rare earths)



Example: Siemens/EPCOS

MO Resistors



1. Production of homogeneous slurry by wet-mixing of oxide powders
2. Drying and granulation in a spray dryer
3. Compacting the granulate to form resistor blocks
4. Sintering to obtain dense ceramic bodies
5. Addition of electrical contacts and a protective coating
6. Electrical testing
7. MO resistors ready for assembly

[Cigré TB 544]

MO Resistors

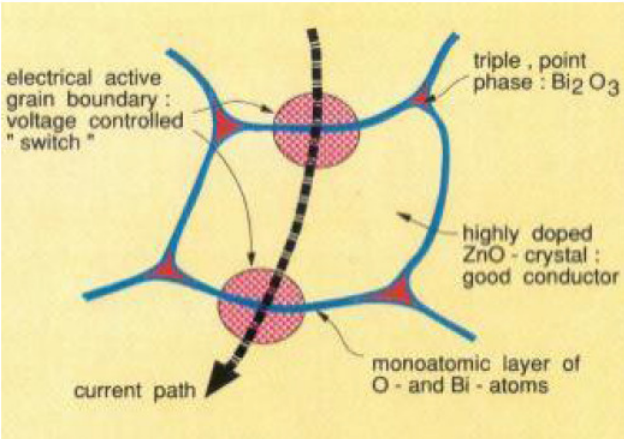


Figure 2.8: Schematic view of the "electrical" microstructure of a MO-varistor [Gre 1989]

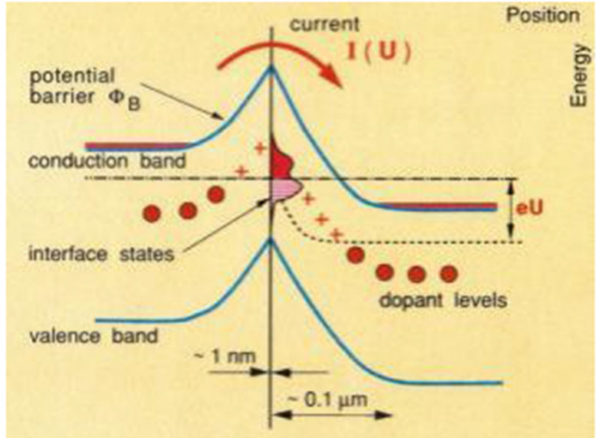
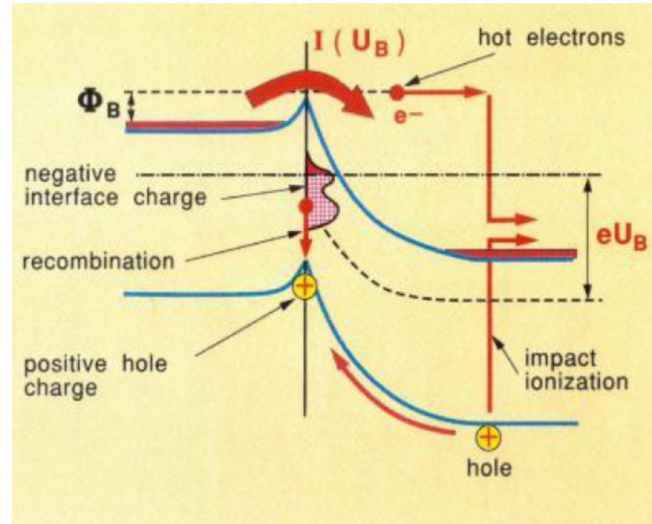
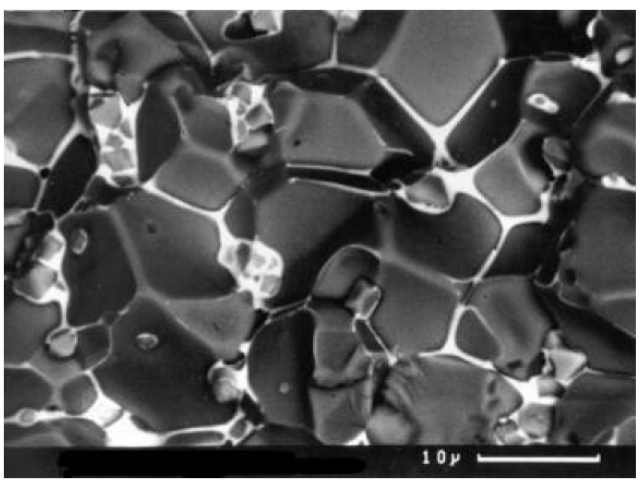
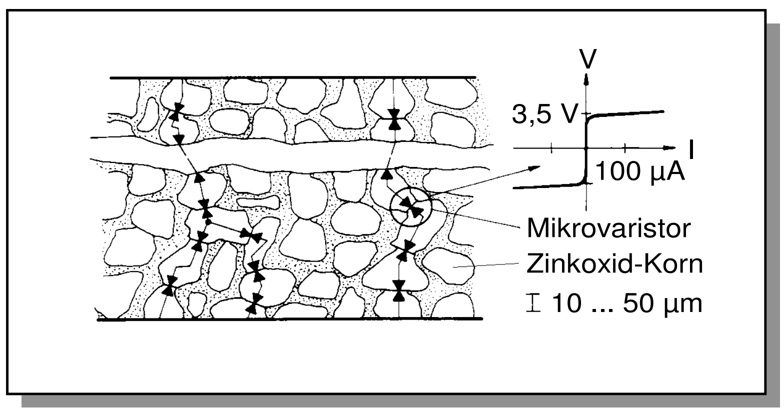


Figure 2.9: Band diagram of a single grain boundary, showing the Double Schottky Barriers DSB formed by charge trapping in interface states [Gre 1989] (dash-dotted/dotted lines: Fermi or quasi Fermi level [Bla 1986])



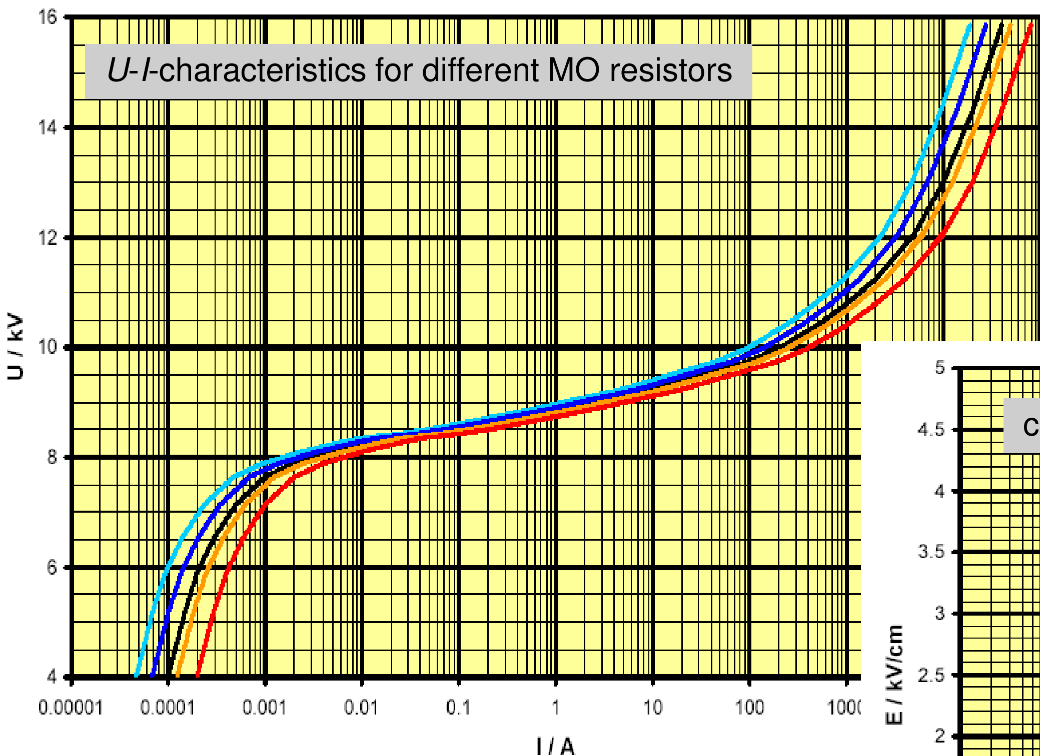
2.10: Band diagram scheme of the hole induced breakdown mechanism [Gre 1989]

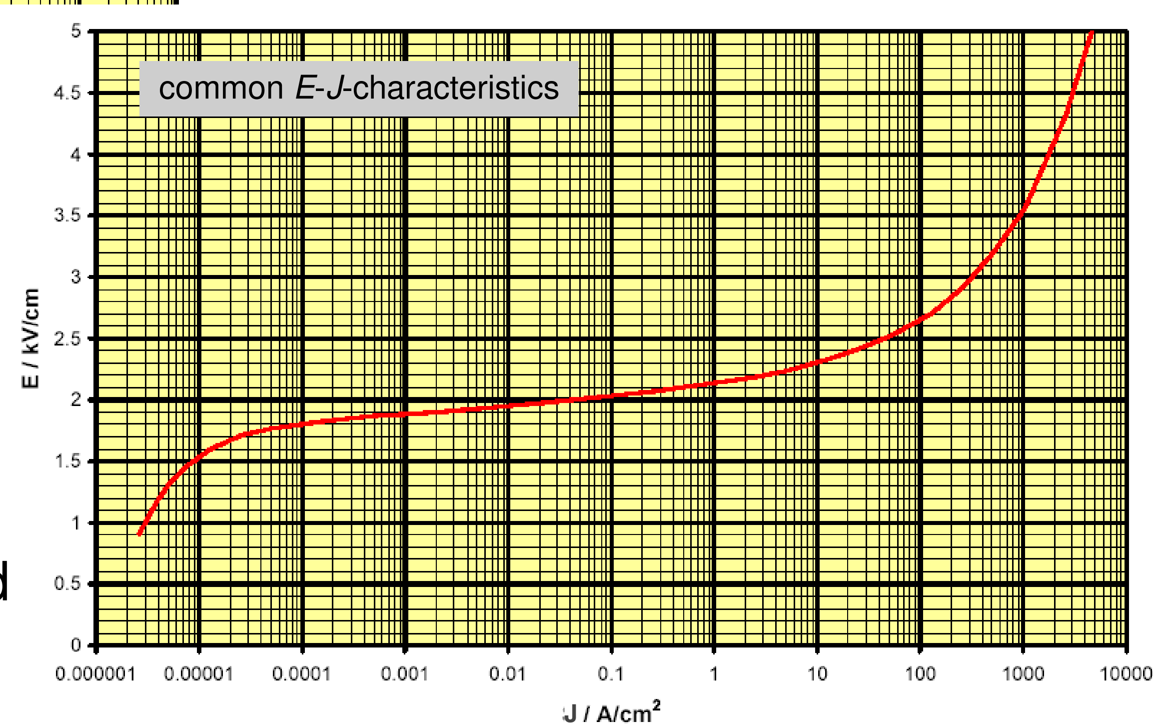




[Cigré TB 544]

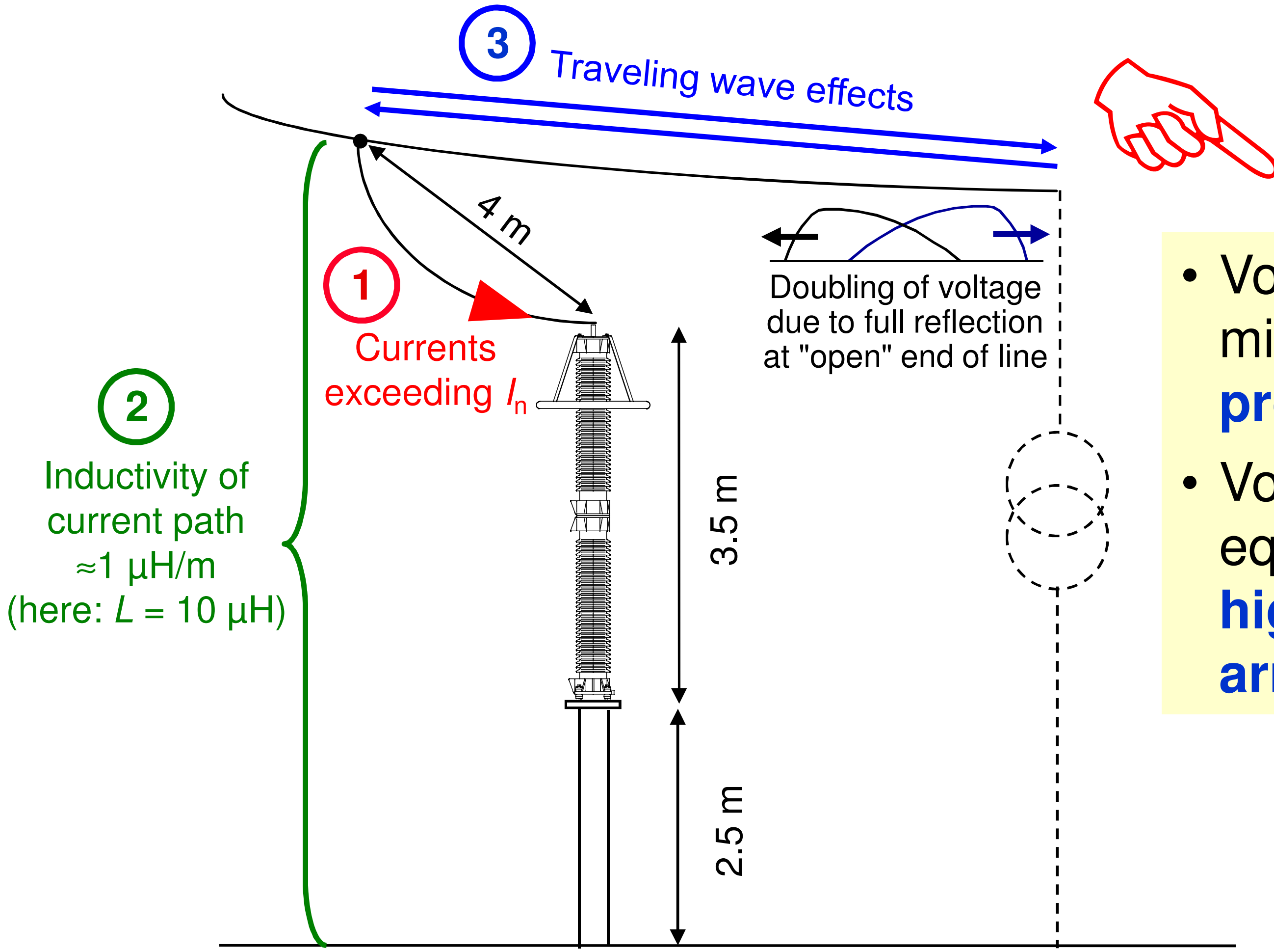
U-I- vs. *E-J-*Characteristics





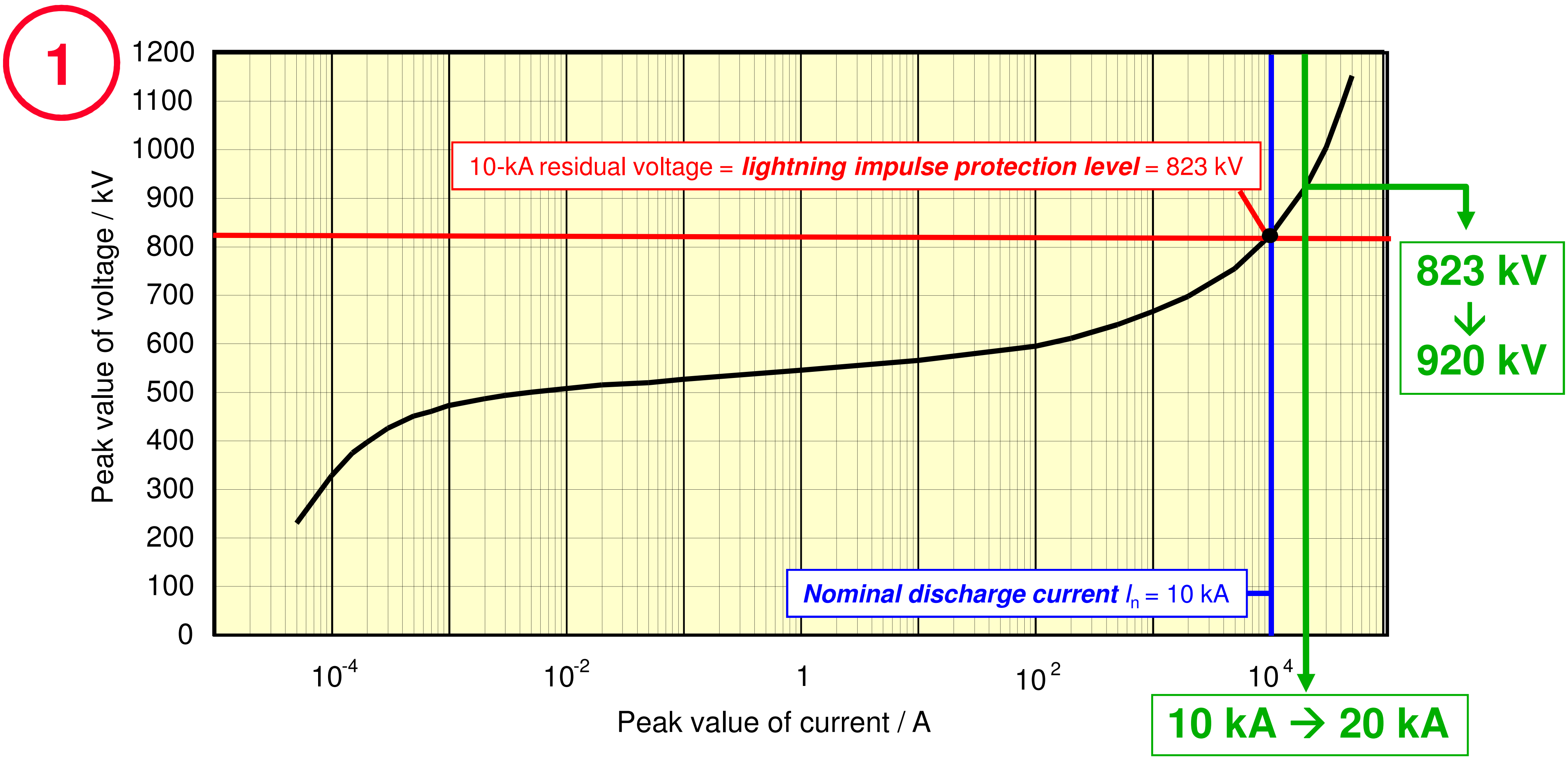
All *U-I*-characteristics based on the material's *E-J*-characteristics by choosing resistor diameter and height

LI Protection Characteristics



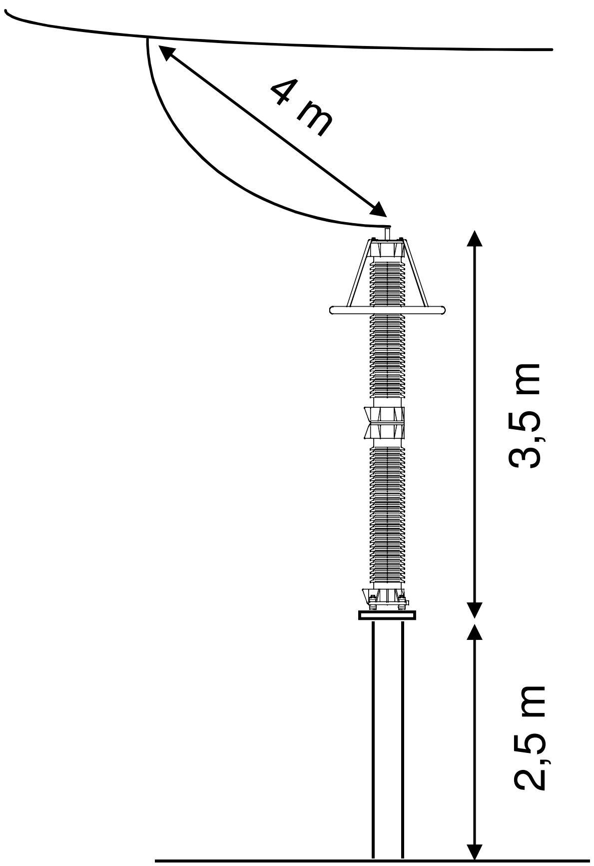
- Voltage at arrester terminal might be **higher than the LI protection level**
- Voltage at terminals of equipment to be protected are **higher than voltage at the arrester terminal**

Voltage-Current Characteristic of an MO Arrester (U_s = 420 kV)



Increase of Protection Voltage by Inductive Voltage Drops

2



Example: outdoor arrester U_s = 420 kV

U_r = 336 kV

$u_{10kA,\ 8/20\ \mu s}$ = 823 kV (= U_{pl})

$u_{10kA,\ 1/<20\ \mu s}$ = 872 kV (see next slide!)

Specific inductance of surge current path ≈ 1 µH/m

Length of surge current path ≈ 10 m

⇒ Inductance of surge current path ≈ 10 µH

Steepness of surge current impulse ≈ 10 kA/µs

⇒ Additional inductive voltage drop ≈ 100 kV

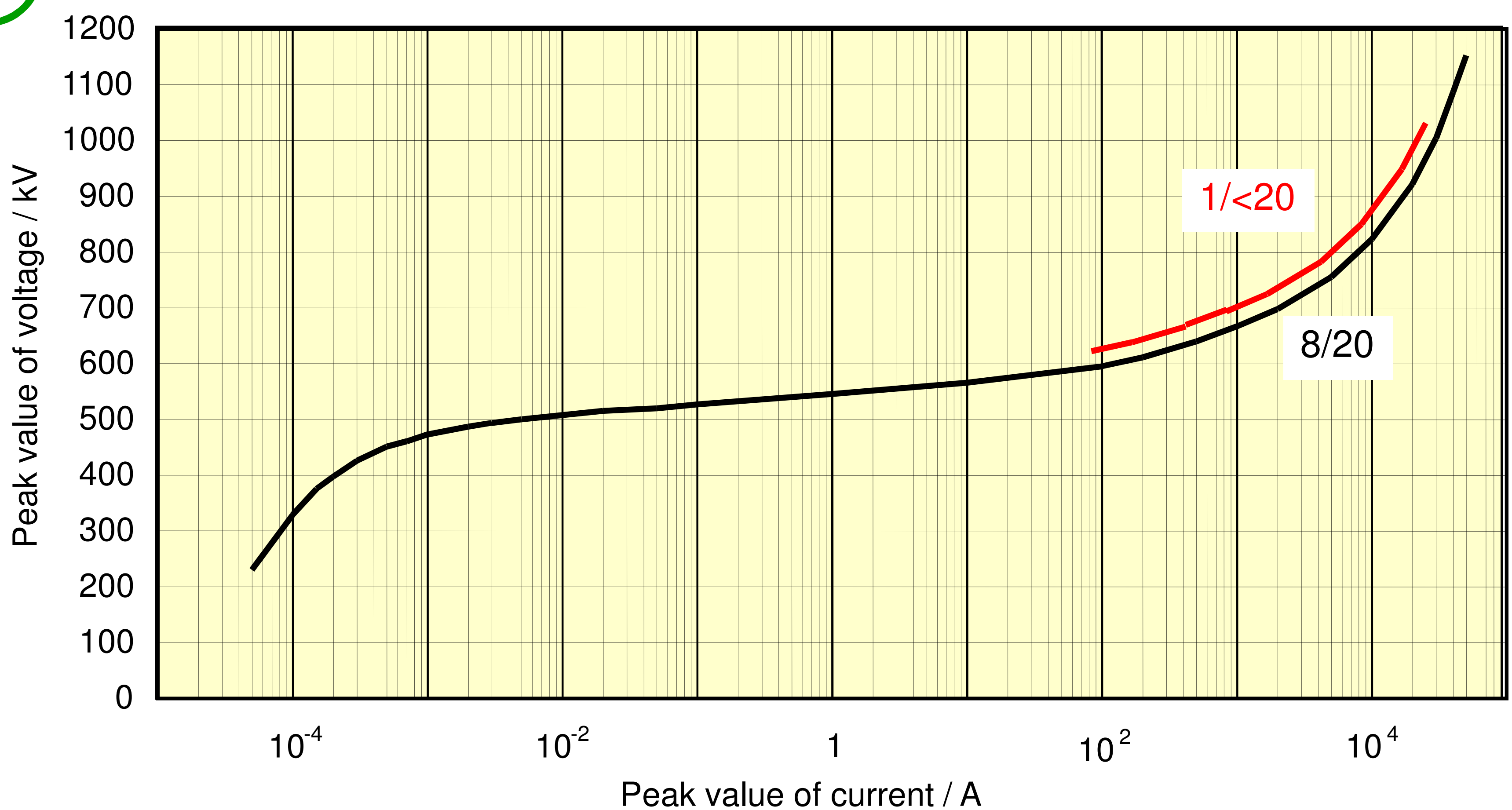
$\hat{U}_{resulting,\ 10\ kA,\ 1/<20}$ = 972 kV *)

*) worst case consideration

Voltage-Current Characteristic of an MO Arrester (U_s = 420 kV)

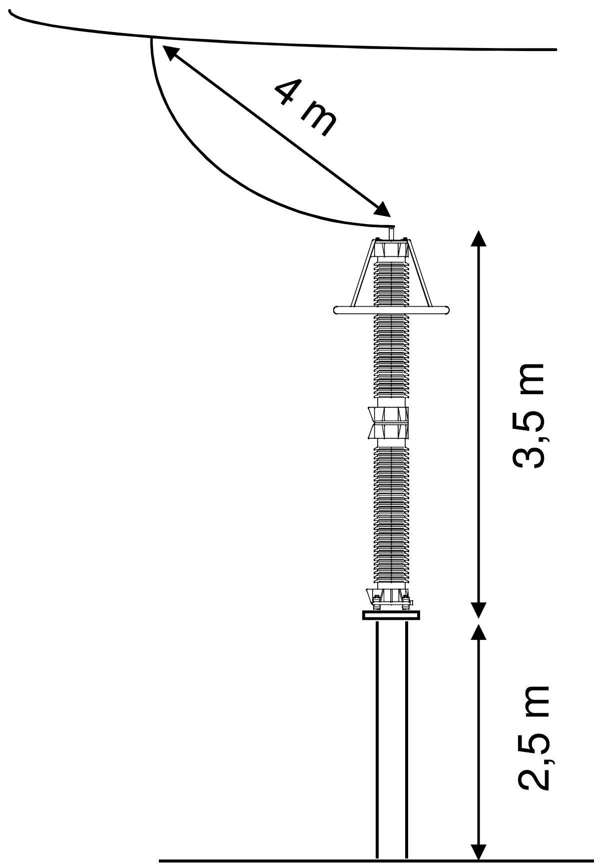
2

Increase of ≤ **5%** in residual voltage at short rise time (T_1 = 8 µs → T_1 = 1 µs)
= Property of the ZnO material



Increase of Protection Voltage by Inductive Voltage Drops

2



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Σ: Increased residual voltage under impact of steep impulse currents **for two reasons**:

- due to *U*-*I*-characteristic, shifted by 5%
- due to inductive voltage drop for geometrical reasons

Traveling Waves on Lines – A Very Short "Course" by 6 Slides

3

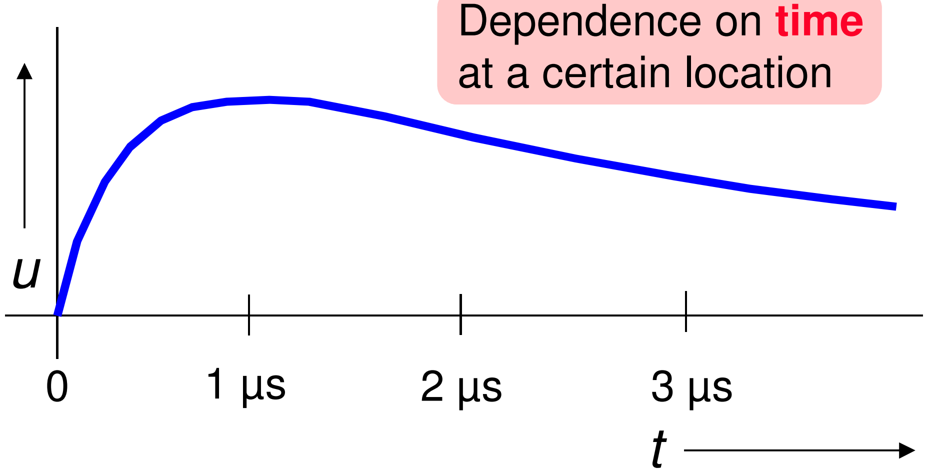
Each electromagnetic wave has a certain **velocity of propagation** (in the free space/on a line: 300 m/µs).

Changes of voltage and current result in **traveling waves** on the line.

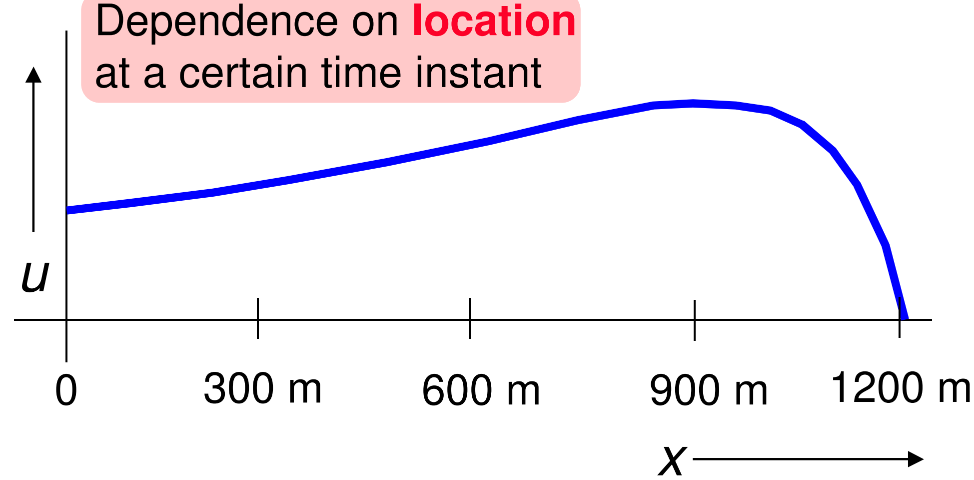
→ Dependence on **time** and **location**

Example: lightning overvoltage on an OHL

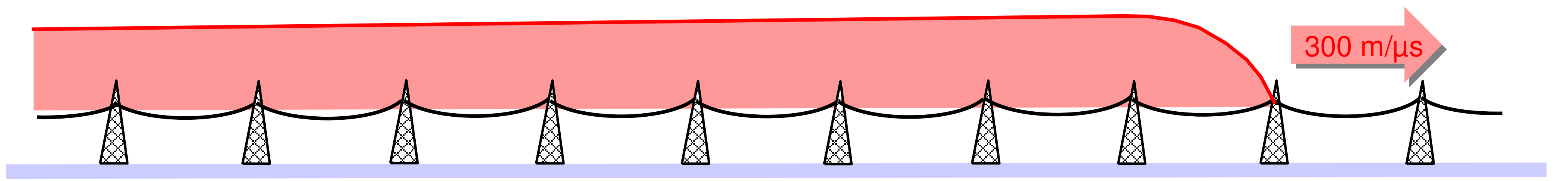
Dependence on **time** at a certain location



Dependence on **location** at a certain time instant

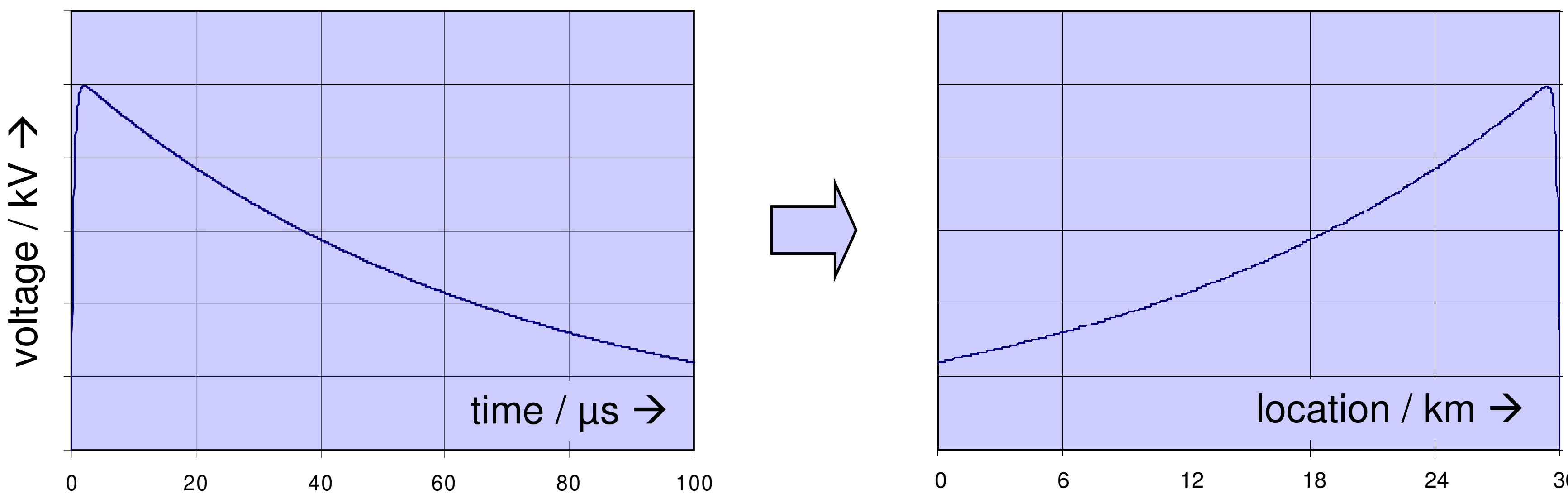


Traveling Waves – Example: Lightning Overvoltage on an OH Line

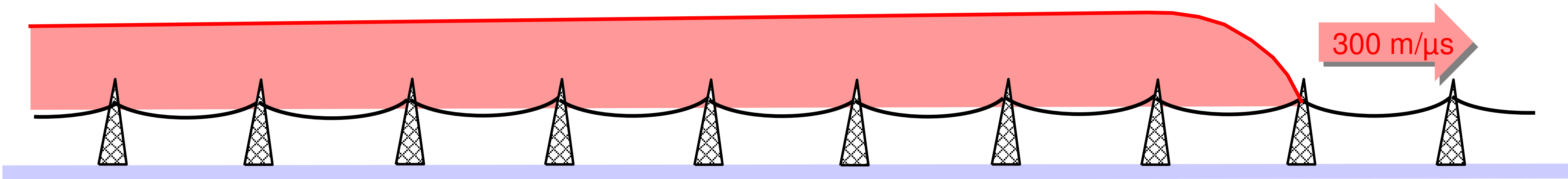


Span length (typ.): 300 m
Time to crest (typ.): 1 µs
Time to half value (typ.): (10…100) µs

In the (theoretical) case of a standard lightning impulse voltage 1.2/50:



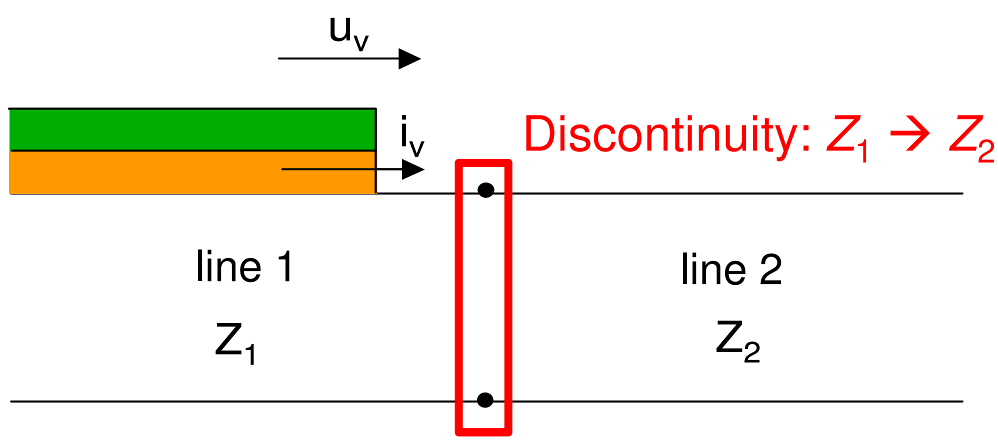
Traveling Waves – Example: Lightning Overvoltage on an OH Line



Span length (typ.): 300 m
Time to crest (typ.): 1 µs
Time to half value (typ.): (10…100) µs

- For a standard lightning impulse of 1 µs rise time (corresponding to 300 m spatial distribution) every line up to approx. 3 km (10 times 300 m) length has to be considered as **"electrically long"**, and traveling wave effects have to be regarded. This is e.g. the case within every substation.
- For a standard switching impulse of 250 µs rise time (corresponding to 75 km spatial distribution), all phenomena in a substation happen on **"electrically short"** lines, and traveling wave effects do not play a role here.

Traveling Waves - Reflection and Refraction



$u_v = Z_1 \cdot i_v$

u_v and i_v suffer **changes** at locations of discontinuity

Refraction (forward waves proceed at increased or reduced amplitudes)

Reflection (waves travel back from the location of discontinuity)

Traveling Waves - Reflection and Refraction

$$\frac{u_{2\mathrm{v}}}{u_{1\mathrm{v}}} = \frac{2 \cdot Z_2}{Z_1 + Z_2} = b_\mathrm{u}$$

voltage refraction factor

$$\frac{i_{2\mathrm{v}}}{i_{1\mathrm{v}}} = \frac{2 \cdot Z_1}{Z_1 + Z_2} = b_\mathrm{i}$$

current refraction factor

$$r_\mathrm{u} = \frac{u_{1\mathrm{r}}}{u_{1\mathrm{v}}} = b_\mathrm{u} - 1 = \frac{Z_2 - Z_1}{Z_1 + Z_2}$$

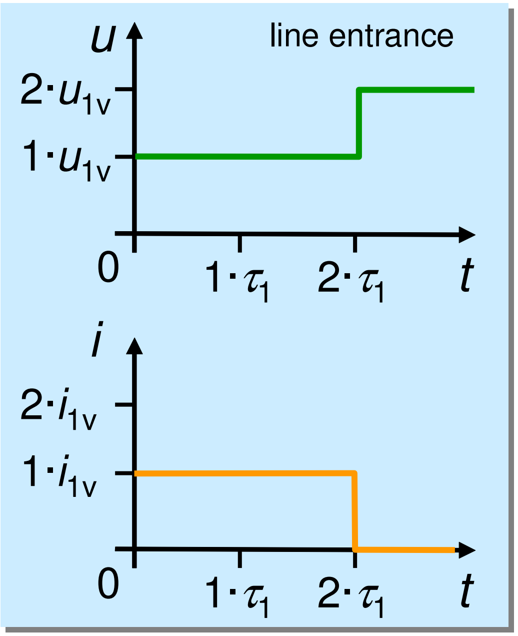
voltage reflection factor

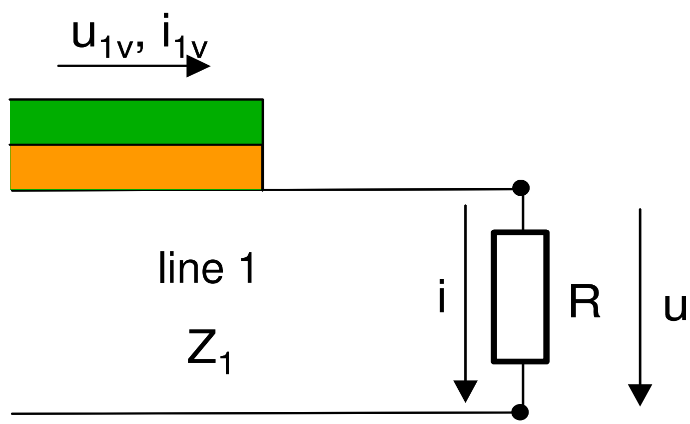
$$r_\mathrm{i} = \frac{i_{1\mathrm{r}}}{i_{1\mathrm{v}}} = b_\mathrm{i} - 1 = \frac{Z_1 - Z_2}{Z_1 + Z_2}$$

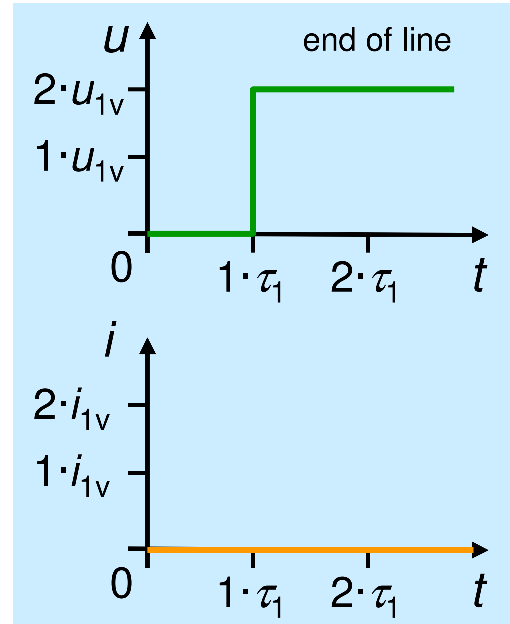
current reflection factor

Only depending on Z_1 and Z_2!

Traveling Waves - Reflection and Refraction at End of Line







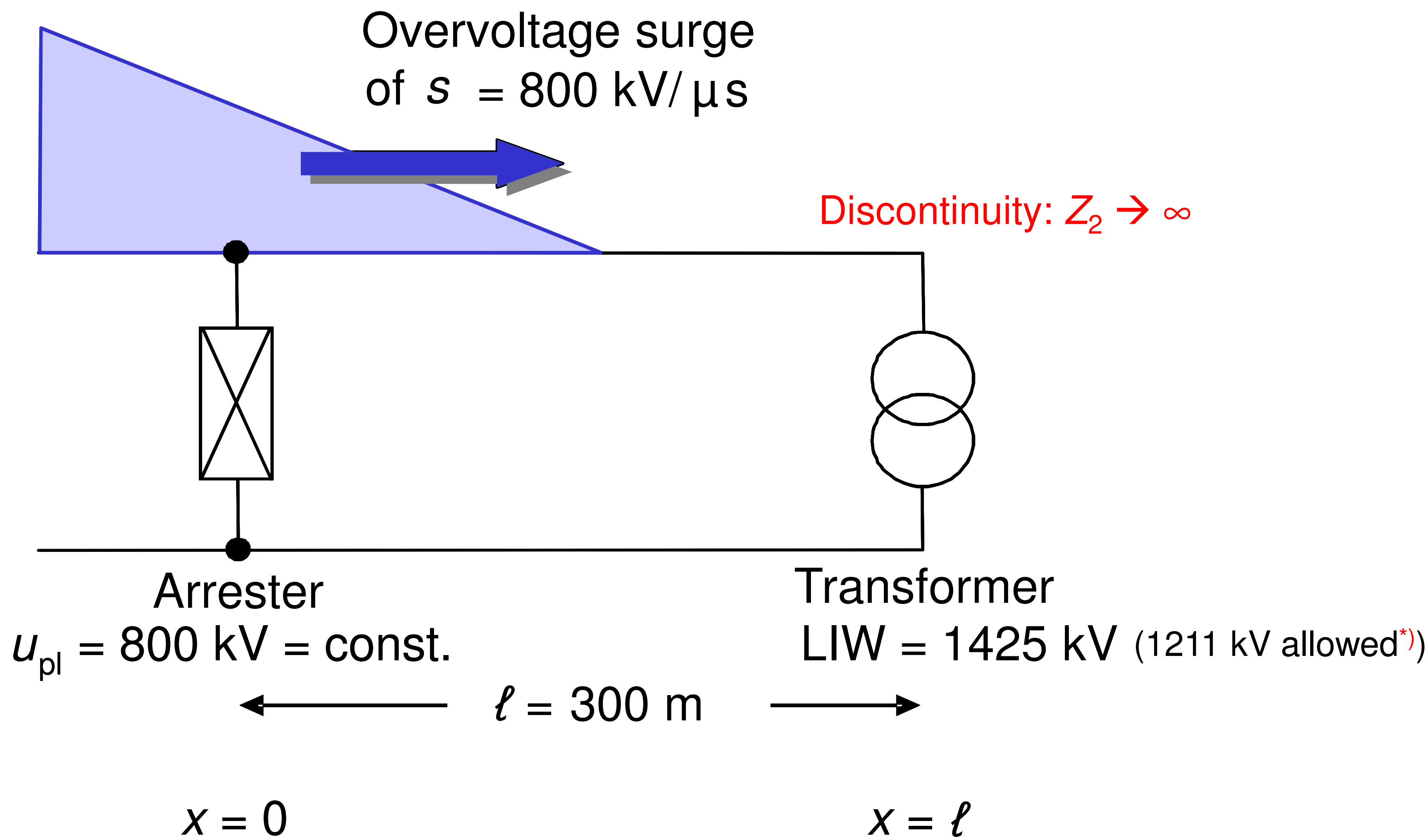
Case: end = open circuit $\Rightarrow$ $\boldsymbol{R \rightarrow \infty}$

$r_u = 1 \Rightarrow u_{1r} = u_{1v} \Rightarrow u = 2 \cdot u_{1v}$

$r_i = -1 \Rightarrow i_{1r} = -\mathrm{i}_{1v} \Rightarrow i = 0$

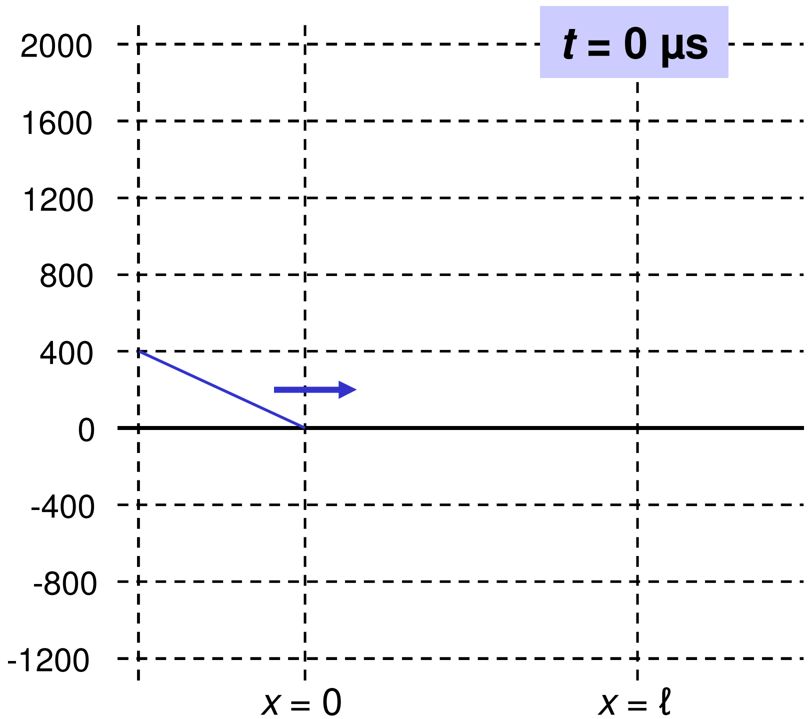
$\Rightarrow$ **Doubling of voltage at line‘s end, current = zero**

Protective Distance – Model Calculation 1 ($U_s = U_m = 420$ kV)



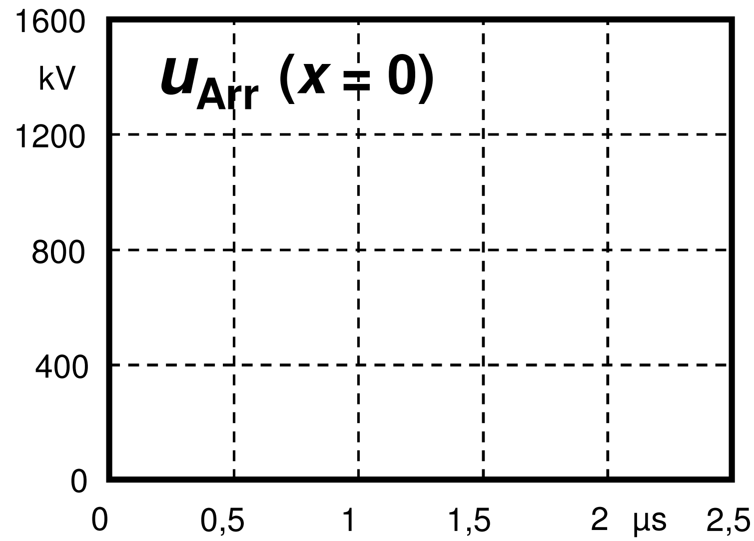
*) 0.85 x 1425 kV = 1211 kV

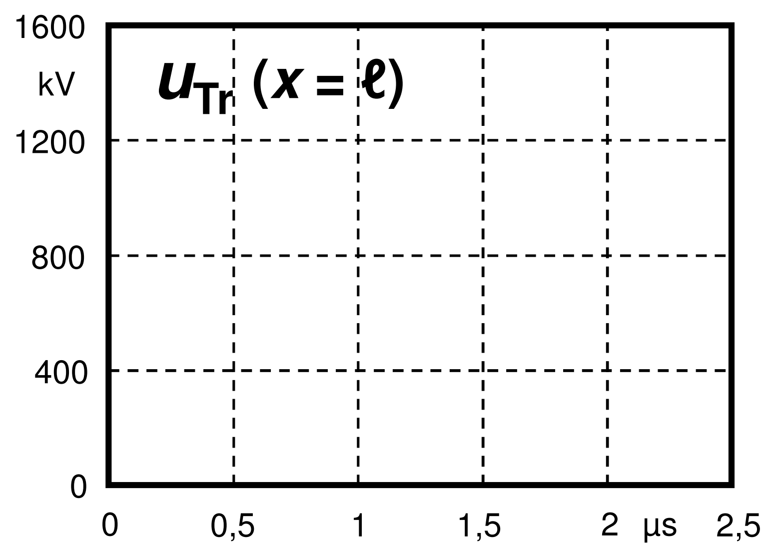
Protective Distance – Model Calculation 1 ($U_s = U_m = 420$ kV)



$x = 0$: u_{Arr} = **0 kV**

$x = \ell$: u_{Tr} = **0 kV**





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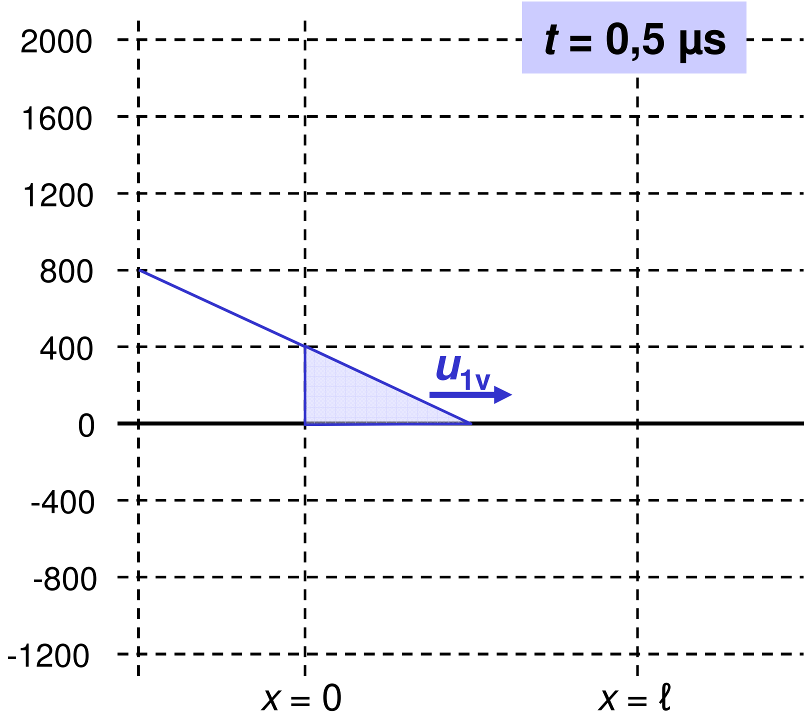
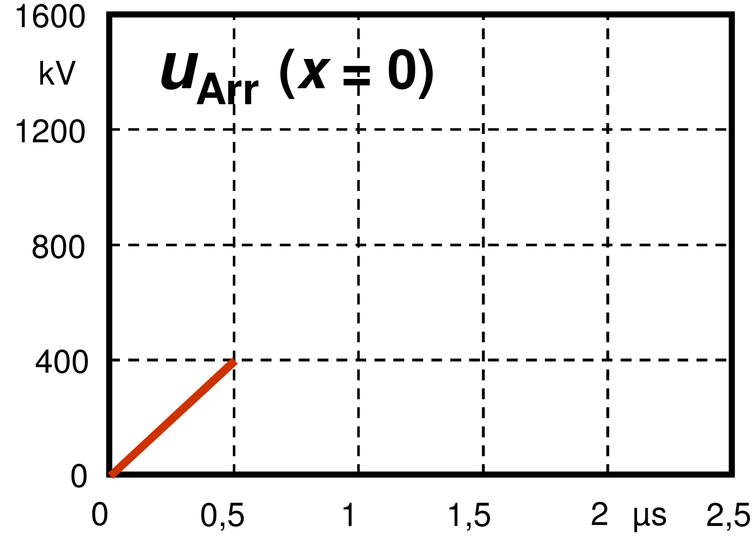
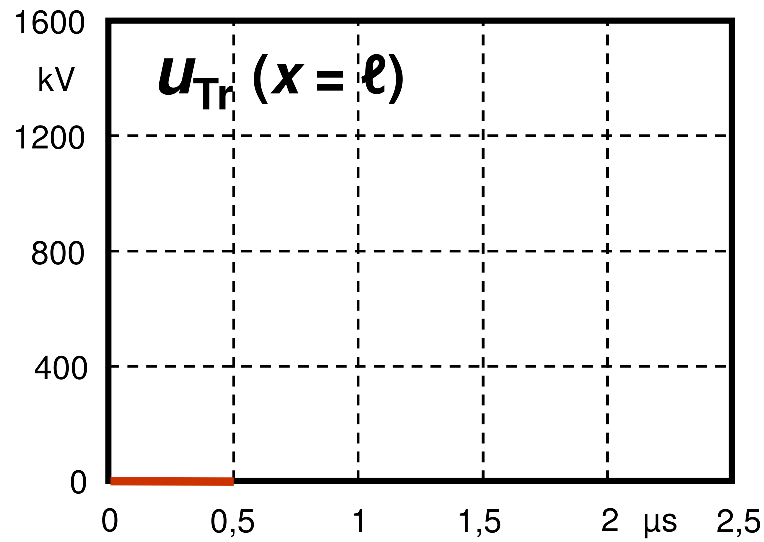


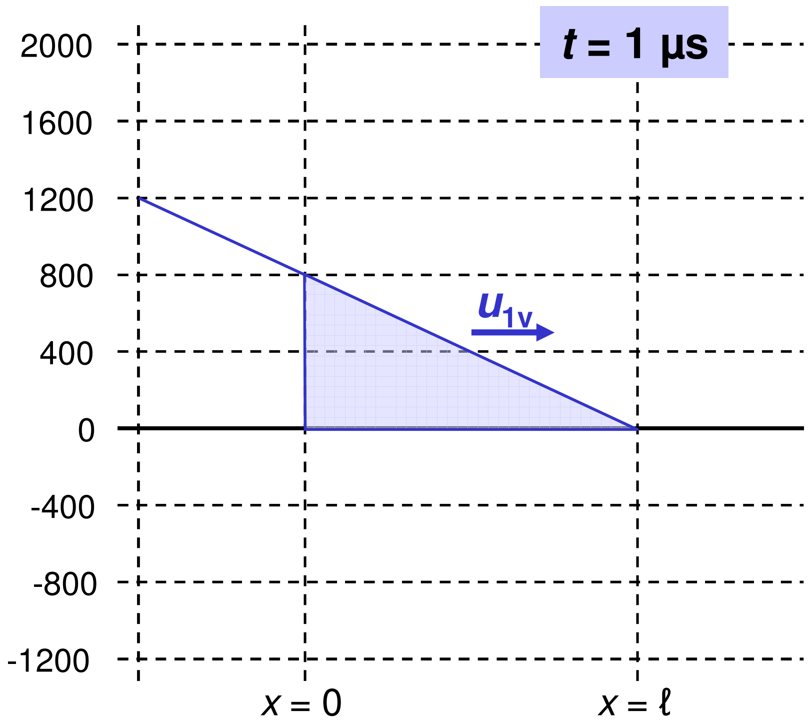


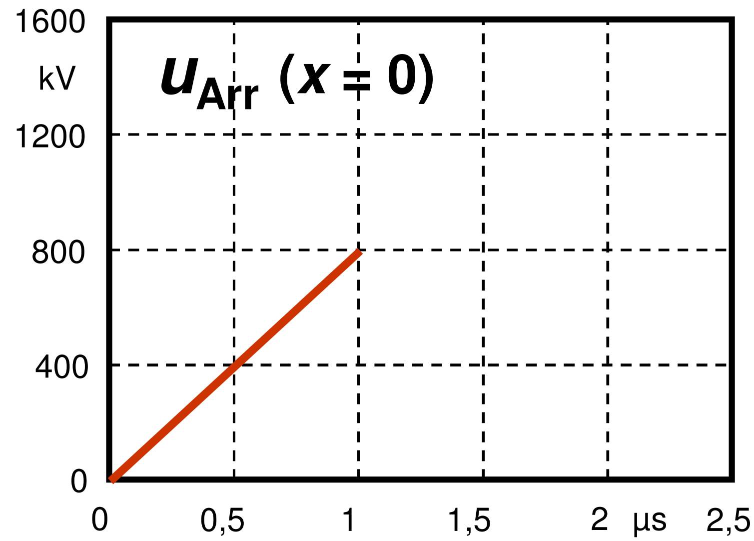


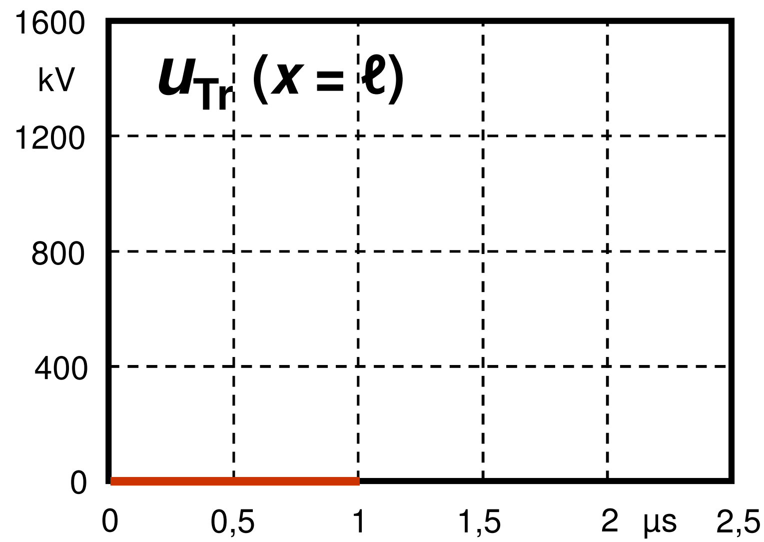
x = 0: $u_{Arr} = u_{1v}$ = **400 kV**

x = ℓ: $u_{Tr} = u_{1v}$ = **0 kV**

Protective Distance – Model Calculation 1 ($U_s = U_m = 420$ kV)



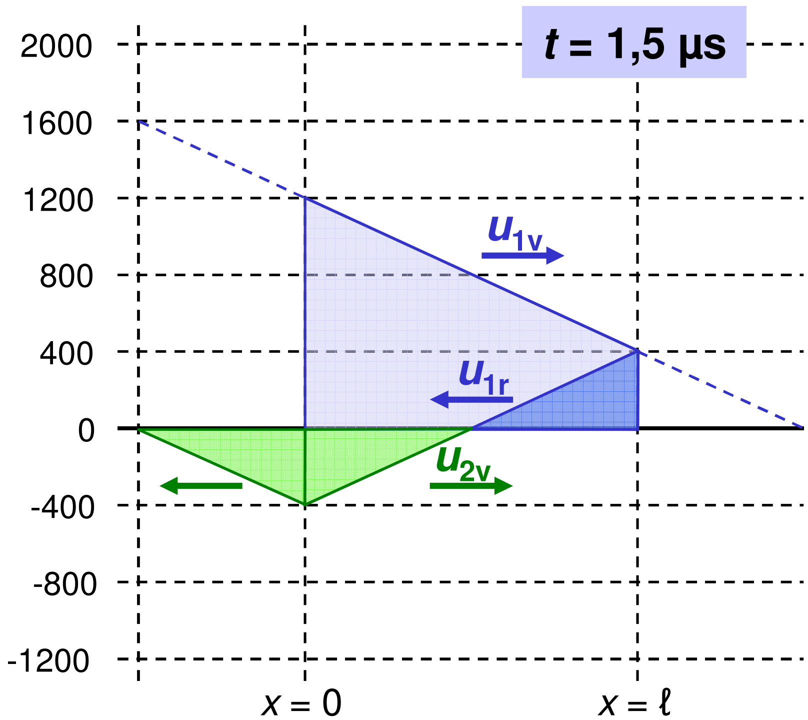




$\boldsymbol{x} = 0$: $u_{Arr} = u_{1v} = \mathbf{800\ kV}$

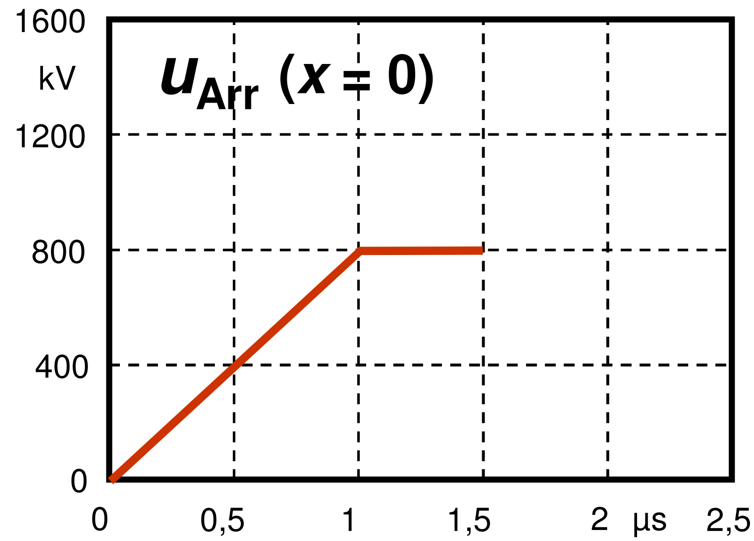
$\boldsymbol{x} = \boldsymbol{\ell}$: $u_{Tr} = u_{1v} = \mathbf{0\ kV}$

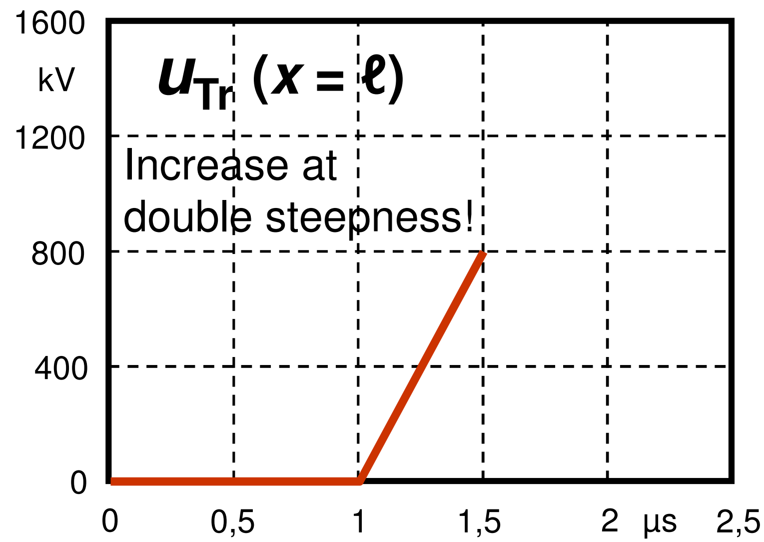
Protective Distance – Model Calculation 1 ($U_s = U_m = 420$ kV)



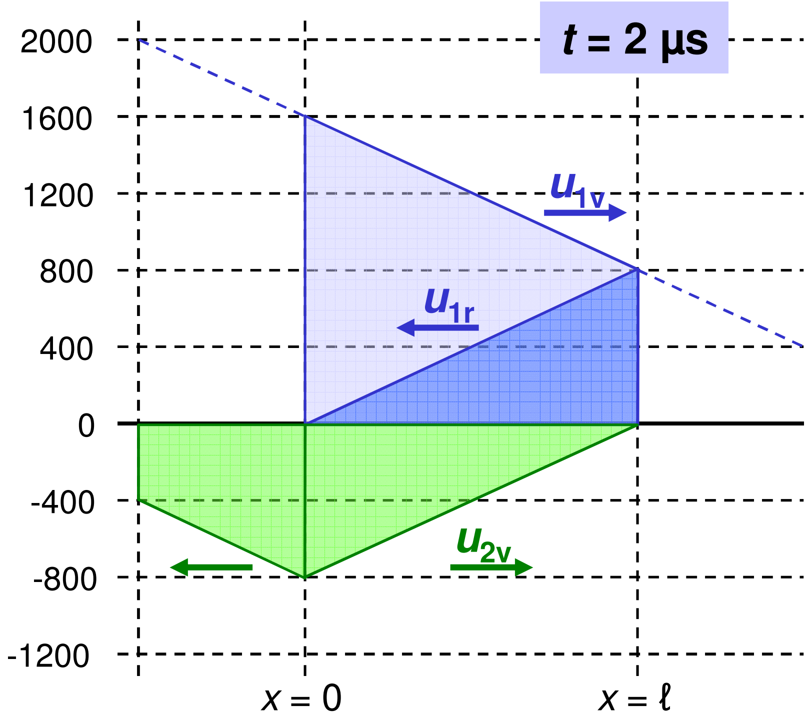
x = 0: $u_{Arr} = u_{1v} + u_{2v}$ =
(1200 – 400) kV = **800 kV**

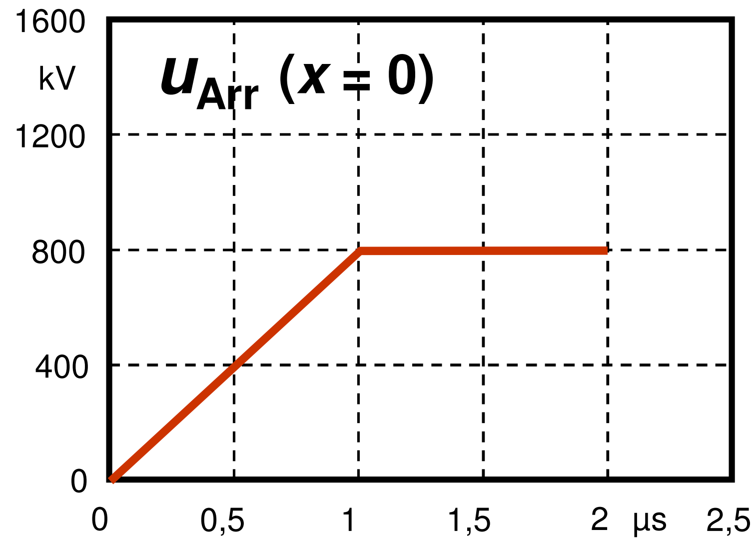
x = ℓ: $u_{Tr} = u_{1v} + u_{1r}$ =
(400 + 400) kV = **800 kV**

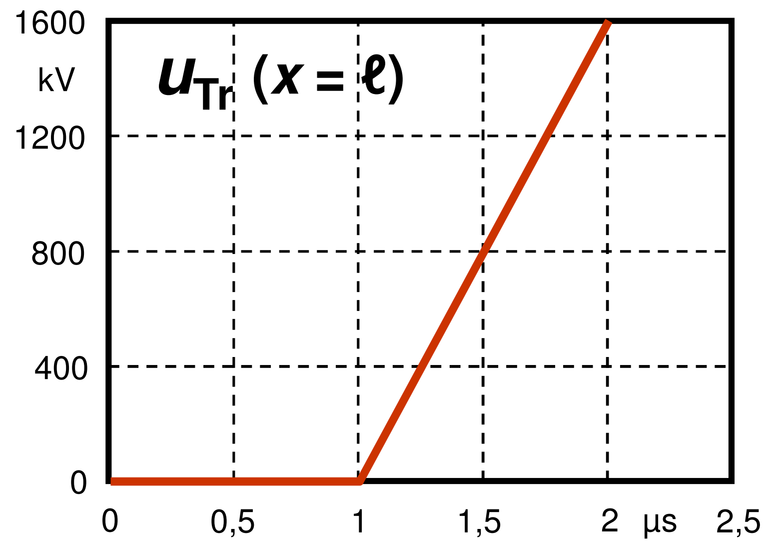




Protective Distance – Model Calculation 1 ($U_s = U_m = 420$ kV)



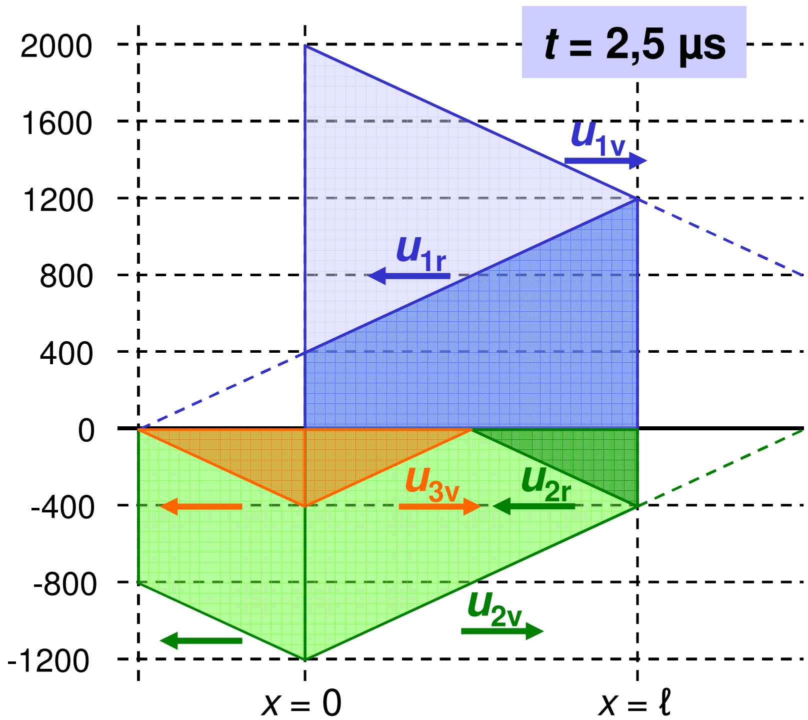


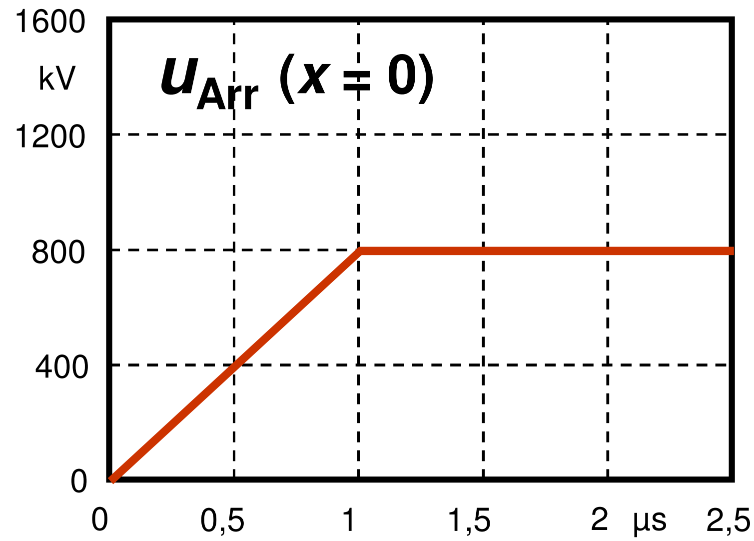


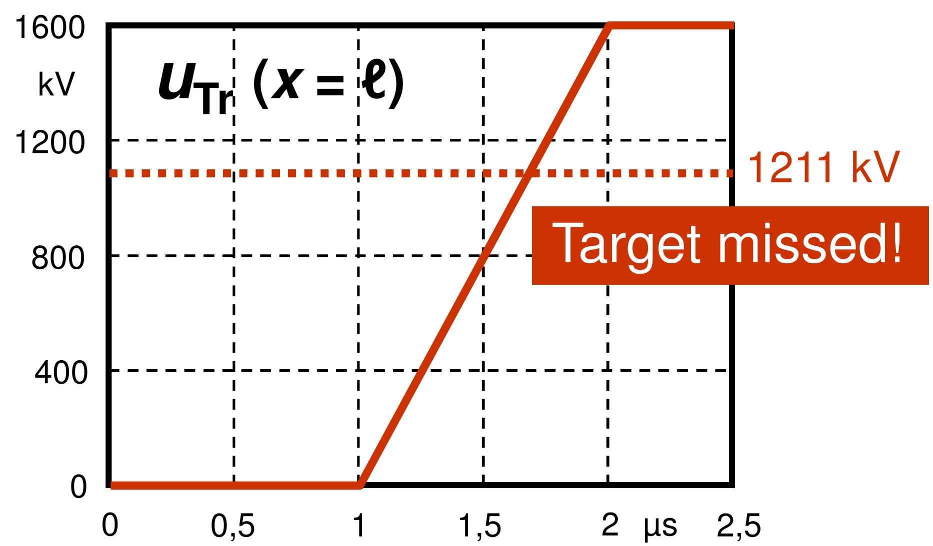
$\boldsymbol{x} = \mathbf{0}$**:** $u_{Arr} = u_{1v} + u_{2v} =$
$(1600 - 800)$ kV = **800 kV**

$\boldsymbol{x} = \boldsymbol{\ell}$**:** $u_{Tr} = u_{1v} + u_{1r} =$
$(800 + 800)$ kV = **1600 kV**

Protective Distance – Model Calculation 1 ($U_s = U_m = 420$ kV)



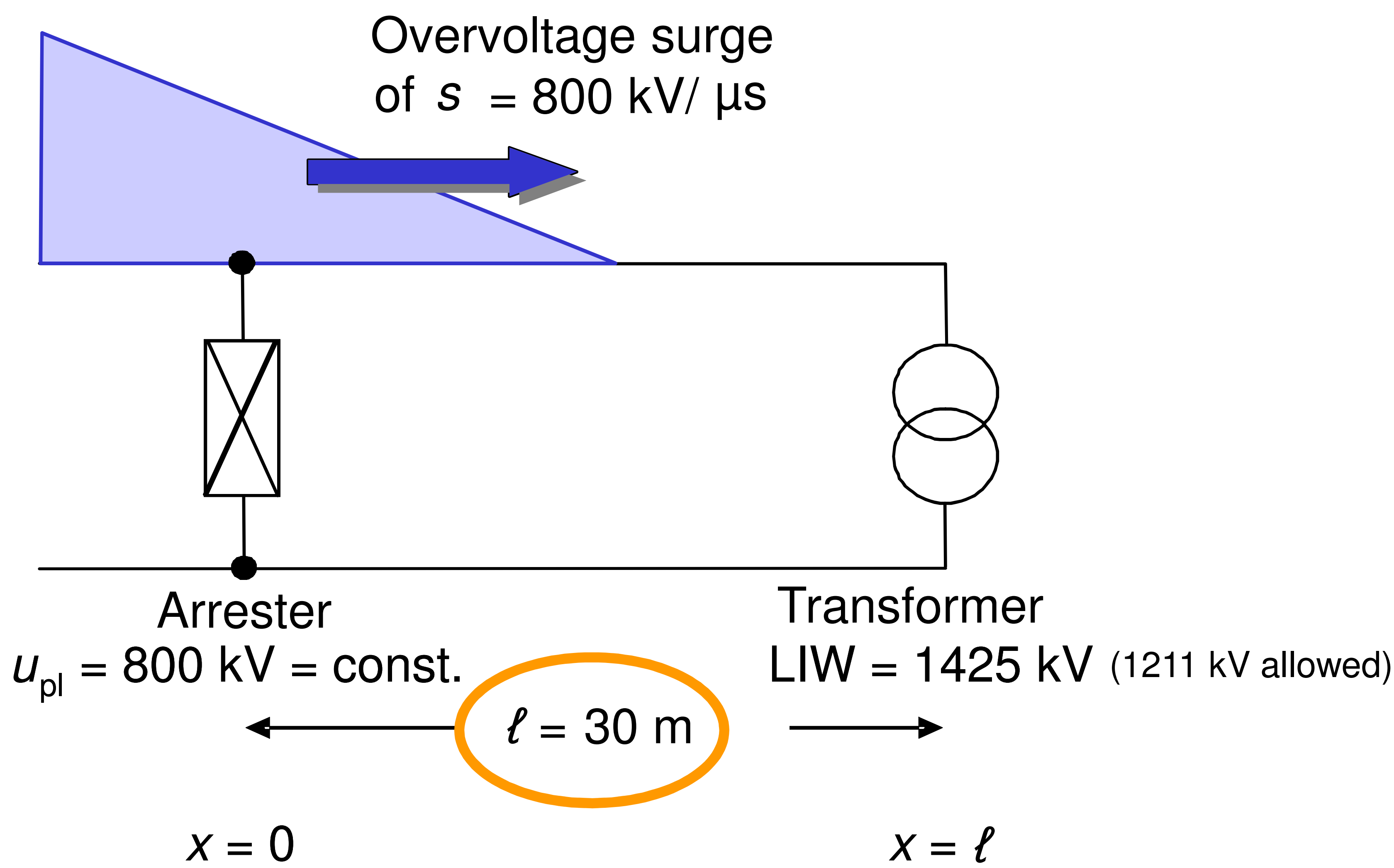




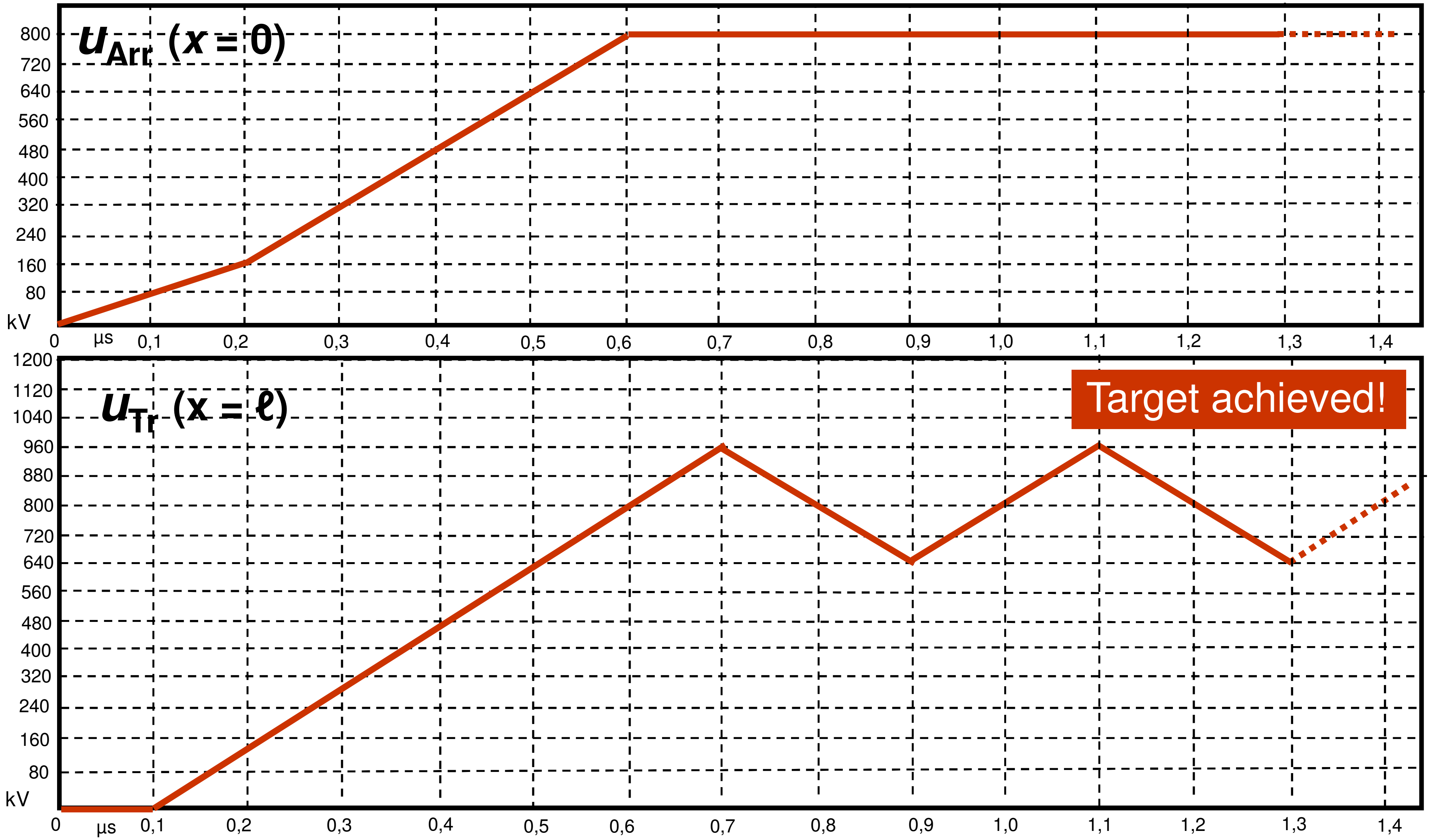
x = 0: $u_{Arr} = u_{1v} + u_{1r} + u_{2v} + u_{3v} =$
(2000 + 400 – 1200 – 400) kV = **800 kV**

x = ℓ: $u_{Tr} = u_{1v} + u_{1r} + u_{2v} + u_{2r} =$
(1200 + 1200 – 400 – 400) kV = **1600 kV**

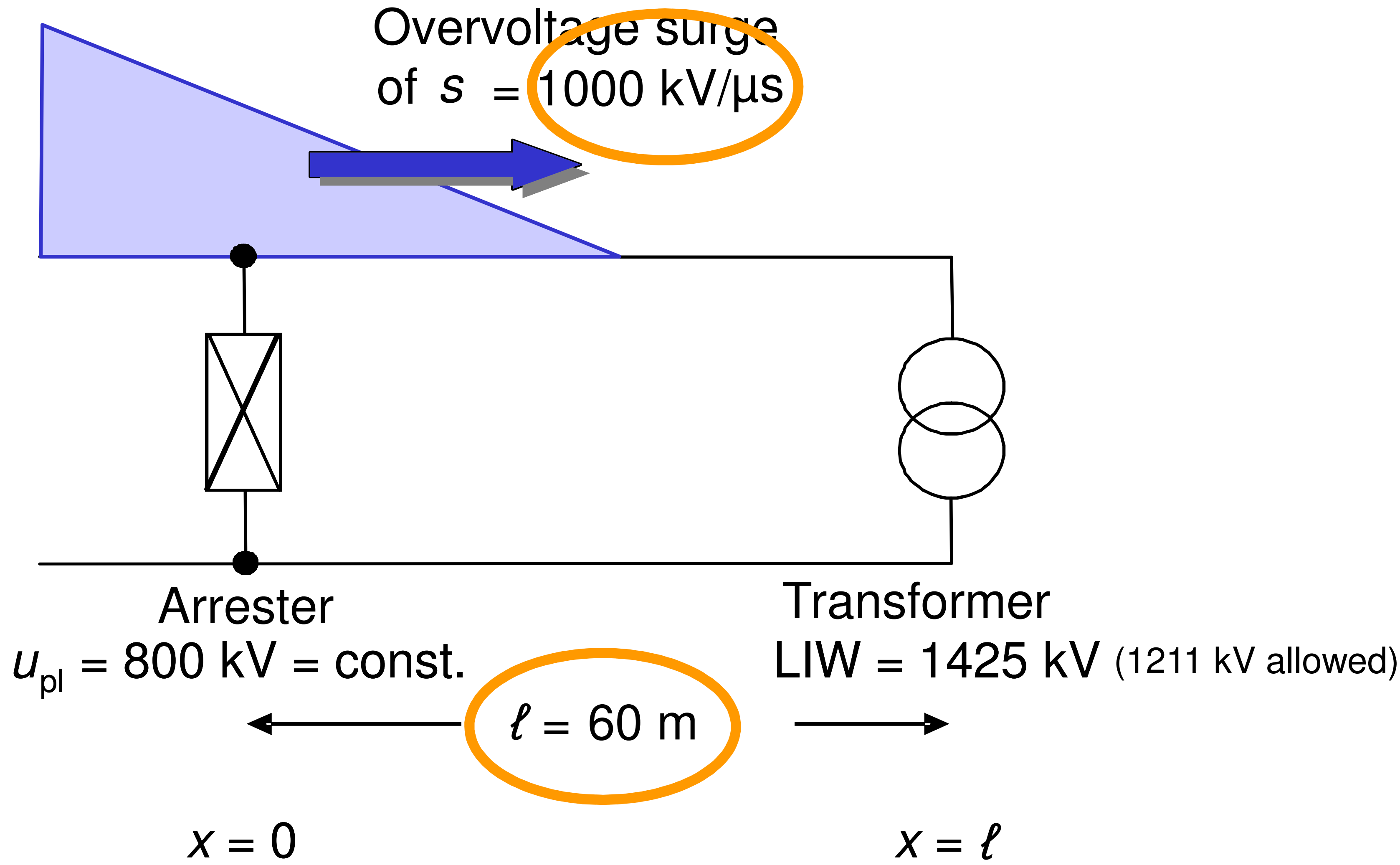
Protective Distance – Model Calculation 2 ($U_s = U_m$ = 420 kV)



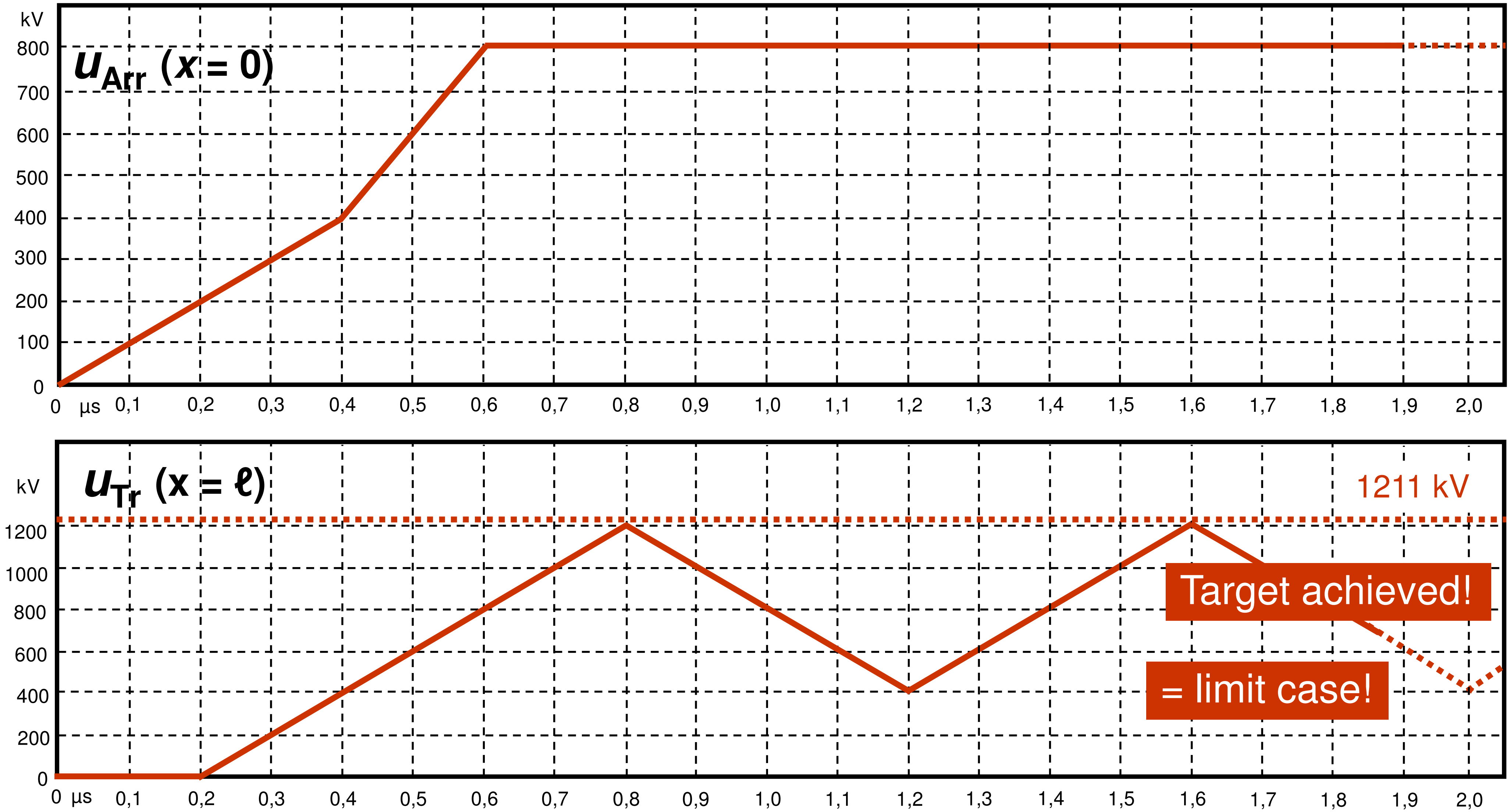
Protective Distance – Model Calculation 2 (U_s = U_m = 420 kV)



Protective Distance – Model Calculation 3 (U_s = U_m = 420 kV)



Protective Distance – Model Calculation 3 ($U_s = U_m = 420$ kV)



Protective Distance – Estimation (Rule of Thumb)

Due to traveling wave effects on the line the protection of the equipment by an arrester can be guaranteed **only for short distances** between arrester and equipment.

Simplified estimation of the protective distance *):

$$x_s = \frac{(\mathrm{LIWV} / 1.15) - U_{pl}}{2 \cdot s} \cdot v_{tw}$$

x_s	protective distance [m]
LIWV	standard rated lightning impulse withstand voltage [kV]
U_{pl}	LI protection level of the arrester [kV]
s	front steepness of the overvoltage [kV/µs] (in the range of 1000 kV/µs)
v_{tw}	propagation speed of traveling wave: - 300 m/µs (overhead line) (equals "c_0") - (150 ... 200) m/µs (cable)

*) For more detailed information see IEC 60099-5, IEC 60071-1 and IEC 60071-2

Example 1: Distribution network, $U_m = U_s = 24$ kV, insulated neutral, arrester of $U_r = 30$ kV:

$$x_s = \frac{(125 / 1.15) - 80}{2 \cdot 1000} \cdot 300 = \boxed{4.3\ \mathrm{m}}\ !!!$$

Example 2: Transmission network, $U_m = U_s = 420$ kV, effectively earthed, arrester of $U_r = 336$ kV:

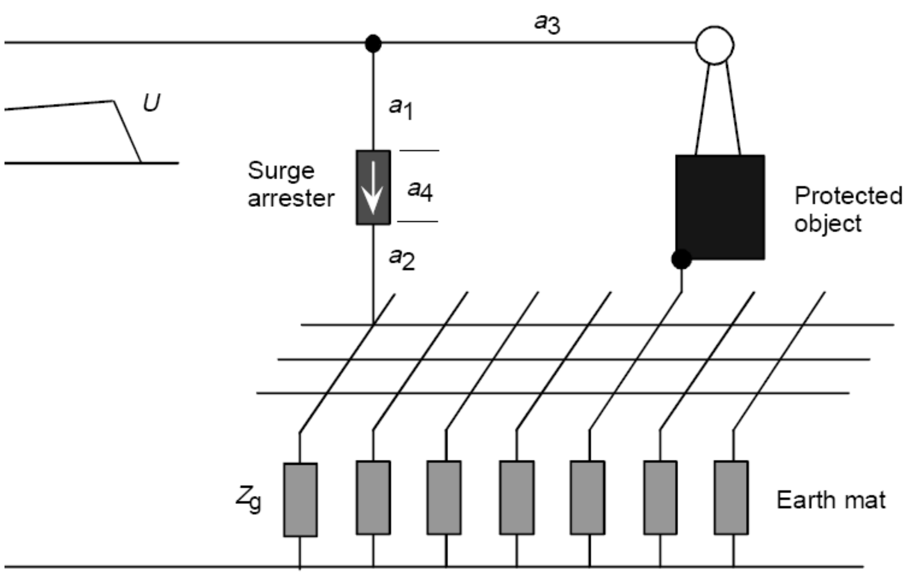
$$x_s = \frac{(1425 / 1.15) - 823}{2 \cdot 1000} \cdot 300 = \boxed{62.4\ \mathrm{m}}\ !!!$$

Representative Overvoltage (acc. to IEC 60071-2)

$$U_{rp} = U_{pl} + \frac{A}{n} \frac{L}{\left(L_{sp} + L_t\right)}$$

$$L_t = \frac{\text{adopted return rate}}{\text{shielding failure rate} + \text{back flashover rate}} \quad \frac{1/\text{a}}{1/\text{a} \cdot \text{m}}$$

→ **Statistical approach!**



L_{sp} ... span length in m

L ... distances $a_1 + a_2 + a_3 + a_4$ in m

n ... number of connected lines

A ... factor describing the lightning performance of the OHL in kV (see next slide)

Note: *n* should reasonably be set to ***n* = 1** (if only **one** line is connected) or ***n* = 2** (if **two or more** lines are connected). Assuming $n > 2$ could yield too optimistic results that are not valid in a real failure scenario (e.g. possible loss of lines).

Representative Overvoltage (acc. to IEC 60071-2)

Factor A describing the **lightning performance** of an OHL
(considers corona damping factor)

Table F.2 – Factor *A* for various overhead lines

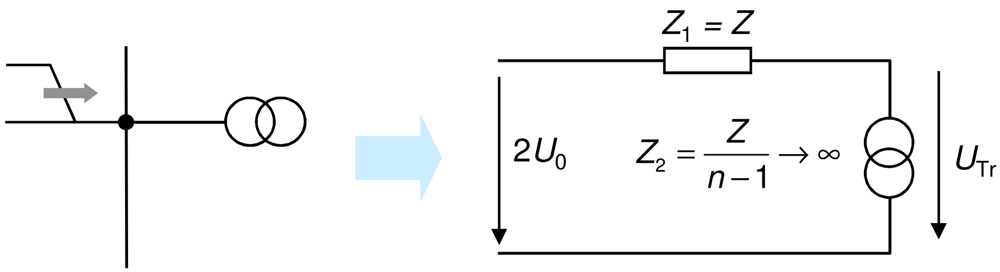
Type of line	*A* (kV)
Distribution lines (phase-phase flashovers):	
– with earthed crossarms (flashover to earth at low voltage)	900
– wood-pole lines (flashover to earth at high voltage)	2700
Transmission lines (single-phase flashover to earth)	
– single conductor	4500
– double conductor bundle	7000
– four conductor bundle	11000
– six and eight conductor bundle	17000

[IEC 60071-2]

Protection by Surge Arresters and Representative Overvoltage

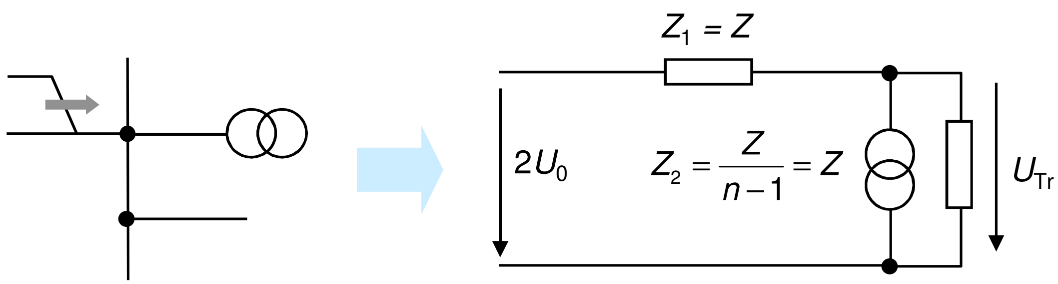
Considerations on steepness S – Impact of number of connected lines of surge impedance Z

$n = 1$:



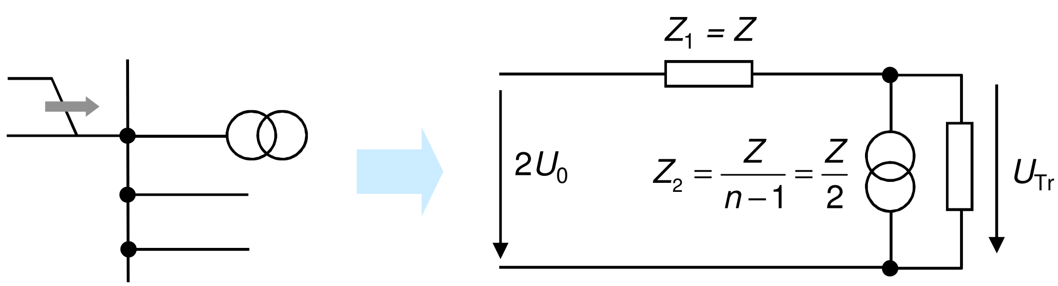
$$U_{Tr} = 2U_0$$

$n = 2$:



$$\frac{U_{Tr}}{2U_0} = \frac{Z}{2Z} \Rightarrow U_{Tr} = \frac{1}{2} \cdot 2U_0$$

$n = 3$:



$$\frac{U_{Tr}}{2U_0} = \frac{Z}{3Z} \Rightarrow U_{Tr} = \frac{1}{3} \cdot 2U_0$$

… and when the voltage amplitude is reduced, steepness is reduced proportionally.

Representative Overvoltage (acc. to IEC 60071-2)

Example: $U_m = U_s = 420$ kV

- $U_{pl} = 825$ kV;
- $A = 11000$ kV (four conductor bundle) (from Table F.2)
- $L = 30$ m
- $L_{sp} = 400$ m
- ≥ 2 lines connected;
- Shielding failure rate (typical value; one OHGW): 2.5 per 100 km and year = $2.5 \cdot 10^{-5}$ (a·m)$^{-1}$
- Adopted return rate: $1 \cdot 10^{-3}$ a^{-1}

$$L_t = \frac{1 \cdot 10^{-3}}{2.5 \cdot 10^{-5}} = 40 \text{ m}$$

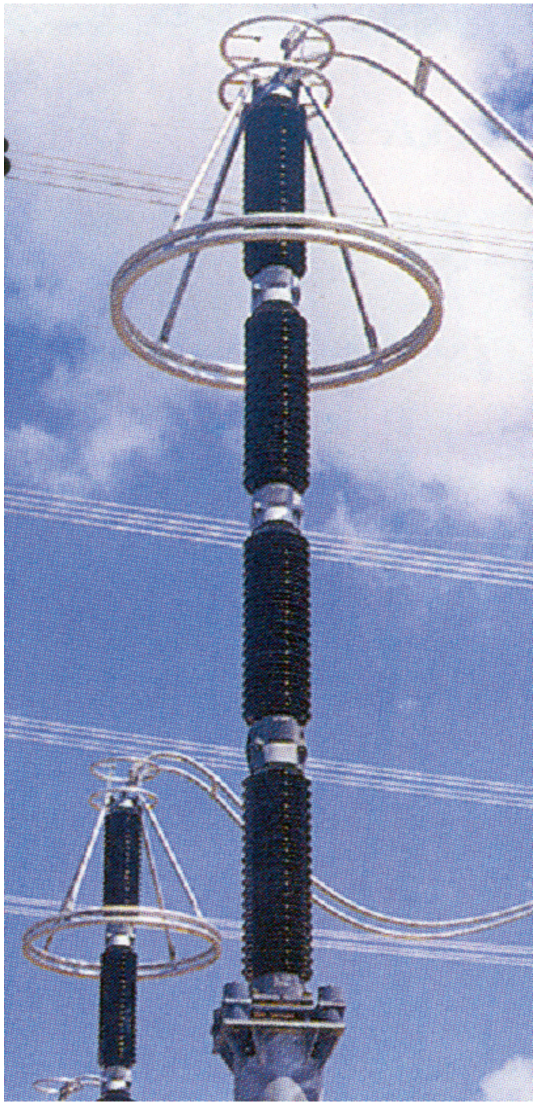
$$U_{rp} = U_{pl} + \frac{A}{n} \frac{L}{L_{sp} + L_t} = 825 \text{ kV} + \frac{11000 \text{ kV}}{2} \cdot \frac{30 \text{ m}}{(400+40) \text{ m}} = 1200 \text{ kV}$$

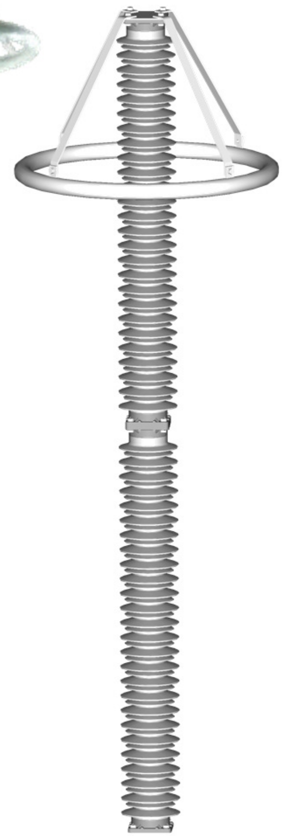
Note 1:
These equations yield **"representative"** overvoltages, which are **not implicitly the real** overvoltages in the system!

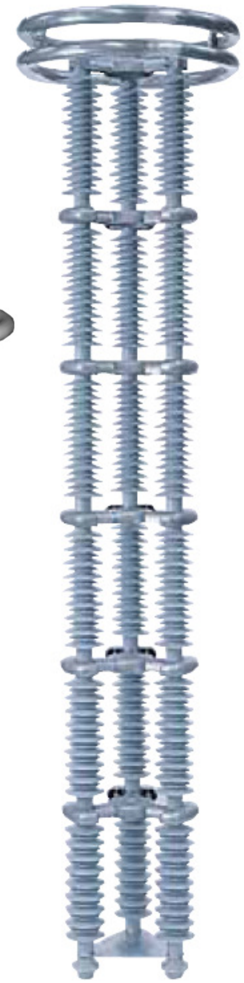
Note 2:
No effect of the lightning overvoltage **amplitude**!

Part 2:
HV Arrester Designs

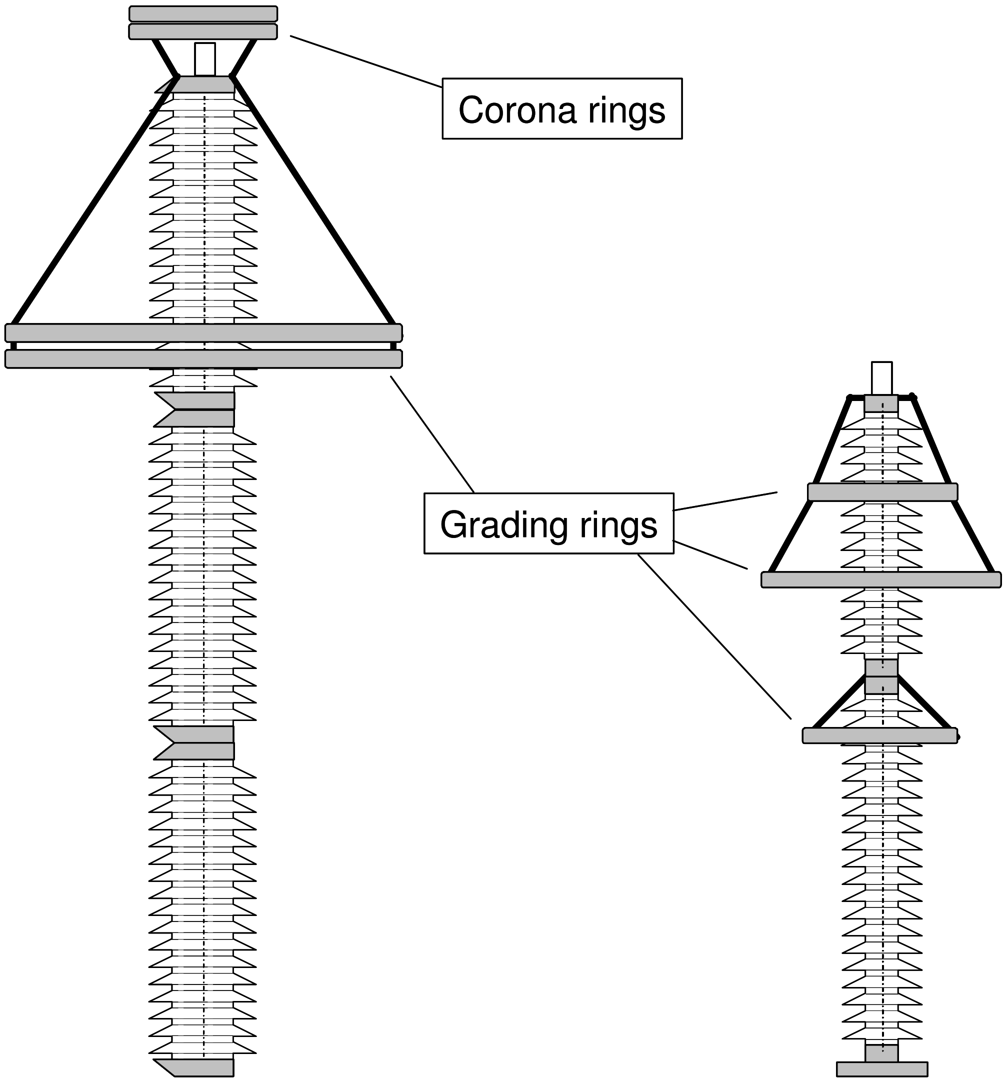
Examples of High-Voltage Arresters





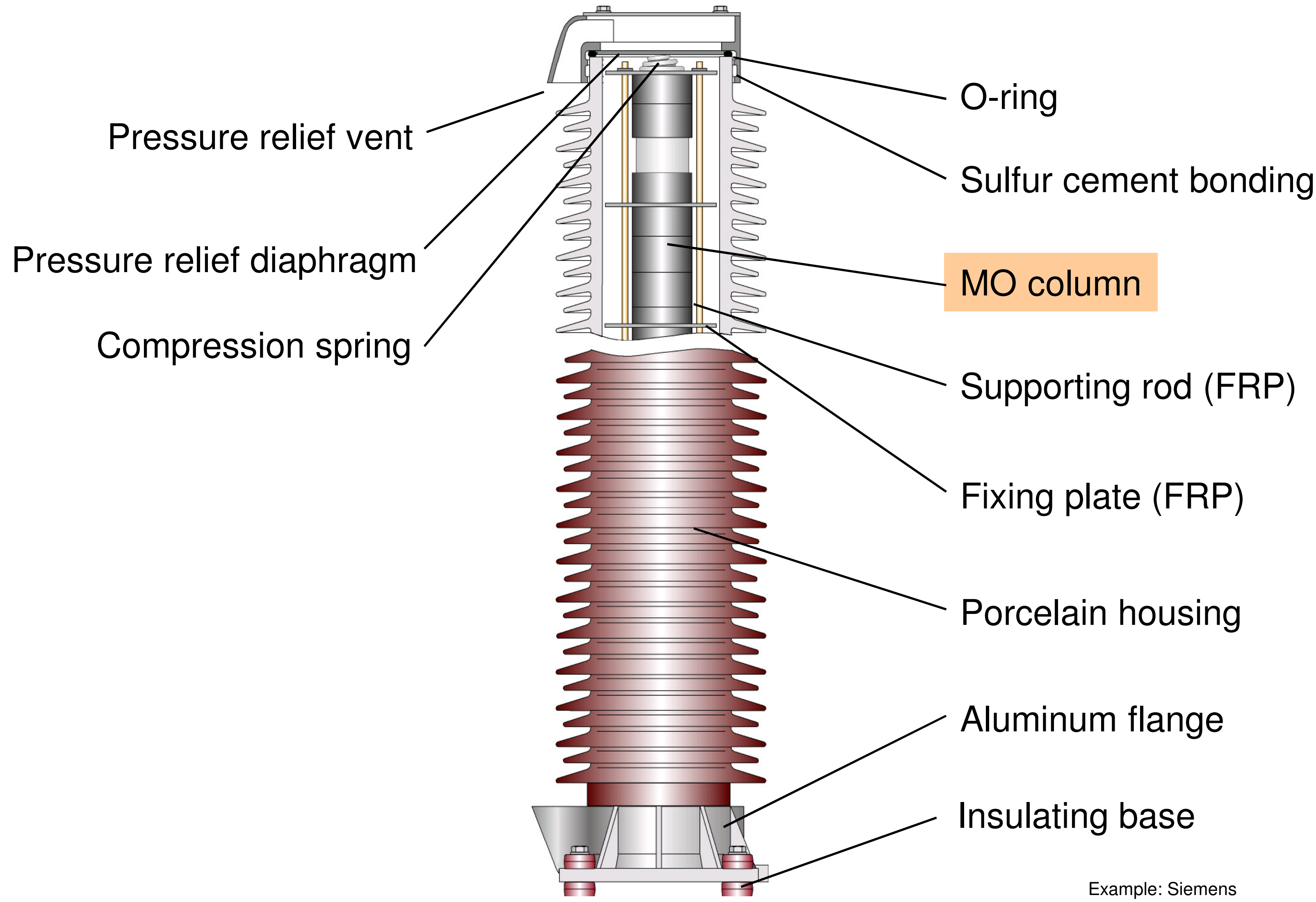


Grading Rings – Corona Rings



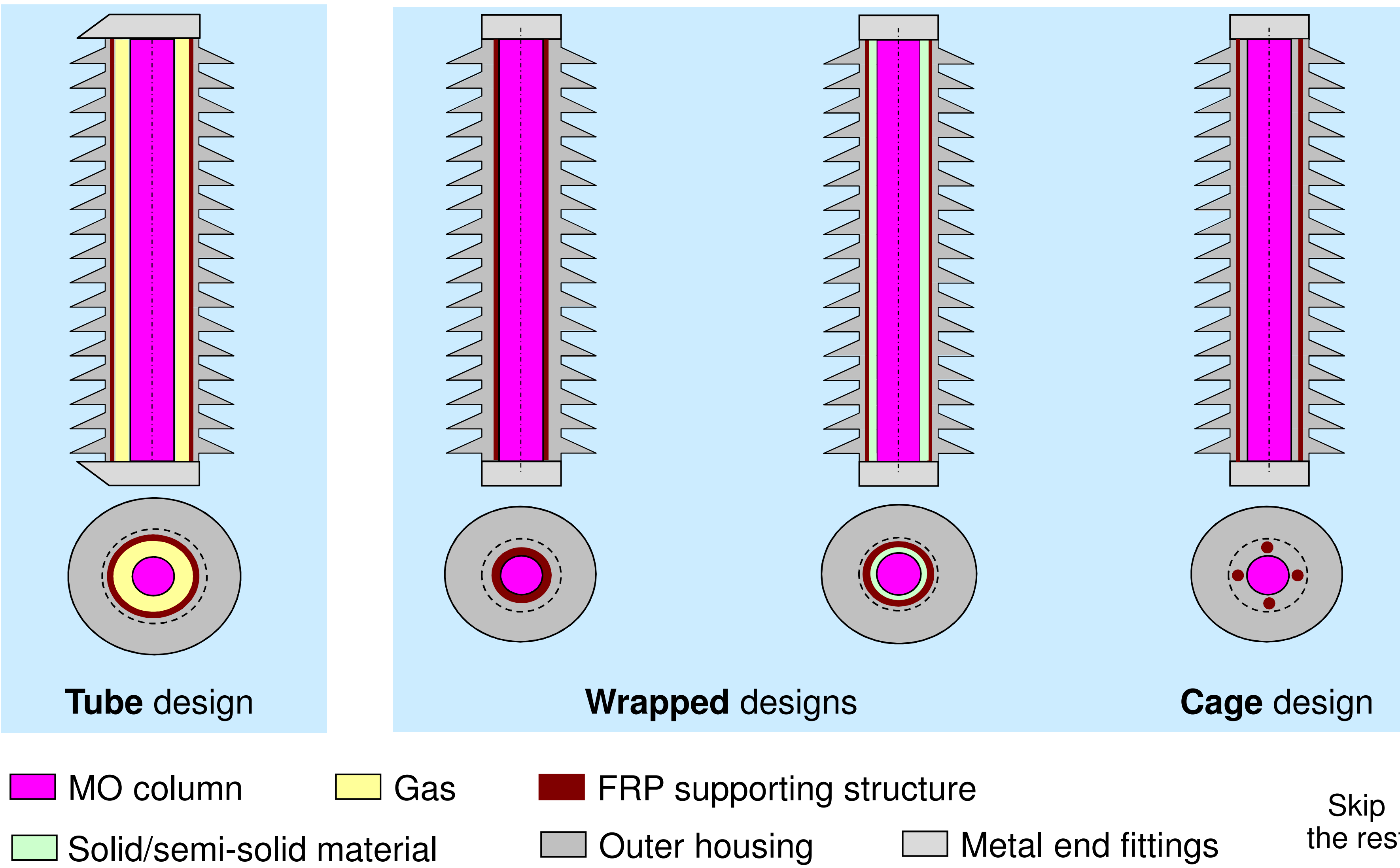
- Beginning with a height of about 1.5 m to 2 m arresters need **grading rings** for control of voltage distribution along the arrester axis.
- **Corona rings** serve to reduce RIV, usually applied in system voltages of 550 kV and higher.

Design of a Porcelain Housed High-Voltage Arrester



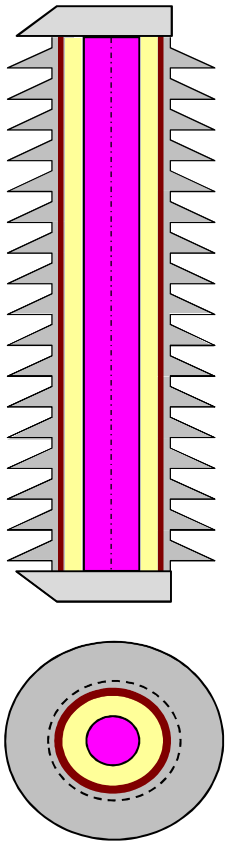
Example: Siemens

Basic Designs of Polymer Housed High-Voltage Arresters



Skip the rest

Type A "Tube Design"



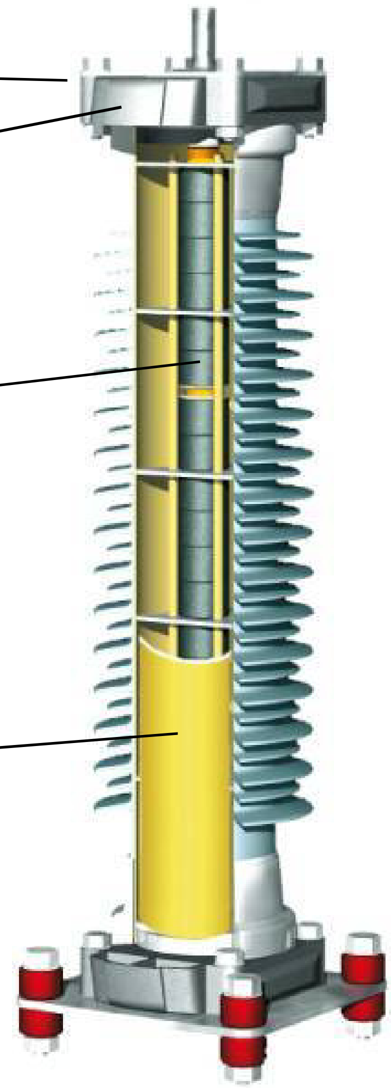
Porcelain/**Type A**

Type A → "tube design"

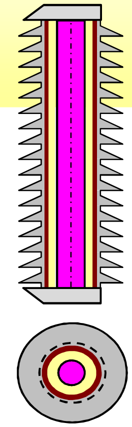
- "conventional" approach (like porcelain type)
- gas volume included
- separate sealing system
- pressure relief vents
- outer housing: silicone rubber (SR) (all types: HTV, RTV, LR/LSR)

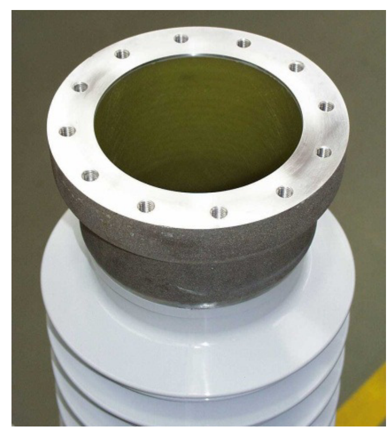
MO column | Gas | FRP supporting structure | Solid/semi-solid material | Outer housing | Metal end fittings

Type A "Tube Design"

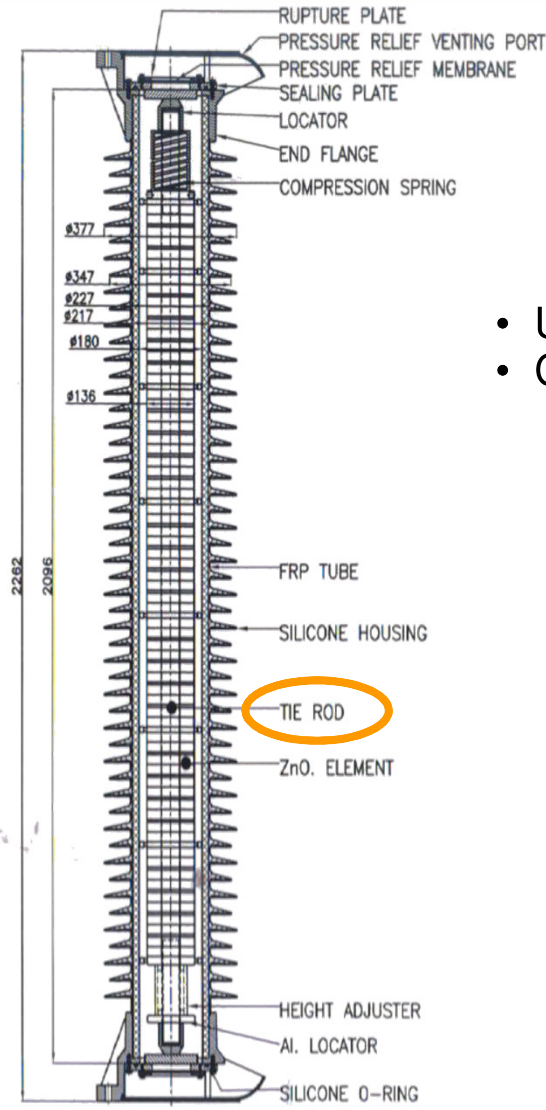


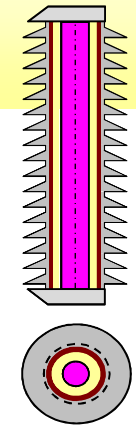
Example: Siemens





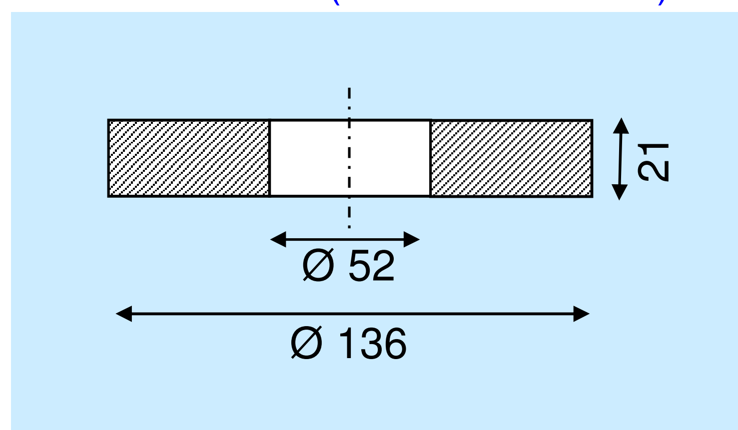
Type A "Tube Design"





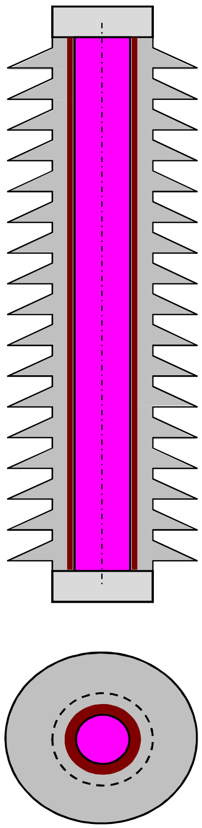
- Use of "donut" shaped MO resistors
- Central clamping rod

MO resistor (for UHV arrester)



Example: Oblum

Basic designs of polymer housed high-voltage arresters



Type B

• no (intentional) gas volume included

Type B1 → "wrapped design"

Type B1a → "wrapped design"

• FRP material **directly** wrapped onto MO stack

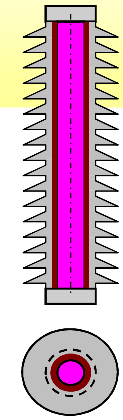
• outer housing slipped over or molded on (SR, EPDM, EPDM/SR blends …)

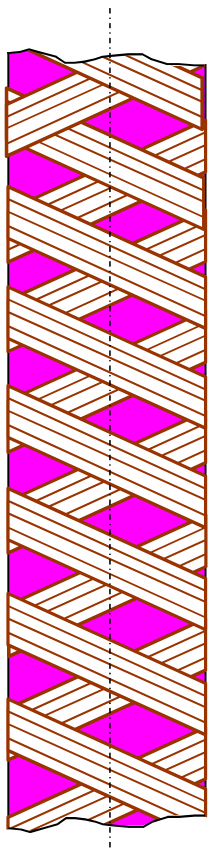
Type B1a

MO column | Gas | FRP supporting structure

Solid/semi-solid material | Outer housing | Metal end fittings

Type B1a "Wrapped Design"





Implementation example 1:

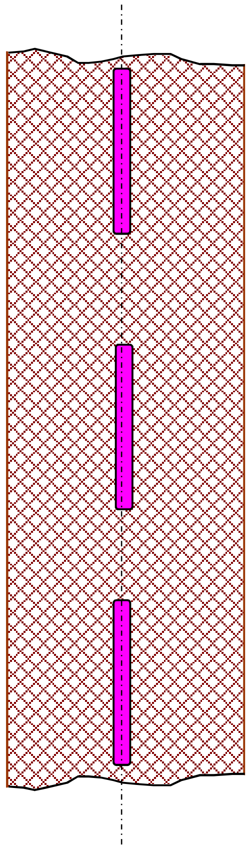
- Fiber glass rovings soaked in uncured epoxy resin or pre-impregnated ribbons are wound crosswise around the MO stack.
- They do not fully overlap and form rhombic "windows".
- Best compromise between mechanical strength and short-circuit performance must be found.

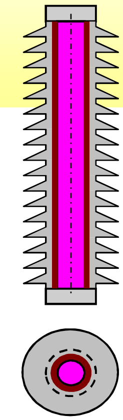
MO column FRP wrap

main orientation of glass fibers

Example: Ohio Brass

Type B1a "Wrapped Design"



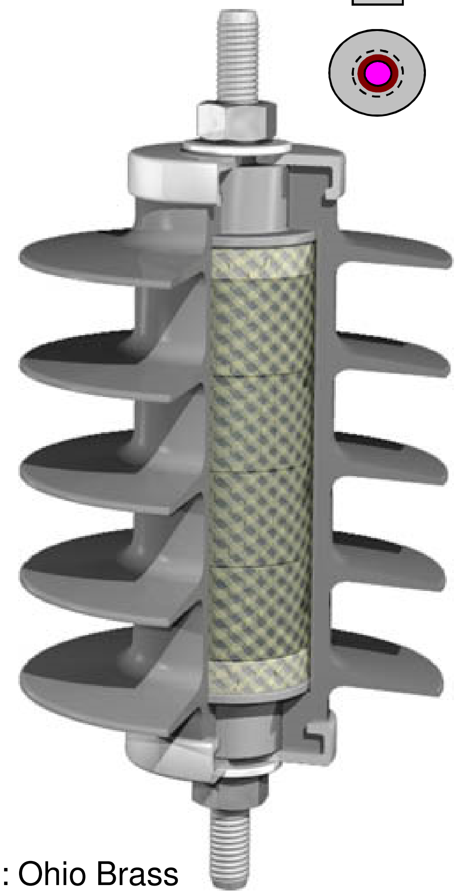


Implementation example 2:

- Full overlapping of the ribbons or pre-impregnated FRP mats with appropriate (**crosswise**) orientation of the glass fibers
- Forms a closed tube (good for mechanical strength, bad for short-circuit performance)
- Slots as pre-determined weakened breaking areas

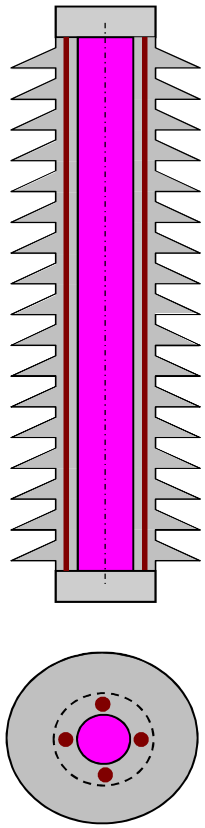
MO column FRP wrap

main orientation of glass fibers



Example: Ohio Brass

Basic designs of polymer housed high-voltage arresters



Type B

• no (intentional) gas volume included

Type B2 → "cage design"

• FRP rods or loops form an **open cage** around the MO stack

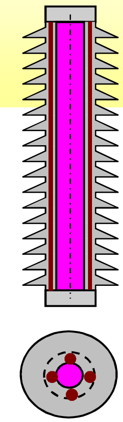
• outer housing directly molded onto the MO stack (silicone rubber)

Type B2

MO column | Gas | FRP supporting structure

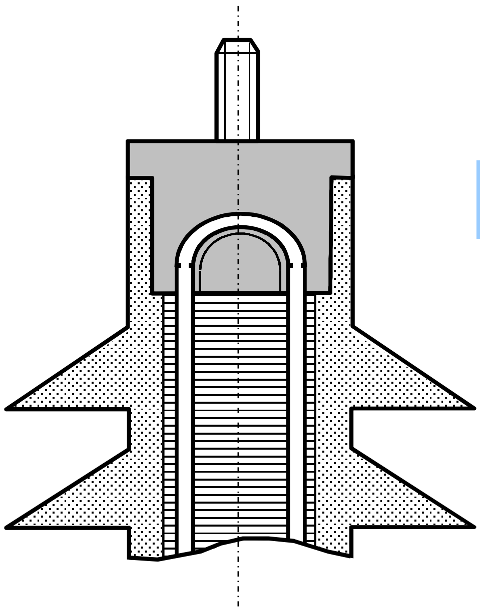
Solid/semi-solid material | Outer housing | Metal end fittings

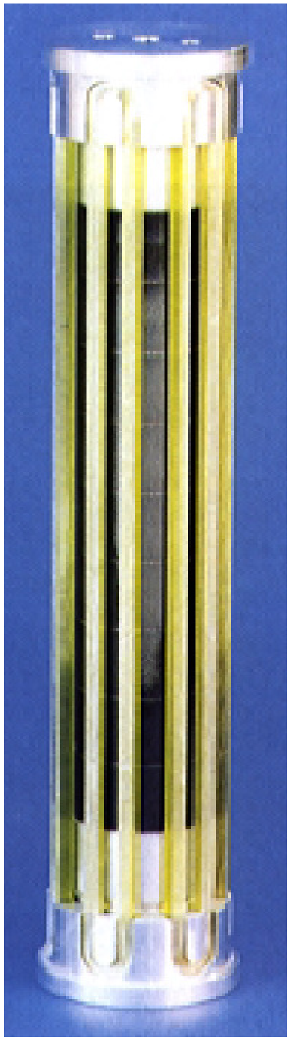
Type B2 "Cage Design"



1st sub-variant

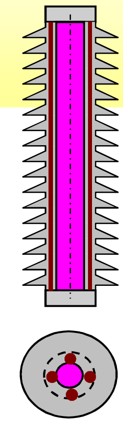
Loops





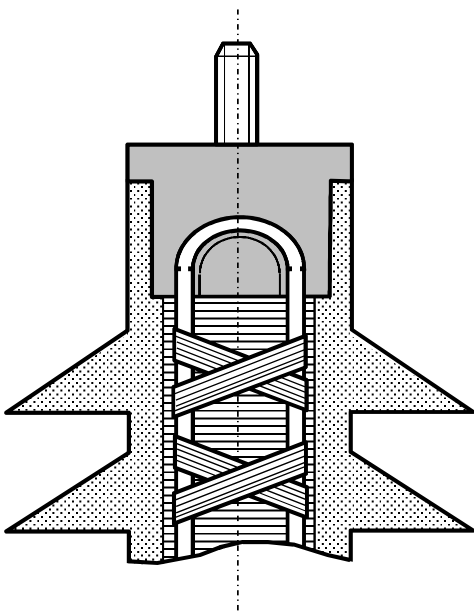
Example: ABB Switzerland

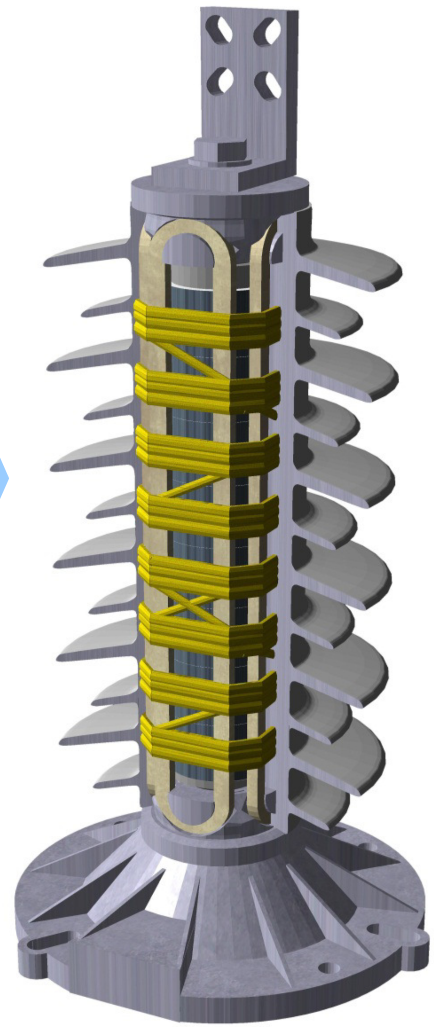
Type B2 "Cage Design"



2nd sub-variant

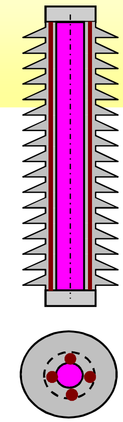
Loops + bondage





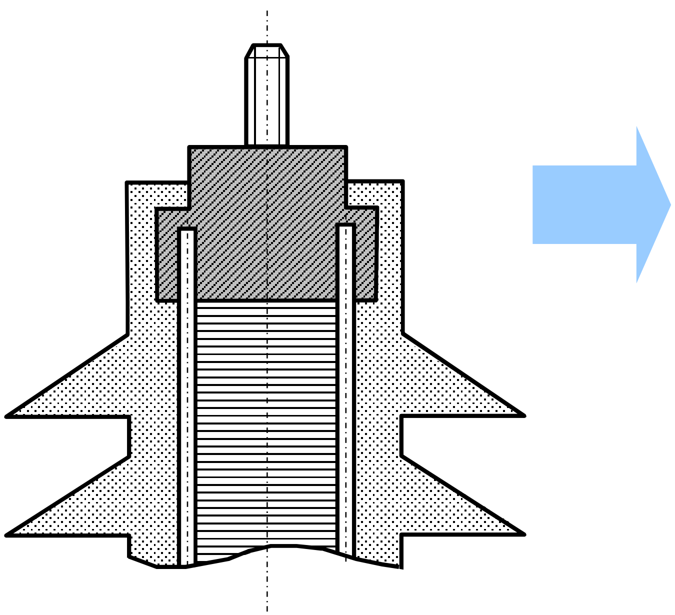
Example: ABB Sweden

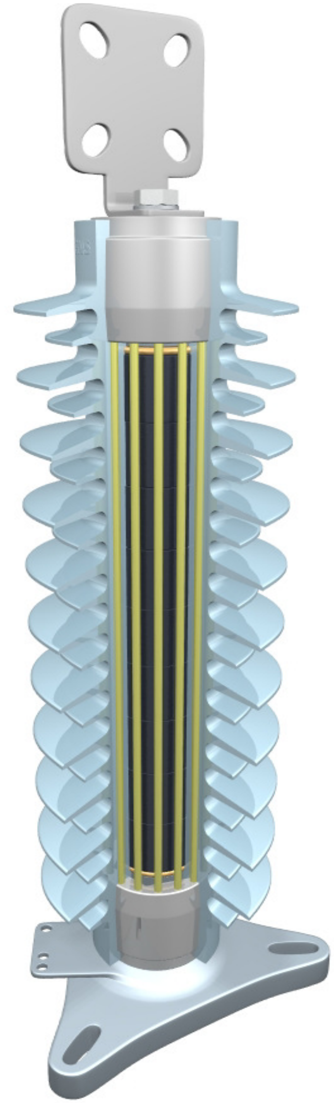
Type B2 "Cage Design"



3rd sub-variant

Rods





Example: Siemens

Part 3: Configuring Arresters

Arrester standards – Definitions, Requirements, Tests

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

IEC 60099-4

Edition 2.2 2009-05

INTERNATIONAL STANDARD

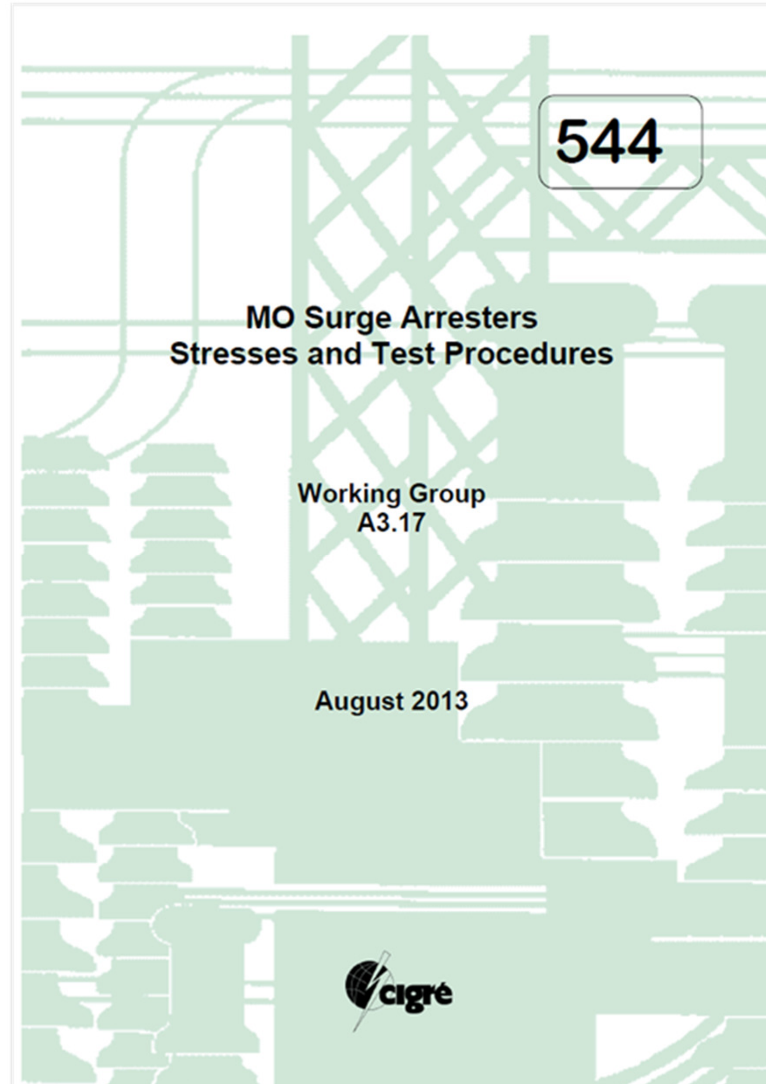
NORME INTERNATIONALE

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

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

- Edition 3 published in June 2014
- Far reaching conceptual changes compared to Edition 2.2
- Both approaches must be known to the user today!

IEC Arrester Application Guide and Cigre Technical Brochure



Arrester standards – IEEE Standard

IEEE STANDARDS ASSOCIATION ◆IEEE

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

IEEE Power and Energy Society

Sponsored by the
Surge Protective Devices Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

20 December 2012

IEEE Std C62.11™-2012
(Revision of
IEEE Std C62.11-2005)

Though efforts have been and are being made to unify IEC and IEEE arrester standards there are considerable differences.

This tutorial is exclusively based on the IEC standards.

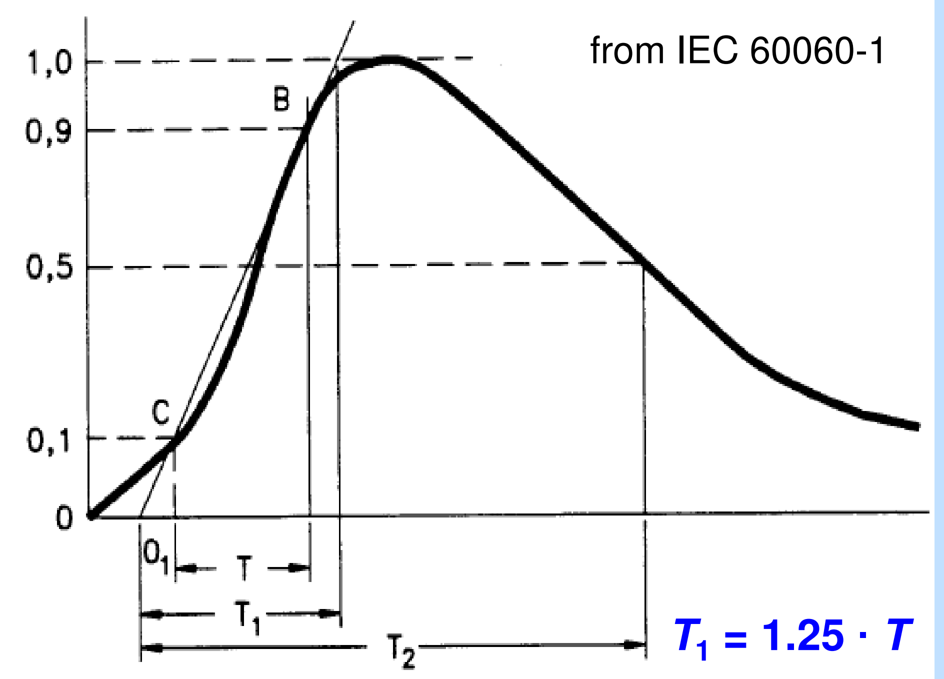
Specified Currents for Residual Voltage Tests on MO Arresters

Double exponential current impulses: definition by T_1/T_2 and $\hat{\imath}$

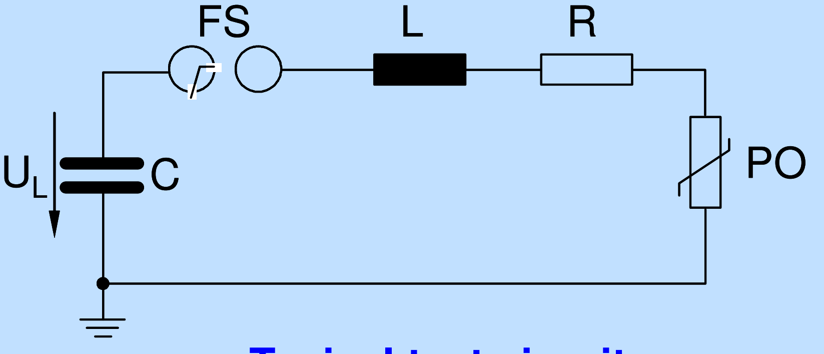
T_1 Front time (µs)

T_2 Time to half value (µs)

$\hat{\imath}$ Amplitude (kA)



$T_1 = 1.25 \cdot T$



Typical test circuit

Specified Currents for Residual Voltage Tests on MO Arresters

- **"Switching current impulse":** $(30…100)/(2 \cdot T_1)$ µs, $\hat{\imath}$ <= 2 kA
- **"Lightning current impulse":** 8/20 µs, $\hat{\imath}$ <= 40 kA
(nominal discharge current I_n usually 5, 10 or 20 kA)
- **"High current impulse":** 4/10 µs, $\hat{\imath}$ <= 100 kA
(typical values 65 and 100 kA)
- **"Steep current impulse":** 1/<20 µs, $\hat{\imath}$ <= 20 kA

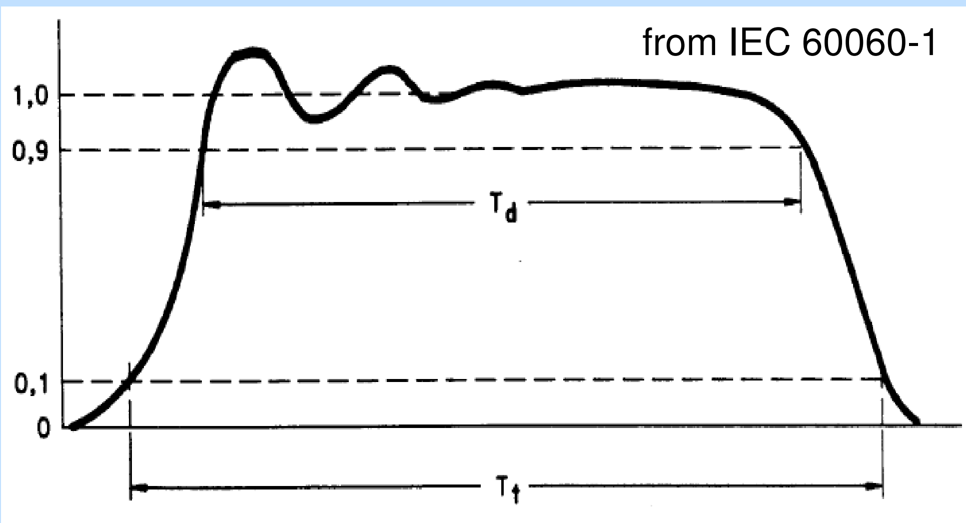
Specified Currents for Energy Tests on MO Arresters

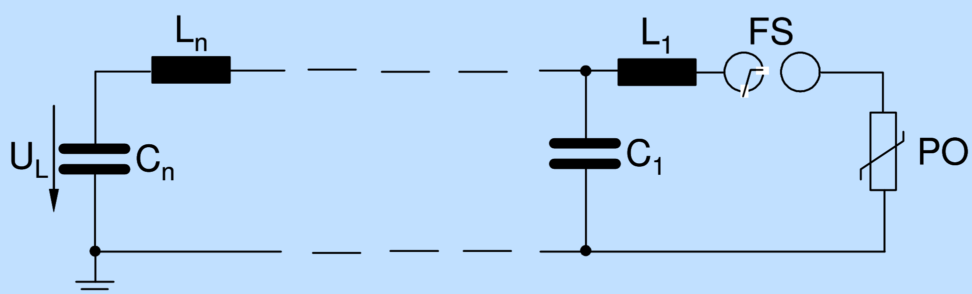
"Long duration current impulse": $\hat{\imath}$ <= 2 kA

T_d Virtual duration of the peak

T_t Virtual total duration

Standard values of T_d: 500, 1000, 2000, 2400, 2800, 3200 µs





Typical test circuit

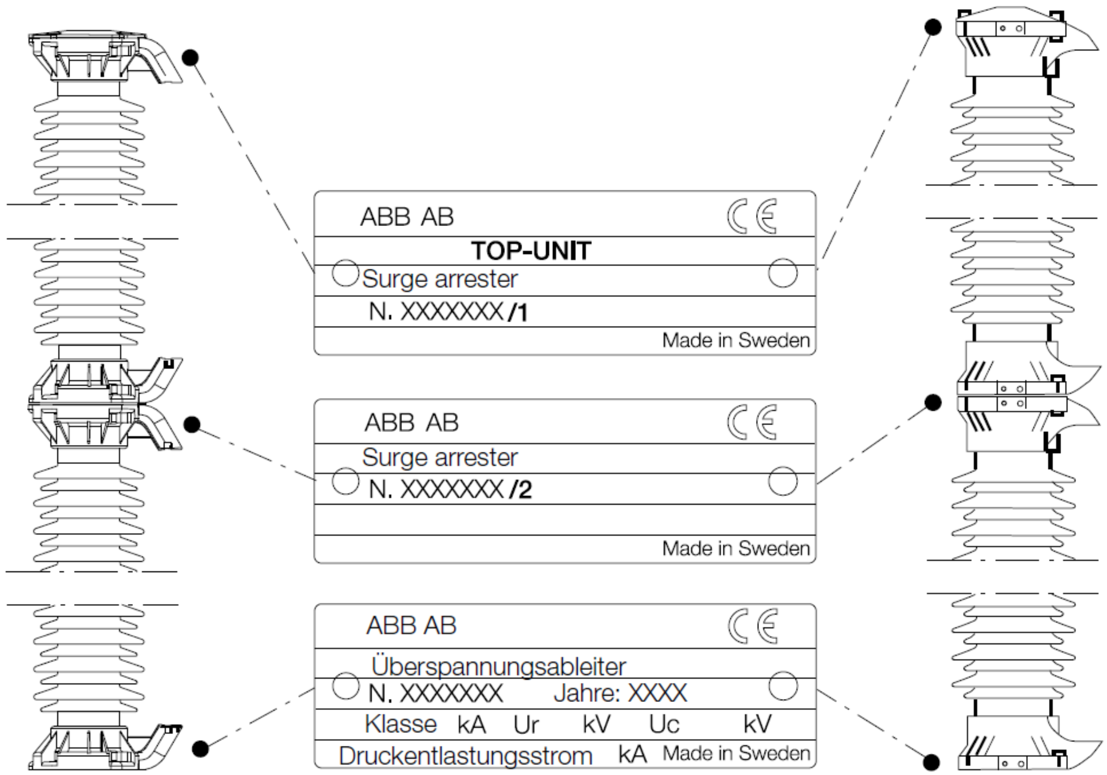
Characteristic Values (1): Main Data

- ~~Line discharge class (LD class)~~ → Application (station or distribution)
- Maximum continuous operating voltage (U_c) (in IEEE: MCOV)
- Rated voltage (U_r)
- Rated frequency (if not 48…62 Hz)
- Nominal discharge current (I_n) (8/20 µs)
- Rated short-circuit current (I_s) (if not specified: "0" must be stated)
- Manufacturer's name, type
- Unit number (in case of multi-unit arresters)
- Year of manufacturing, serial number (for U_r > 60 kV

If enough space available on the name plate:

- Charge transfer rating
- Pollution class

Characteristic Values (2): Main Data



EXLIM R-C und Q-E

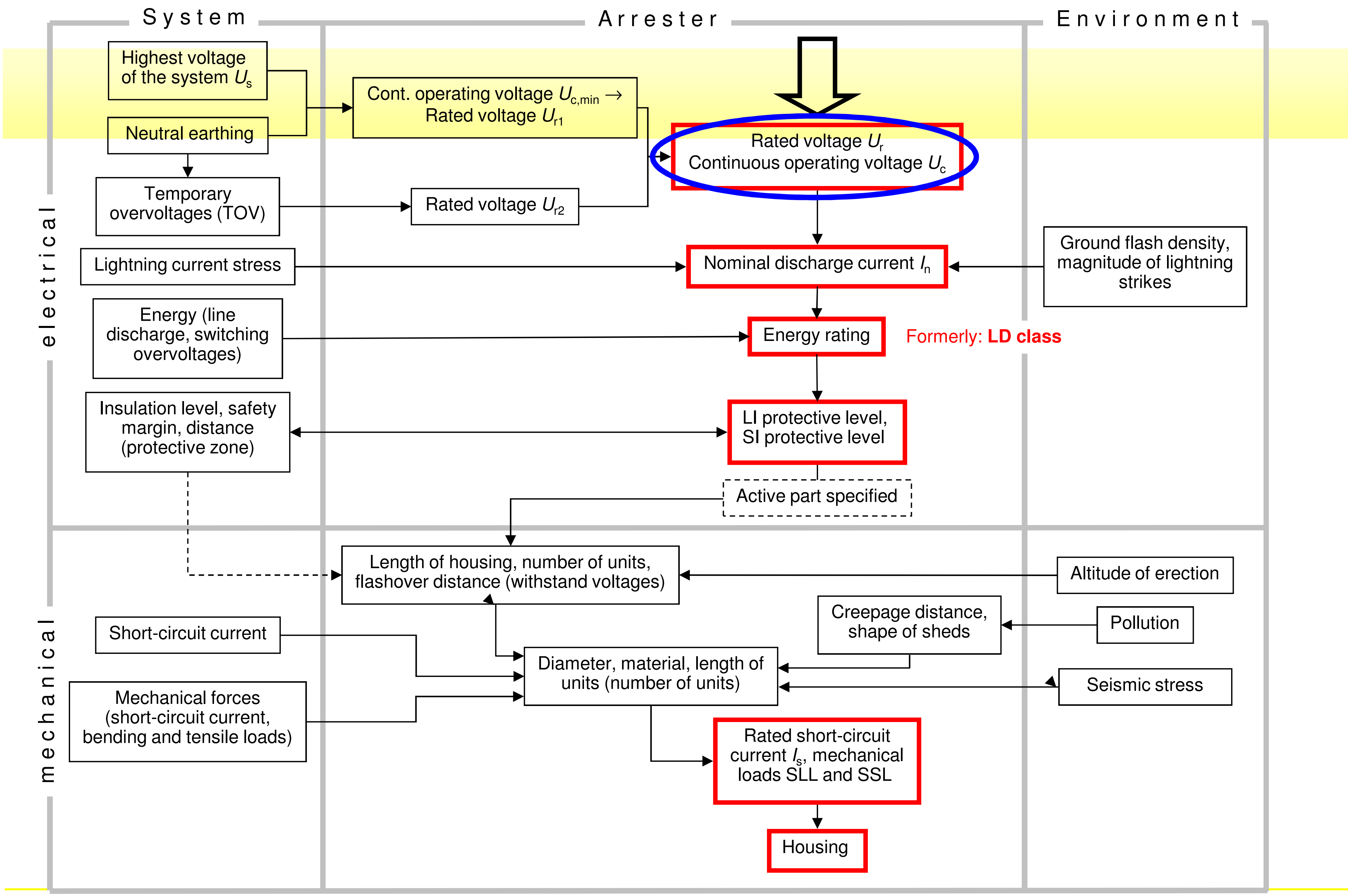
EXLIM Q-D, P-G und T-B

Example **HV arrester**

Example **MV arrester** (limited space!)

Characteristic Values (3): Additional Data

- Thermal energy handling capability (in kJ/kV of U_r)
- High current impulse withstand capability (4/10 µs)
- TOV capability (U-t-characteristics)
- Lightning impulse protection level U_{pl} or LIPL (= residual voltage @ I_n)
- Residual voltage for other current impulse shapes and levels
- Creepage distance of housing
- Withstand voltages of housing
- Mechanical strength (static, dynamic)


System
Arrester
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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 strikes
Energy (line discharge, switching overvoltages)
Energy rating
Formerly: LD class
Insulation level, safety margin, distance (protective zone)
LI protective level, SI protective level
Active part specified
Length of housing, number of units, flashover distance (withstand voltages)
Altitude 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)
Rated short-circuit current I_s, mechanical loads SLL and SSL
Housing

What is the meaning of U_n, U_s and U_m?

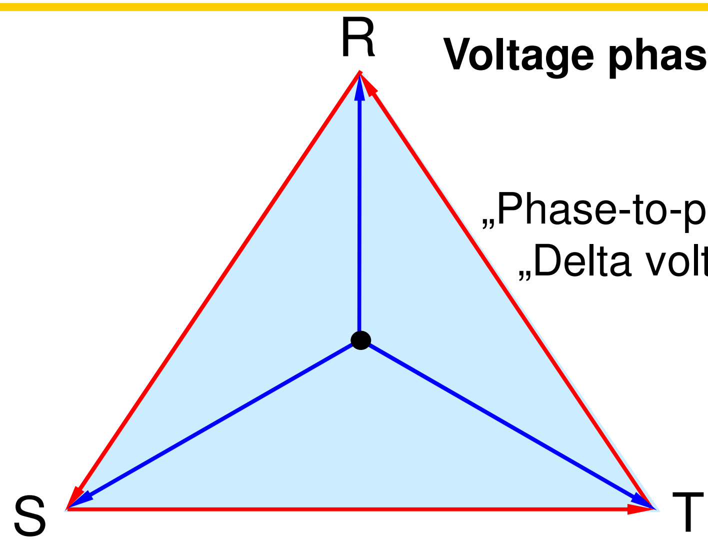
Definition acc. to IEC 60071-1 („Insulation co-ordination“)

nominal voltage of a system
U_n
suitable approximate value of voltage used to designate or identify a system

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

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

Voltage phasor diagram



„Phase-to-phase voltage“
„Delta voltage“

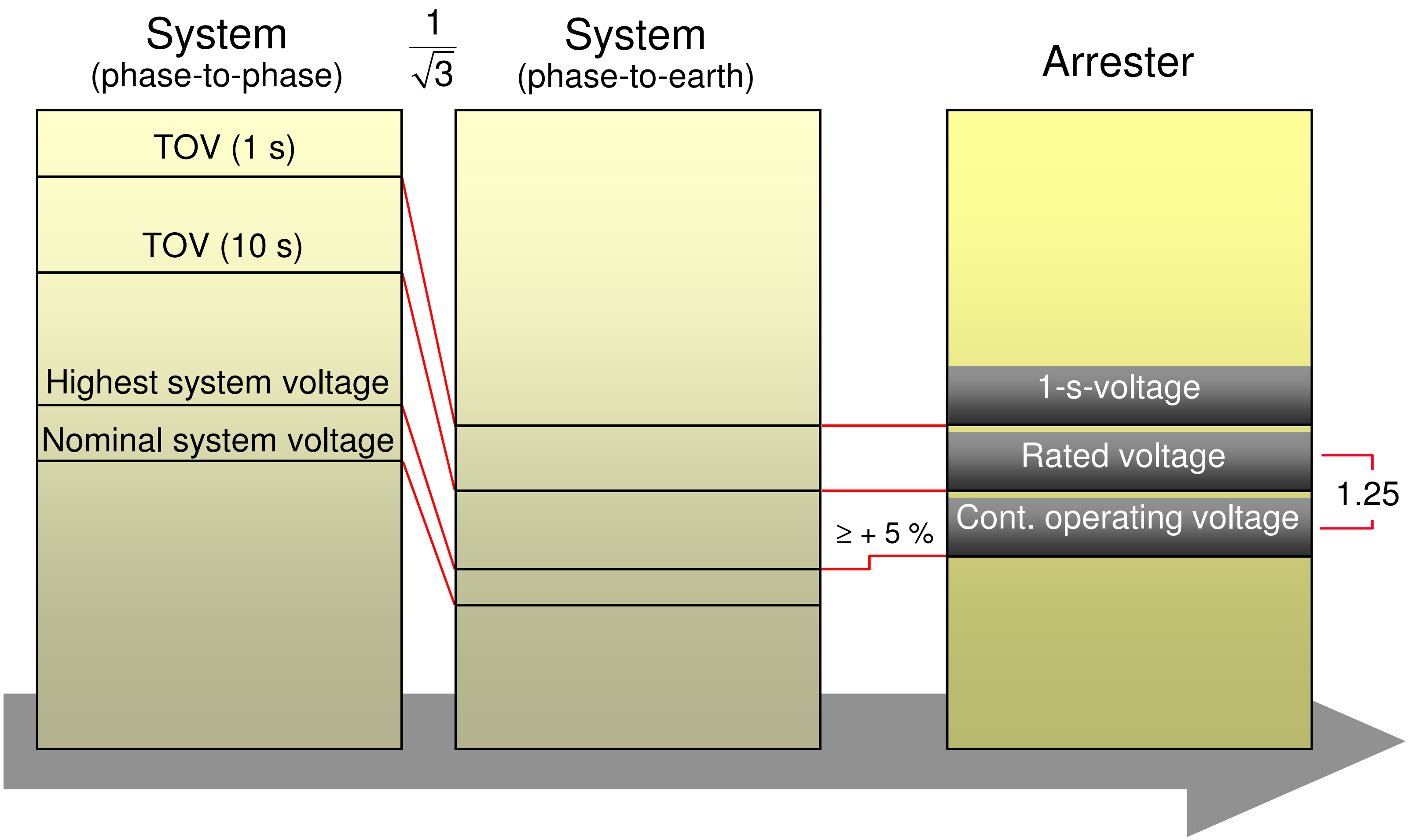
Example: EHV system

U_n = 500 kV
U_s = 550 kV
U_m = 550 kV (usually!)

Line-to-earth voltage:

$$U_{LE} = U_s / \sqrt{3} = 318 \text{ kV}$$

Choice of Continuous Operating and Rated Voltage

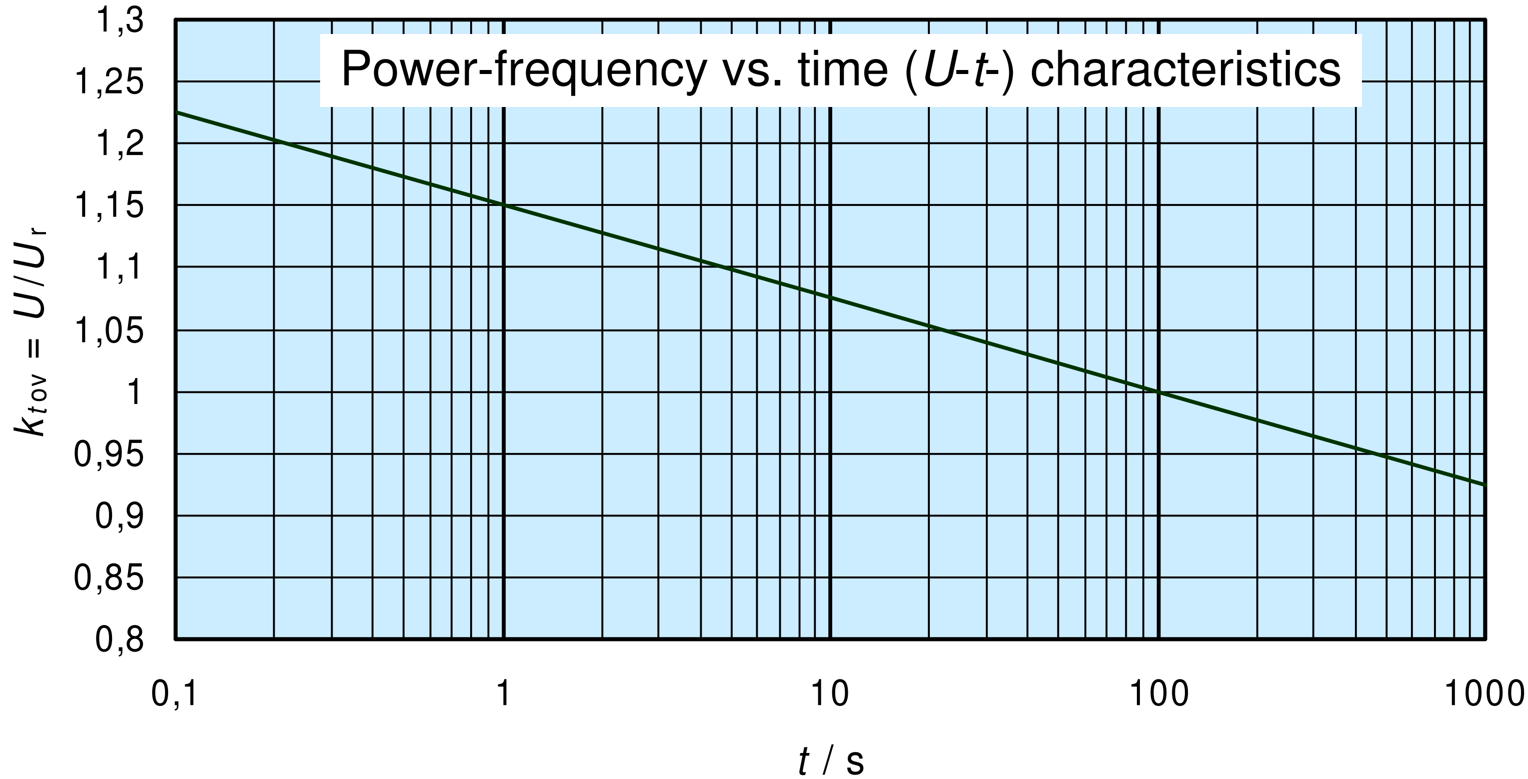


Note: Nominal system voltage of no interest for configuring an arrester!

Choice of Continuous Operating and Rated Voltage

$\boldsymbol{U_{r1}} = 1.25 \cdot U_{c,min} = 1.25 \cdot (1.05 \cdot U_s/\sqrt{3})$

$$\boldsymbol{U_{r2}} = \frac{U_{TOV}}{k_{TOV}} = f(t_{TOV})$$



U_r is the higher value of U_{r1} and U_{r2}, rounded up to a multiple of three

Calculation Example ($U_s = U_m = 420$ kV)

U_s = 420 kV **$U_{10sec} = 1.4 \cdot U_s/\sqrt{3}$ = 340 kV** **(LIWV of equipment = 1425 kV)**

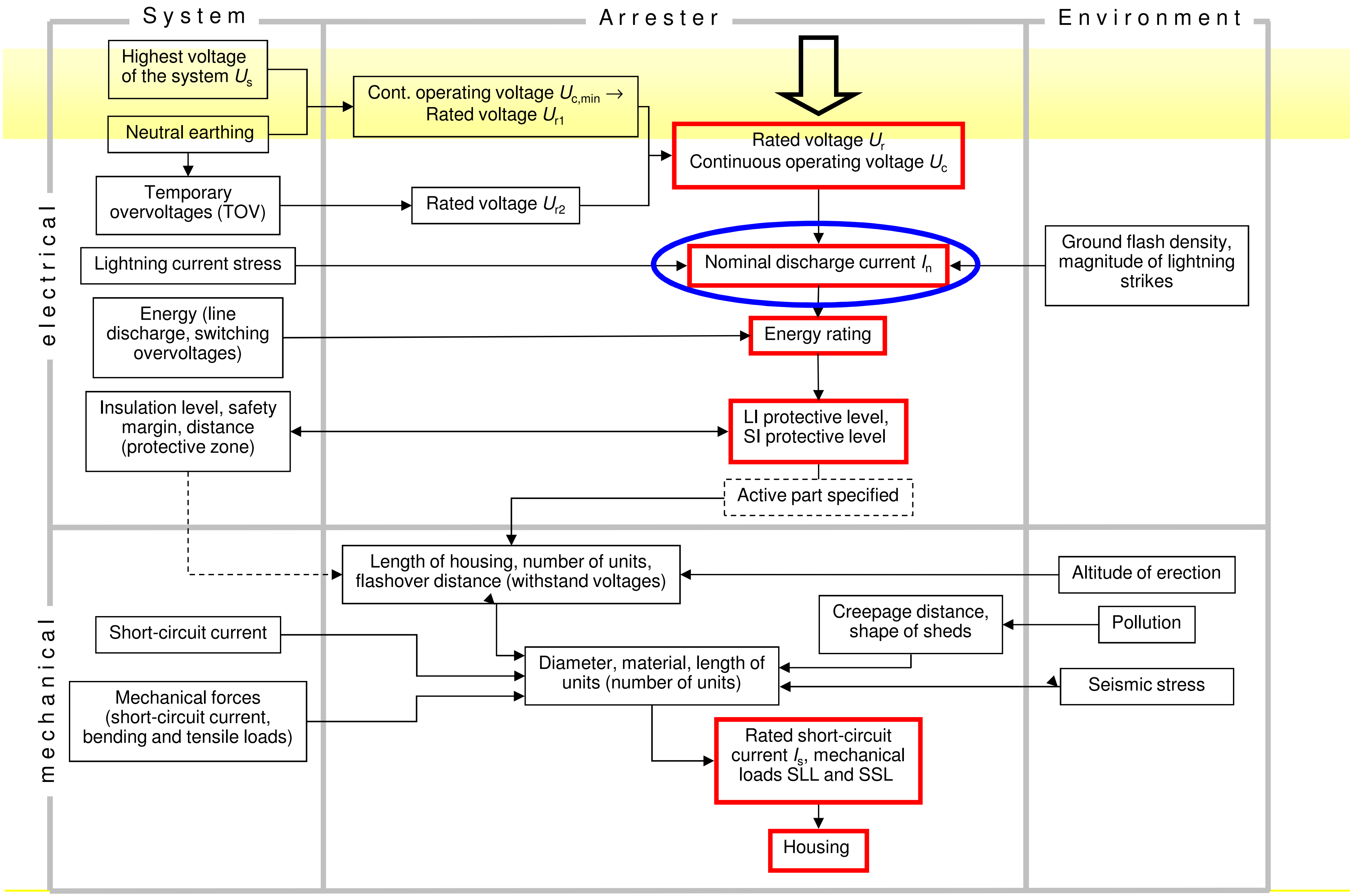
Rated Voltage:

$U_{c,\,min} = 1.05 \cdot U_s/\sqrt{3} = 255$ kV

$U_{r1} = 1.25 \cdot U_{c,\,min} = 319$ kV

$$U_{r2} = \frac{U_{TOV}}{k_{TOV}} = \frac{340}{1.075} = 316 \text{ kV}$$

$\Rightarrow$ **$U_{r,\,min}$ = 321 kV** **$U_{r,\,typ}$ = 336 kV**



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Nominal discharge current I_n
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LI protective level, SI protective level
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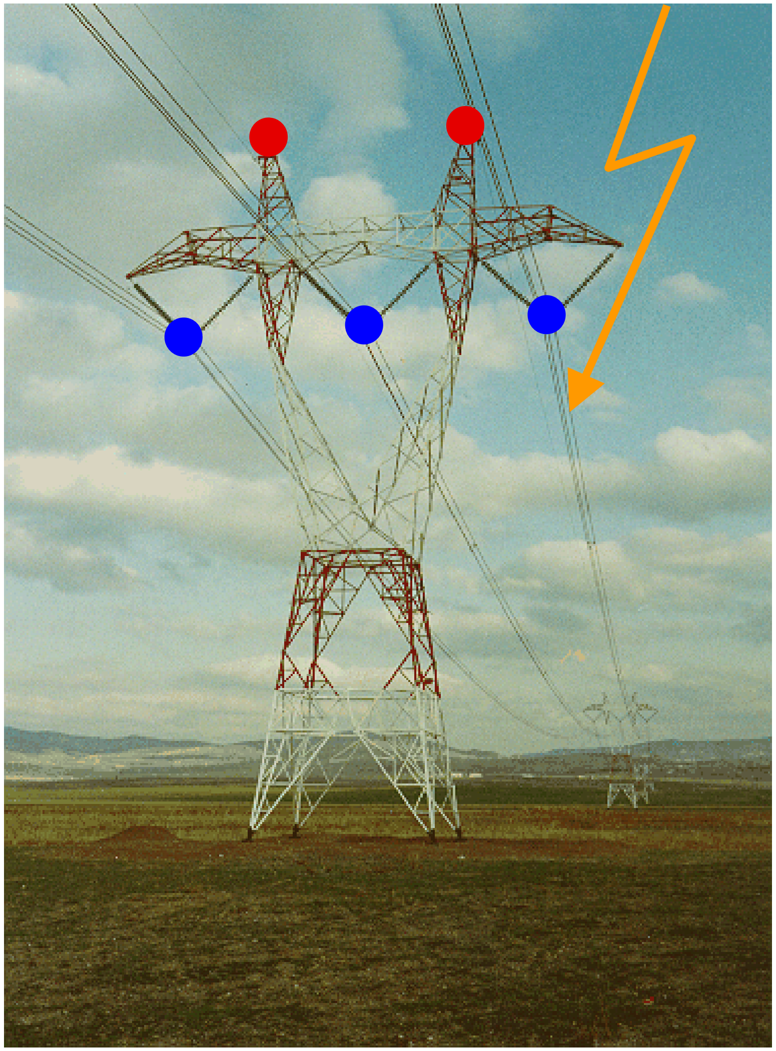
Length of housing, number of units, flashover distance (withstand voltages)
Altitude of erection
Creepage distance, shape of sheds
Pollution
Short-circuit current
Diameter, material, length of units (number of units)
Seismic stress
Mechanical forces (short-circuit current, bending and tensile loads)
Rated short-circuit current I_s, mechanical loads SLL and SSL
Housing

Direct Lightning Strikes to Overhead Line Conductors



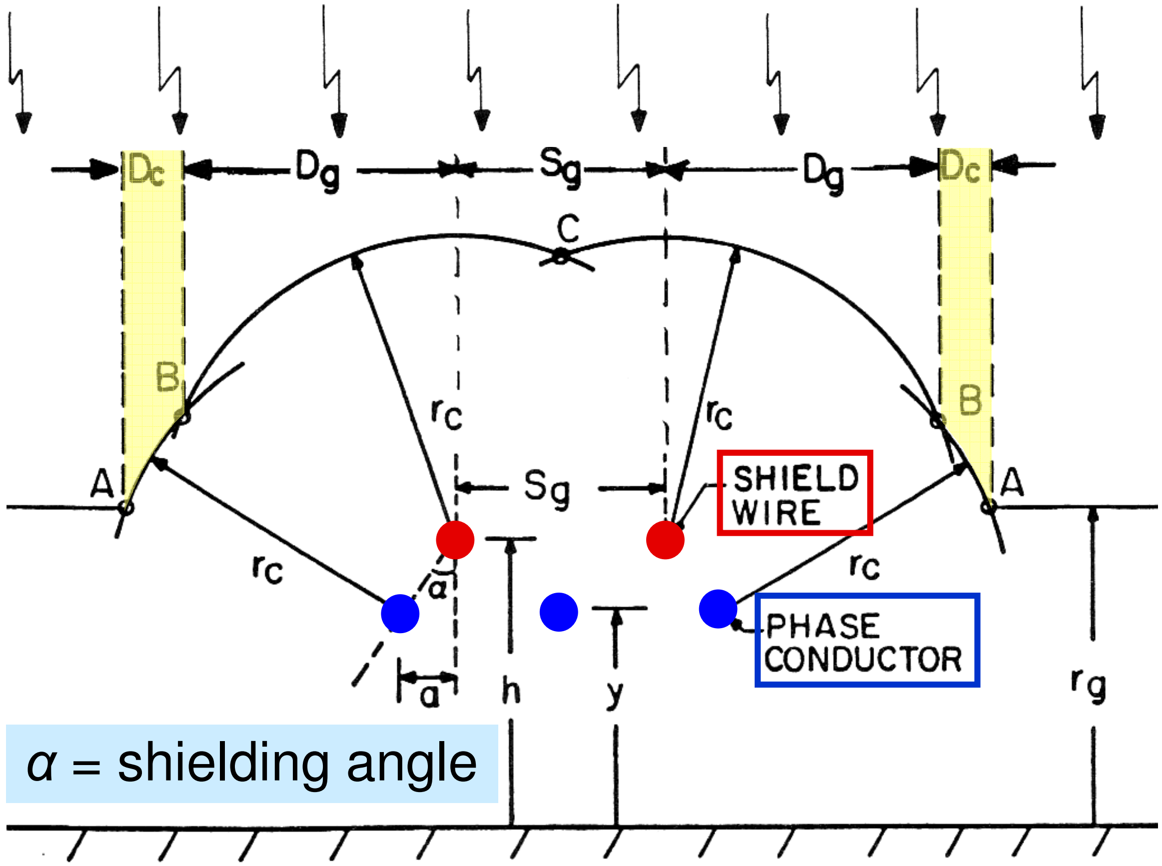
The nominal discharge current I_n is a coordination current on which the protective characteristics and thus insulation coordination are based.

Question: What is a reasonable value for I_n?

To answer this question: what are the highest possible currents of a lightning strike directly into the overhead line conductor?

Direct Lightning Strikes to Overhead Line Conductors

CIGRÉ electro-geometrical model (EGM)



α = shielding angle

strikes between A and B → phase conductor
strikes between B and C → ground wire
strikes beyond A → ground

- r_c and r_g are the maximum striking distances of a return stroke to the stepped leader.
- The higher the strike current, the higher r_c and r_g.
- I_m is the maximum current at and above which no strikes will terminate on the phase conductor ("windows" D_c completely closed):

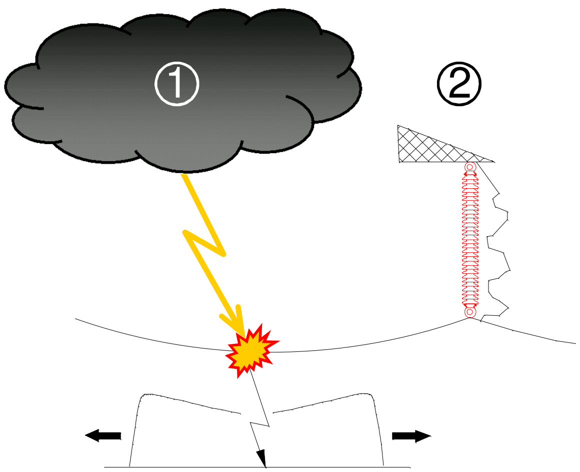
$$I_m \approx \left[\frac{\frac{h+y}{2}}{7.1 \cdot (1-\sin\alpha)} \right]^{\frac{1}{0.75}}$$

Examples:

h = 60 m, y = 45 m, α = 30 °
⇒ $I_m \approx$ **36 kA**

h = 30 m, y = 25 m, α = 15 °
⇒ $I_m \approx$ **9 kA**

Lightning Strike and Surge Propagation on a Transmission Line



① Lightning strike: two traveling waves of $\hat{u} = ½ \cdot Z \cdot \hat{\imath}$ (Example: $\hat{u} = ½ \cdot 350\ \Omega \cdot 20\ \text{kA} = 3.5\ \text{MV}$)

② 1st insulator (and possibly further insulators): flashover

Example:

- 100 % flashover voltage (negative polarity*)): $u_{d100} \approx 2100$ kV for $U_m = 420$ kV
- max. current of propagating wave: $\hat{\imath} = 2100\ \text{kV} / 350\ \Omega =$ **6 kA**

Surge currents are limited to values below 10 kA!

*) More than 90 % of lightning flashes to ground are **negative cloud-to-ground** flashes!

Lightning Impulse Current Stress of Station Arresters

1. Usually, no direct lightning strikes of discharge currents higher than ≈ 20 kA on shielded transmission lines (all other strikes will hit the shield wire or directly the ground)

2. Currents limited by flashover voltage of line insulators and surge impedance of the line:

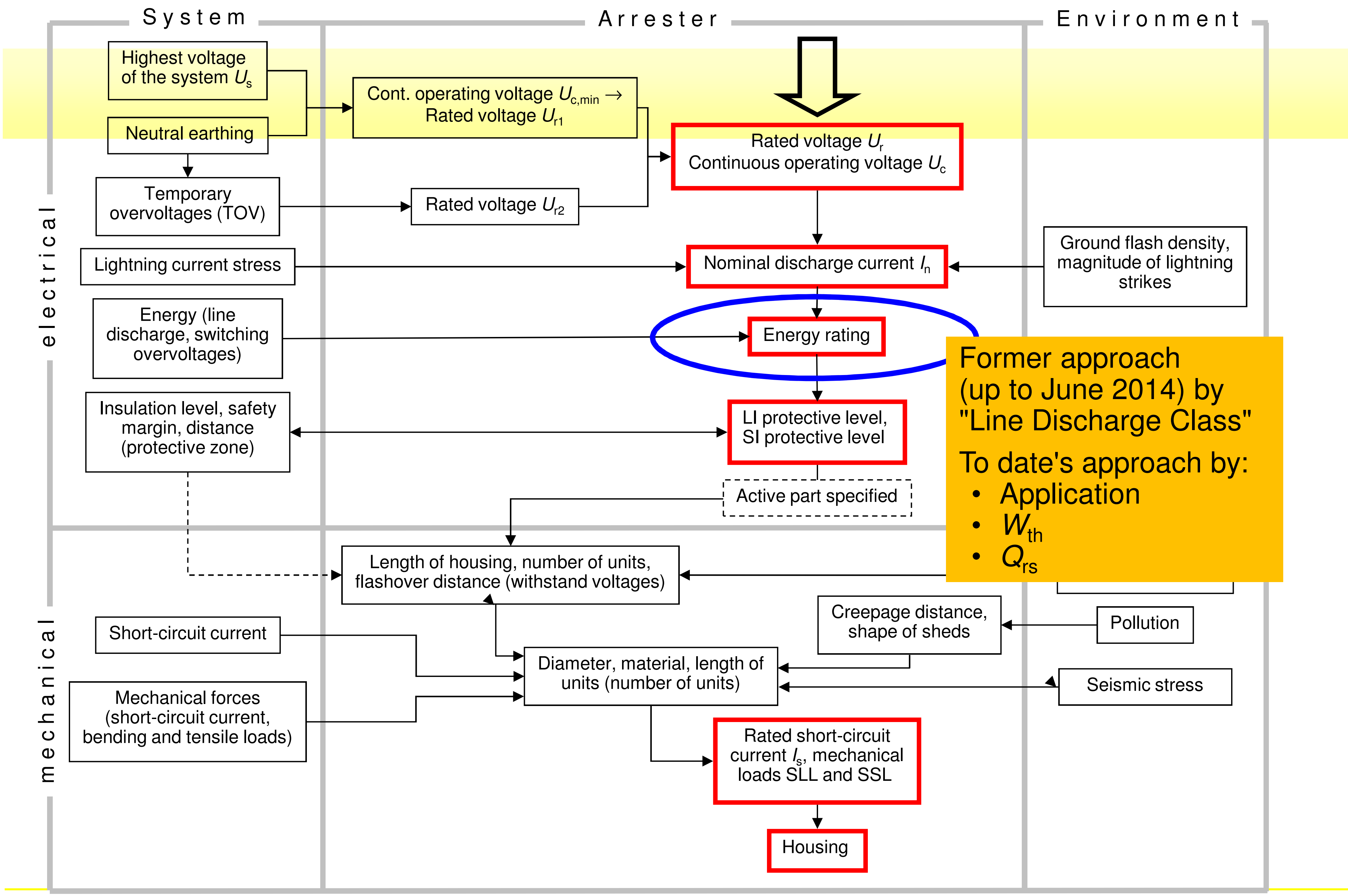
$\hat{i} = \hat{u}_{\text{flashover}}/Z$

Examples:

U_m = 123 kV, $\hat{u}_{\text{flashover}} \approx$ 600 kV, Z = 450 Ω ⇨ **$\hat{i}$ = 1.3 kA**

U_m = 420 kV, $\hat{u}_{\text{flashover}} \approx$ 2 100 kV, Z = 350 Ω ⇨ **$\hat{i}$ = 6 kA**

Though the discharge current will nearly double in the arrester (due to traveling wave effects!), LI currents in the substation arresters usually stay below 10 kA.



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Housing
Former approach (up to June 2014) by "Line Discharge Class"
To date's approach by:
• Application
• W_{th}
• Q_{rs}

Energy Requirements – Basic Considerations

Two aims:

1) Mechanical and electrical integrity of the MO resistors

2) Thermal stability of the complete arrester

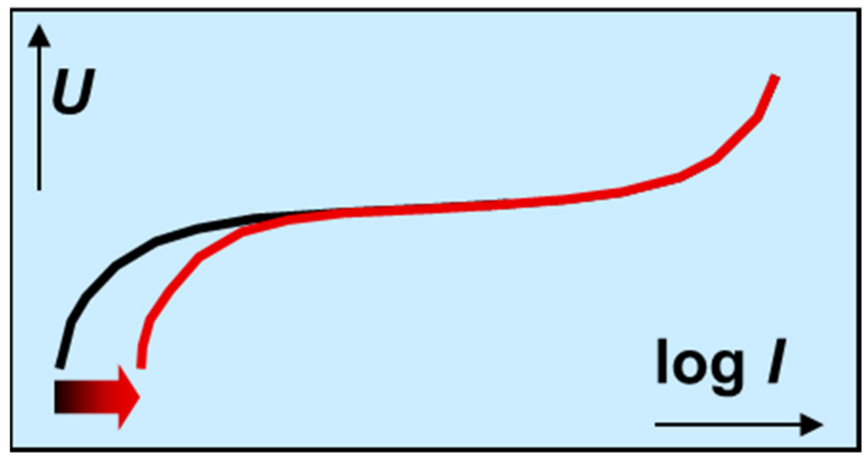
Energy Requirements – Basic Considerations

1) → **Impulse** energy handling capability

- Energetic overloading
  - puncture or thermo-mechanical cracking of one or more MO-resistors)
  - Electrical degradation of the *U-I* characteristic

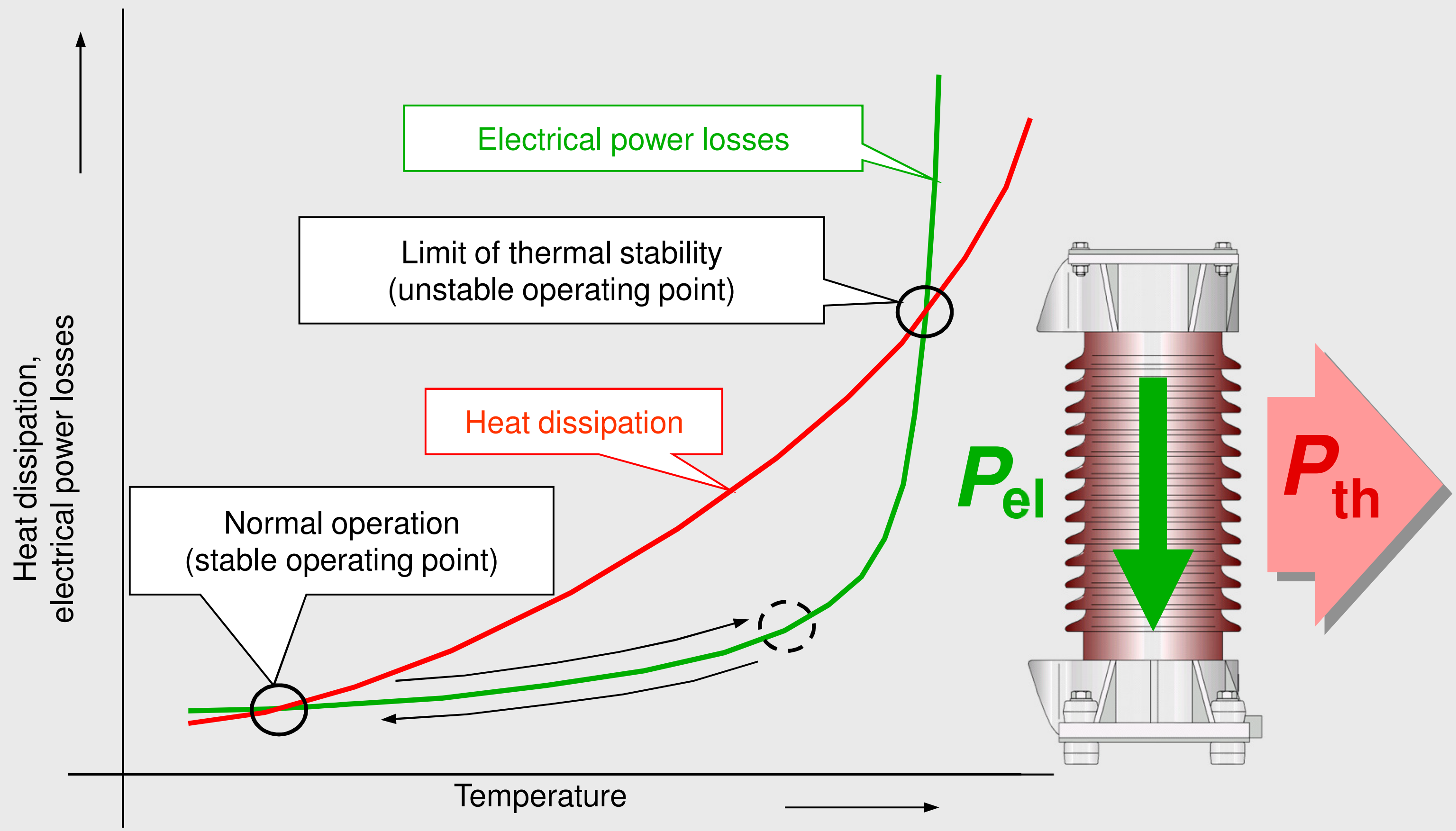
<u>Mechanical damage</u>

<u>Electrical damage</u>



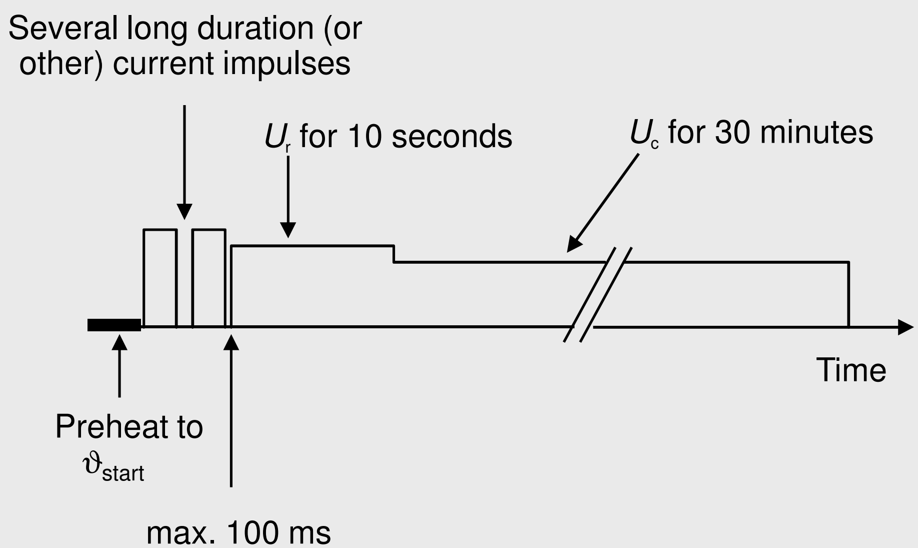
Energy Requirements – Basic Considerations

2) → **Thermal** energy handling capability



"Thermal" and "Impulse" Energy Values – Verification by Tests

"Thermal" (in the housing) [1)]

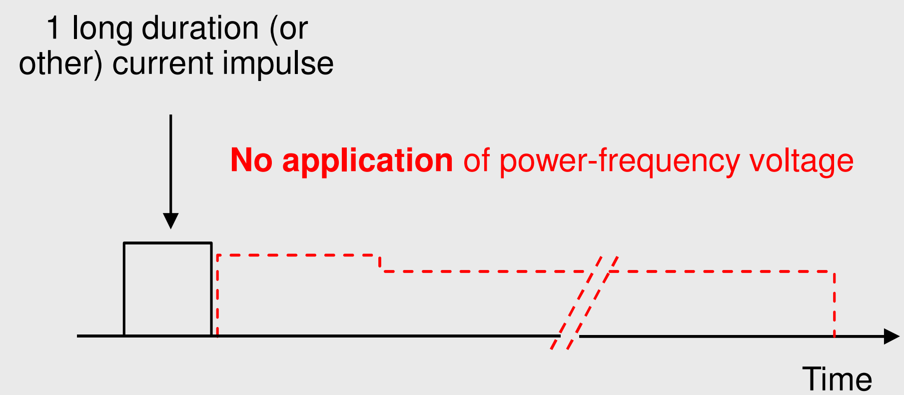


Energy input by **several** (long duration) current impulses (sum energy = specified energy);

Thermal stability under applied voltage required

[1)] **Note:** If no thermal stability has to be guaranteed after energy injection (i.e. arrester de-energized afterwards) higher energy values are allowed.

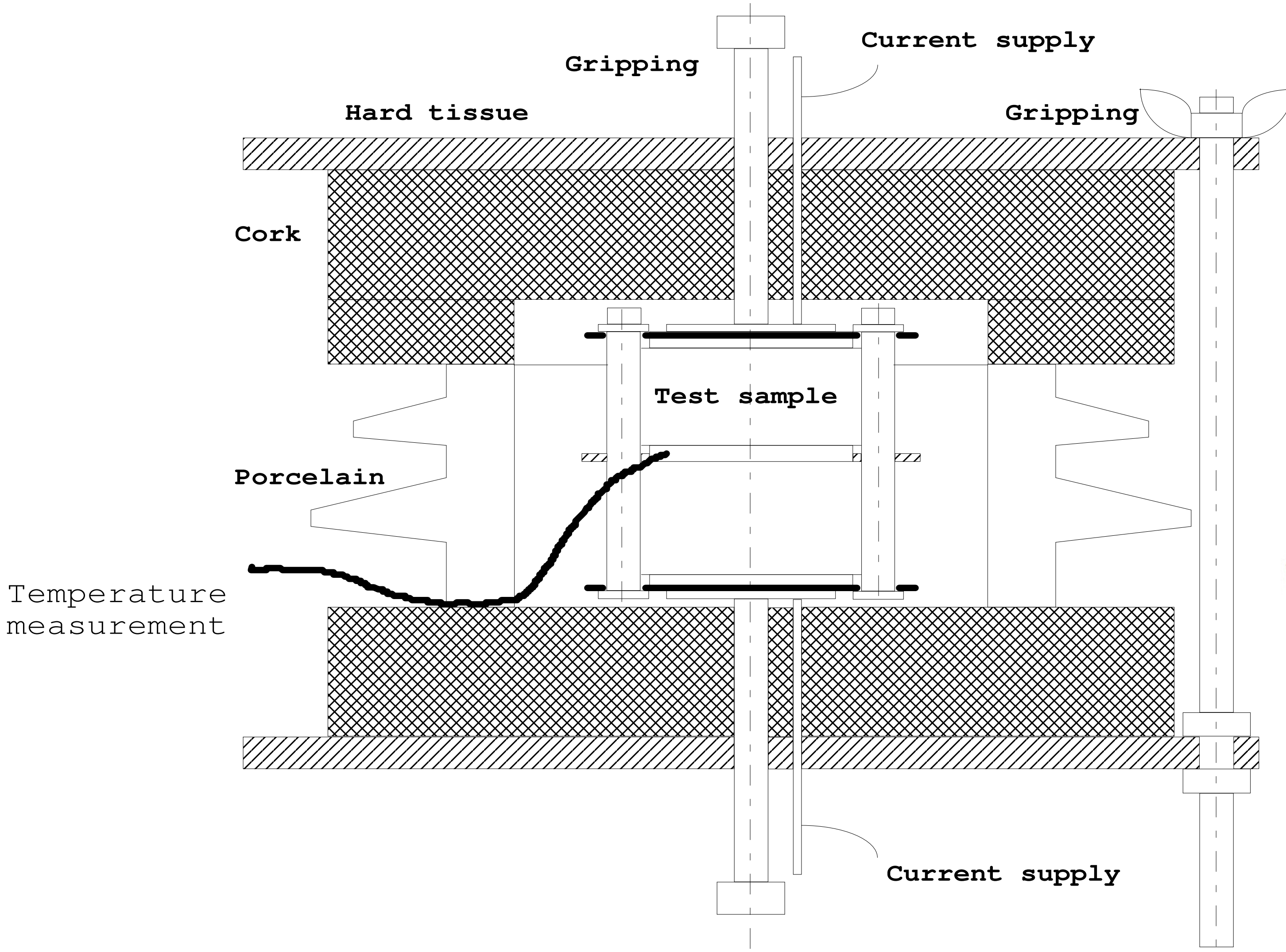
"Impulse" (in open air)



Energy input by **one** (long duration) current impulse $t \geq$ **2 ms**;

Thermal stability not an issue

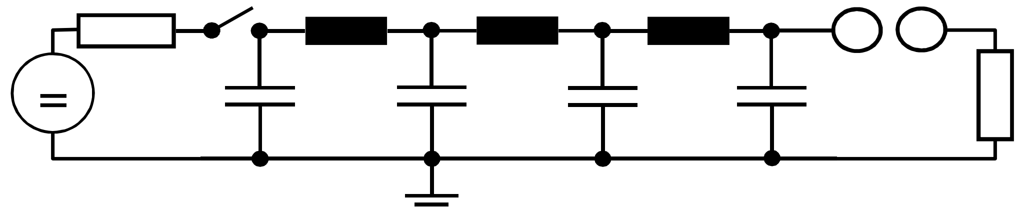
Thermally Equivalent Prorated Section for Operating Duty Test



Meaning of
"in the housing"

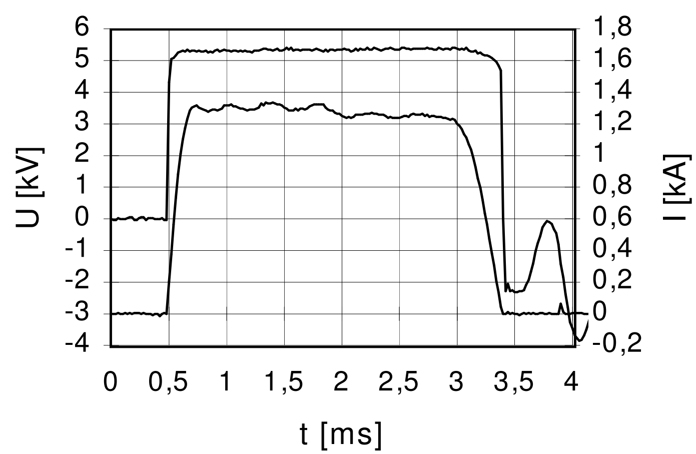
Long Duration Current Generator in the Laboratory

Long duration current impulse generator with LC distributed network



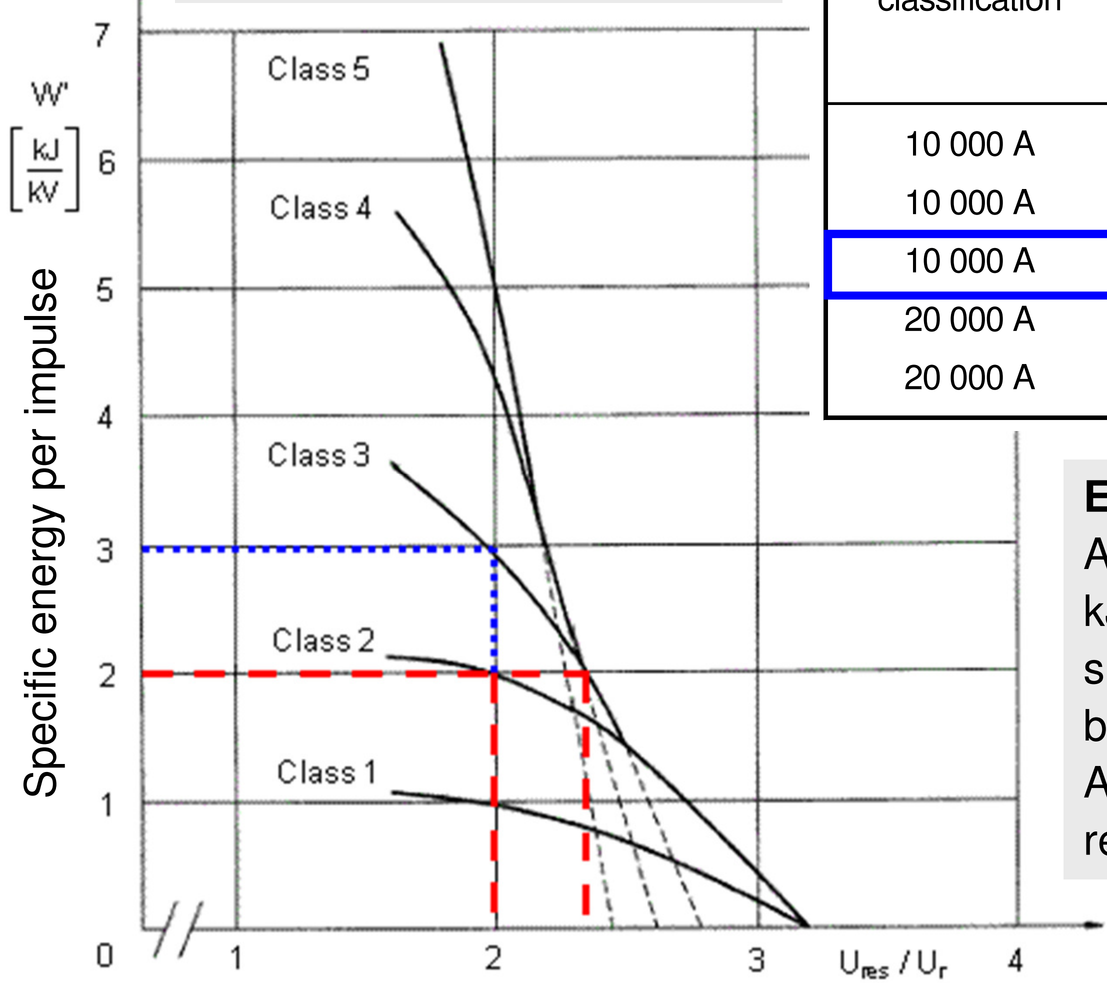
Parameters (to be adjusted):

- inner surge impedance ***Z***
- time duration ***T*** of the impulse
- charging voltage U_L



"Old" Approach: Line Discharge Class – Problem of Definition

$W = U_{res} \cdot (U_L - U_{res}) \cdot 1/Z \cdot T$



Arrester classification	Line discharge class	Surge impedance of the line Z (Ω)	Virtual duration of peak T (μs)	Charging voltage U_L (kV d.c.)
10 000 A	1	4,9 U_r	2 000	3,2 U_r
10 000 A	2	2,4 U_r	2 000	3,2 U_r
10 000 A	3	1,3 U_r	2 400	2,8 U_r
20 000 A	4	0,8 U_r	2 800	2,6 U_r
20 000 A	5	0,5 U_r	3 200	2,4 U_r

Example:
A MO arrester with resistors of **4 kJ/kV** (2·2 kJ/kV) energy absorption capability may be specified as a Class 2 arrester if $U_{res}/U_r = 2$, but as a Class 3 arrester if $U_{res}/U_r = 2.4$.
A Class 3 arrester of $U_{res}/U_r = 2$ needs resistors of **6 kJ/kV** (2·3 kJ/kV).

UHV Arresters – Energy Handling Considerations

Example: U_s = 1200 kV

- U_r = 850 kV
- $U_{res} \approx 0.95 \cdot \text{SIPL} = 0.95 \cdot 1500$ kV = 1425 kV
- Ratio $U_{res}/U_{r,min} \approx 1.68$

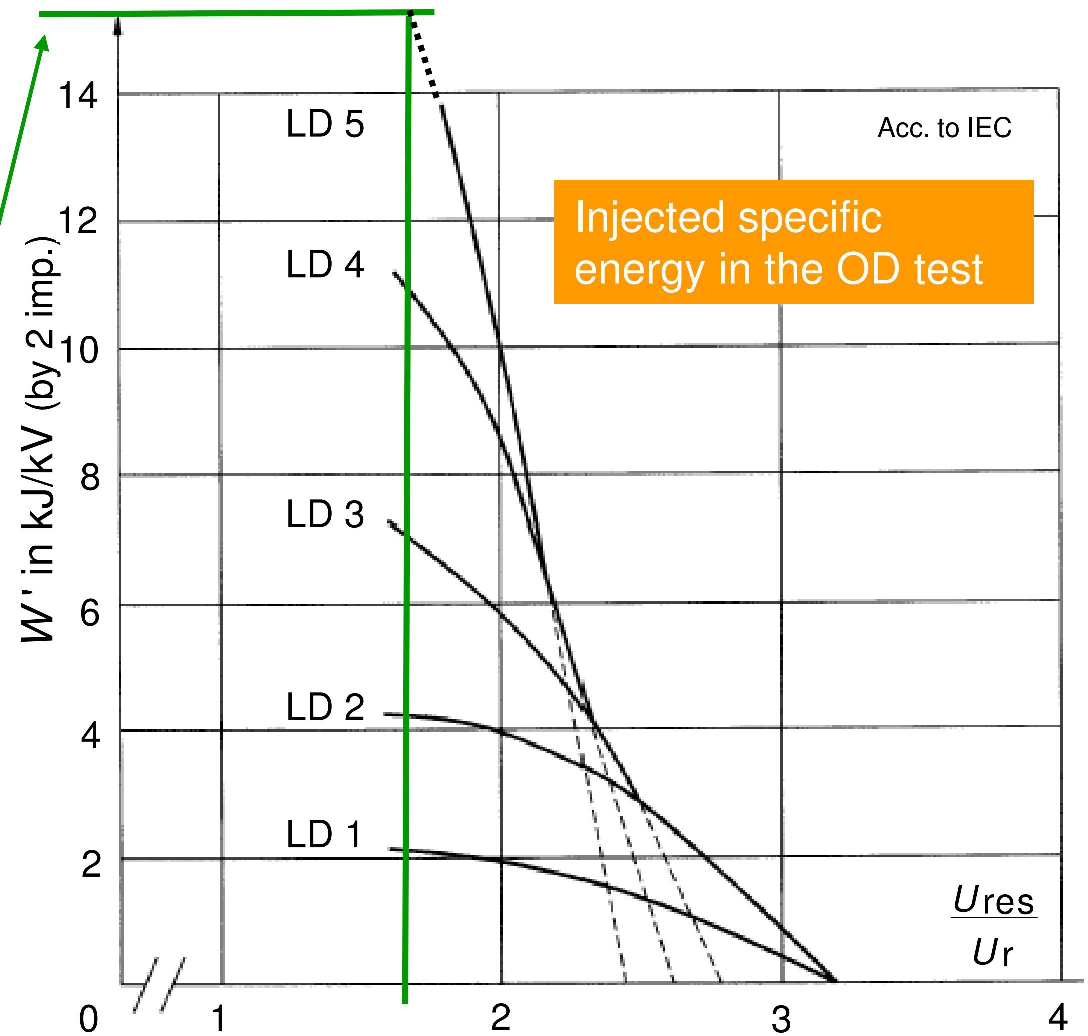
Highest LD class
acc. to IEC 60099-4 Ed. 2.2
LD 5 → W' = 15.5 kJ/kV of U_r

But actual requirement from the system is **W' = 65 kJ/kV of U_r** (total: 55 MJ)

→ **>> LD 5** required

→ must be injected by **> 2 impulses**

→ **Change of the standard** required



"Old" Approach: Further Shortcomings of LD Class System

- Even LD class 5 by far **not sufficient for UHV** arresters
- Meaning of LD class in terms of energy handling capability **unclear** to uninformed users
- Interdependence between LD class and LIPL **unclear** to uninformed users
- Too **complicated** test procedure (unnecessary preconditioning procedure; contradictory requirements on thermally prorated section)
- Energy injection of magnitudes, which are necessary for UHV arresters, **not possible** by only two impulses

IEC 60099-4 Ed. 3.0

The “**new**” **classification** system of IEC 60099-4, Edition 3.0

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

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

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

[IEC]

→ **Class:** Station Distribution

→ **Designation:** High duty Medium duty Low duty

→ **Energy duty:** Q_{rs} W_{th} Q_{th}

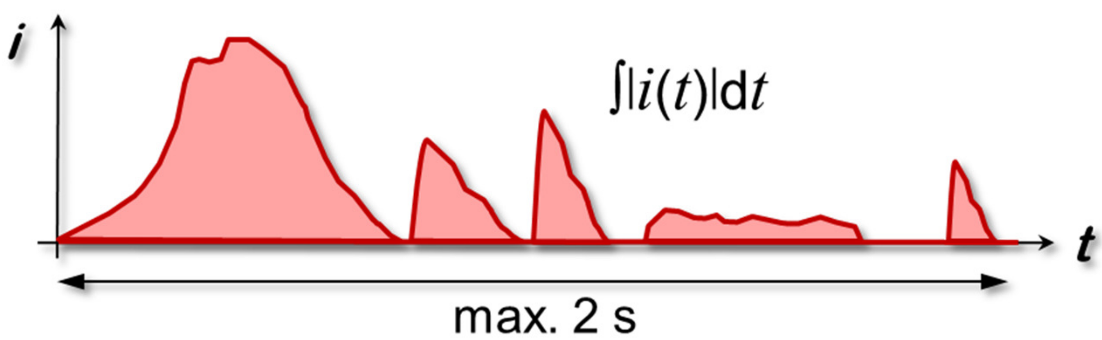
IEC 60099-4 Ed. 3.0

Q_{rs}: Repetitive charge transfer rating

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

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

[IEC]



IEC 60099-4 Ed. 3.0

W_{th}: Thermal energy rating *(Station arresters)*

"Maximum specified energy, given in kJ/kV of U_r, that may be injected into an arrester or arrester section **within 3 minutes** in a thermal recovery test without causing a thermal runaway"

[IEC]

Q_{th}: Thermal charge transfer rating *(Distribution arresters)*

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

[IEC]

Summarized:

- Clear distinction between "thermal" and "impulse" energy handling!
- Advantage over the former approach, which mixed all this up

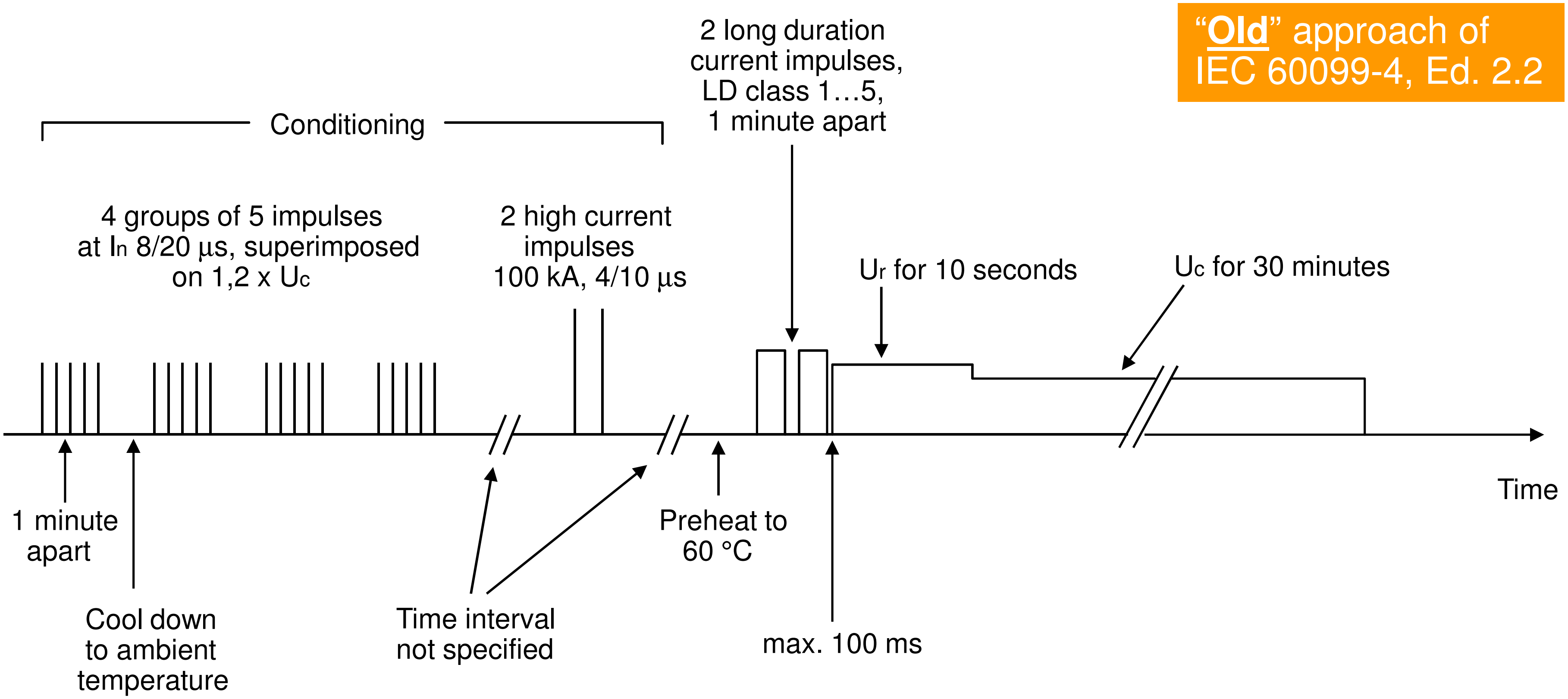
Next slides:

1) Verification test of thermal energy handling capability

2) Verification test of impulse energy handling capability

1) "Switching Surge Operating Duty Test" (IEC 60099-4 Ed. 2.2)

"**Old**" approach of IEC 60099-4, Ed. 2.2

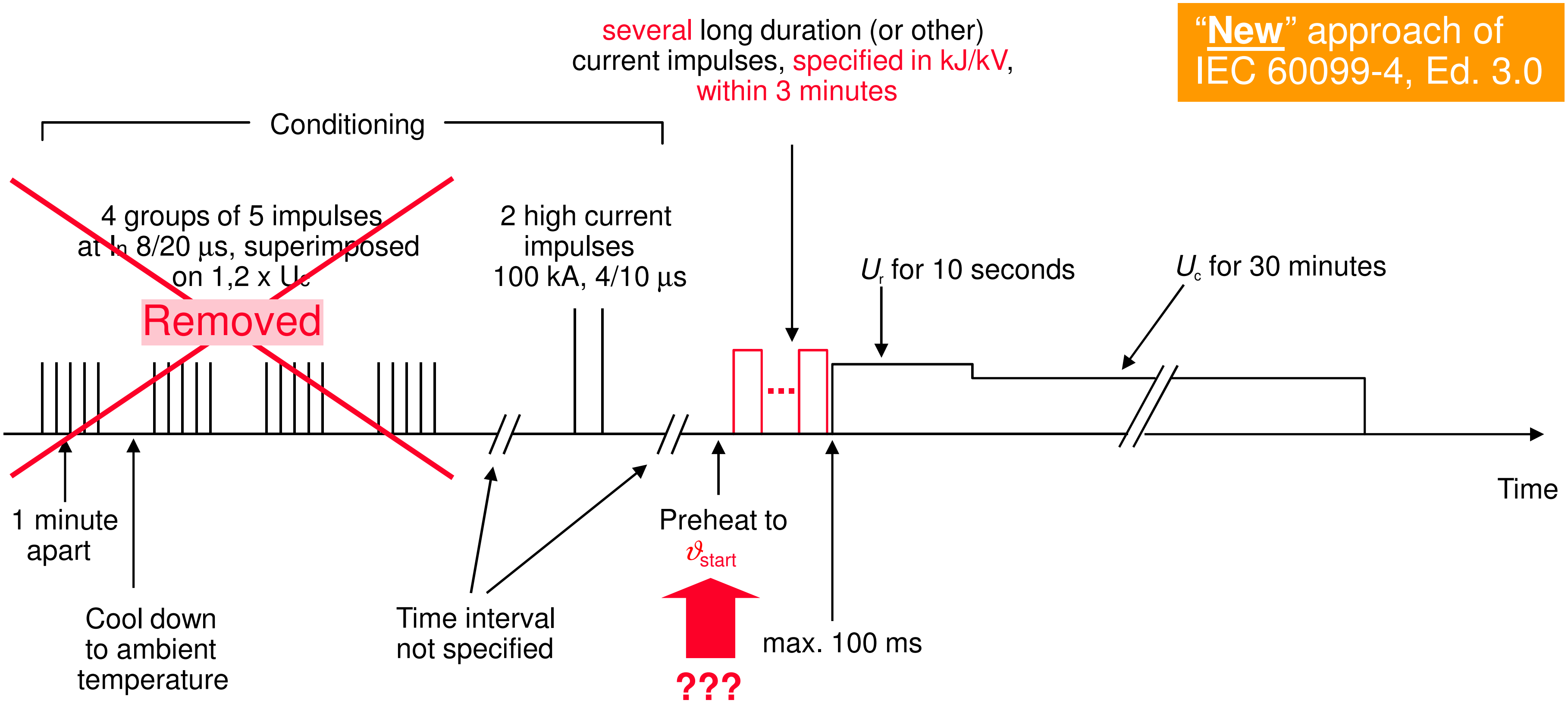


Test evaluation (pass criteria):

- Decrease of temperature, power loss, resistive component of the leakage current
- No significant change of residual voltage (max. 5%)
- No puncture, flashover or cracking of MO blocks

1) "Thermal Recovery Test" (IEC 60099-4 Ed. 3.0)

"**New**" approach of IEC 60099-4, Ed. 3.0



Test evaluation (pass criteria):

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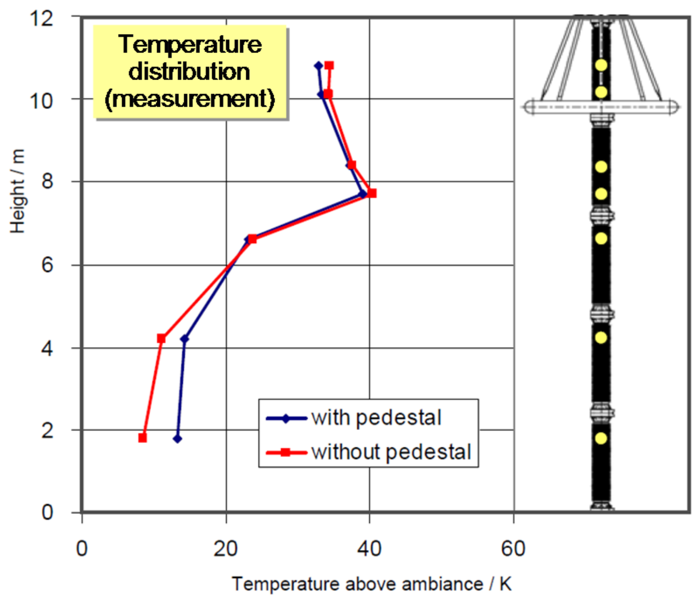
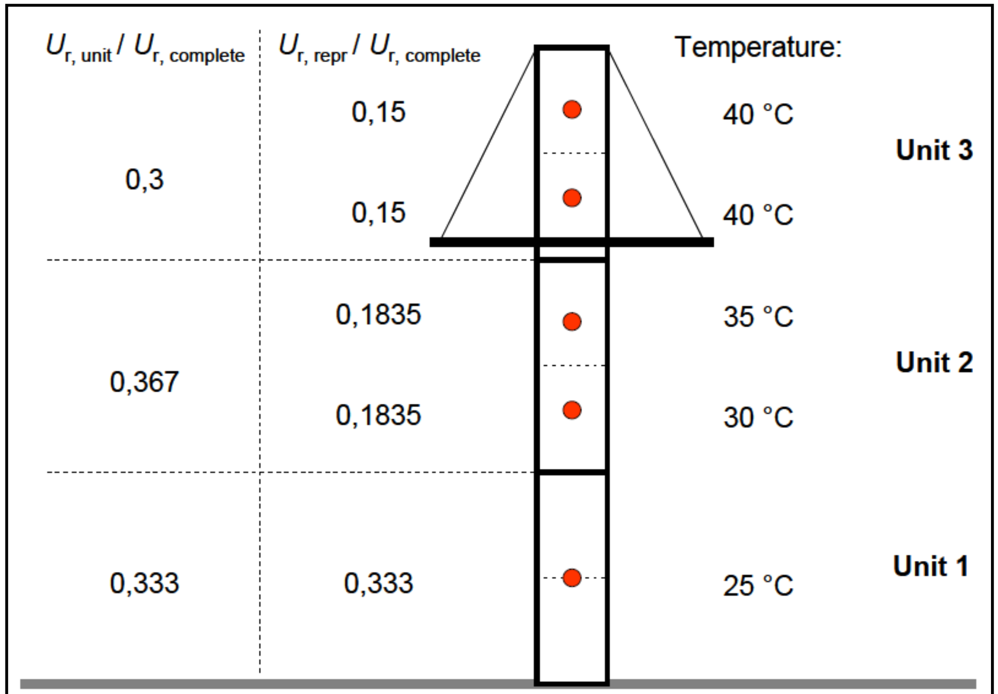
1) "Thermal Recovery Test" (IEC 60099-4 Ed. 3.0)

"**New**" approach of IEC 60099-4, Ed. 3.0



Temperatures in **UHV** arresters may be higher than in HV and EHV arresters.

Determination of **average temperature** ($U = U_c$):



T_{ar} = 0,15·40 + 0,15·40 + 0,1835·35 + 0,1835·30 + 0,333·25 = 32,25 °C

From this temperature, the actual start temperature shall be calculated (acc. to Annex I of 60099-4, Ed. 3.0).

1) "Thermal Recovery Test" (IEC 60099-4 Ed. 3.0)

„Allowed“ impulse current shapes and ways of injection

Test sequence:

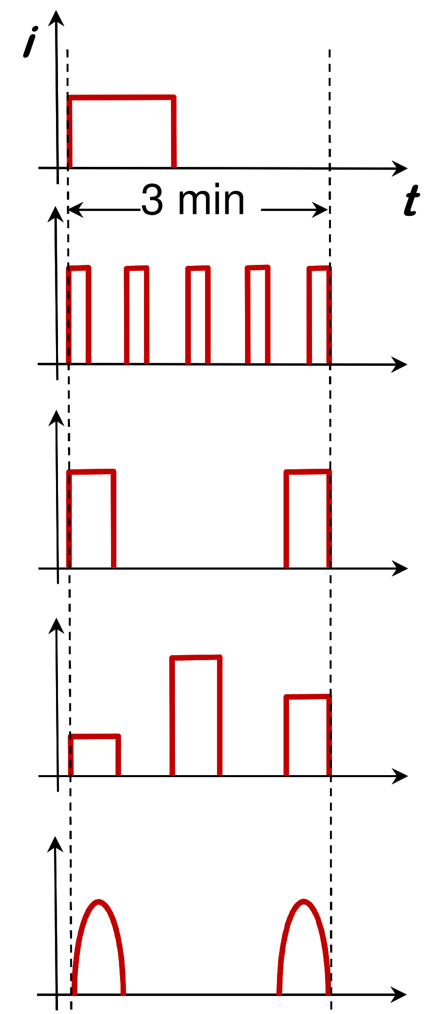
- Start temperature 60 °C, or (UHV) ≥ 60 °C, depending on continuous operating temperature
- Injection of rated thermal energy, W_{th}, within 3 minutes **by one or more** long duration current impulses (2 to 4 ms) **or** by unipolar sine half waves (**only virtually adiabatic heating is intended**)
- Then, within 100 ms, application of rated voltage, U_r, for 10 s, followed by continuous operating voltage, U_c, for at least 30 minutes
- Thermal recovery must be achieved.

→ **Free choice** of the number of energy injections

→ Relatively **free choice** of impulse shape

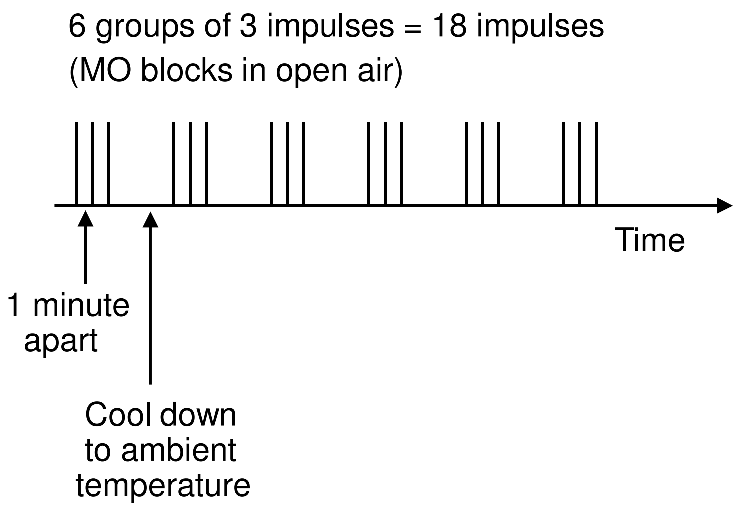
→ Test **simplified** compared to the old standard; reduced (i.e. virtually no) requirements on the test generator

Possible options:



2) "Long Duration Current Impulse Withstand Test" (IEC 60099-4 Ed. 2.2)

"**Old**" approach of IEC 60099-4, Ed. 2.2



Test evaluation (pass criteria):

- No significant change of residual voltage (max. 5%)
- No puncture, flashover or cracking of MO blocks

→ **"54/0" test (3 samples x 18 impulses each, no failure allowed)**

→ Very limited information on MO resistor and arrester performance

2) "Test to verify harge transfer rating, Q_{rs}" (IEC 60099-4 E

"1.1" to cover complete arresters though test is made on resistors only

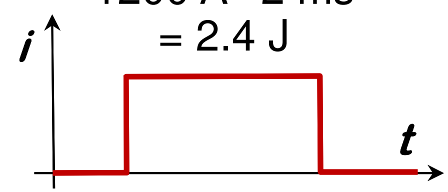
"**New**" approach of IEC 60099-4, Ed. 3.0

Charge injection of 1.1 times Q_{rs}

- 1st run: 20 impulses per sample (10 samples);
- If **not more than one** sample fails in the 1st run: **test passed**.

Charge example:

1200 A · 2 ms = 2.4 J



- If **more than one but not more than two** samples fail in the 1st run: 2nd run with 10 samples and 20 impulses per sample; no further failure allowed → **test passed**.
- If **more than two** samples fail in the 1st run or **one (or more)** samples fail during the 2nd run: **test failed**.

→ **"200/1" or "400/2" test**

→ Improved sensitivity and selectivity (important to UHV arresters!)

→ The Q_{rs} specification has replaced the former, often used "long duration current withstand capability", which was not defined at all, though.

IEC 60099-4 Ed. 3.0

From **"old"** to **"new"** (according to IEC 60099-4, Ed. 3.0, Annex L)

Old LDC	Corresponding *new* thermal energy rating as per 8.7.3 W_{th} kJ/kV	Corresponding *new* repetitive charge transfer rating as per 8.5.4 Q_{rs} C
1	2	0,5
2	4	1
3	7	1,6
4	10	2,4
5	14	3,6

Examples:

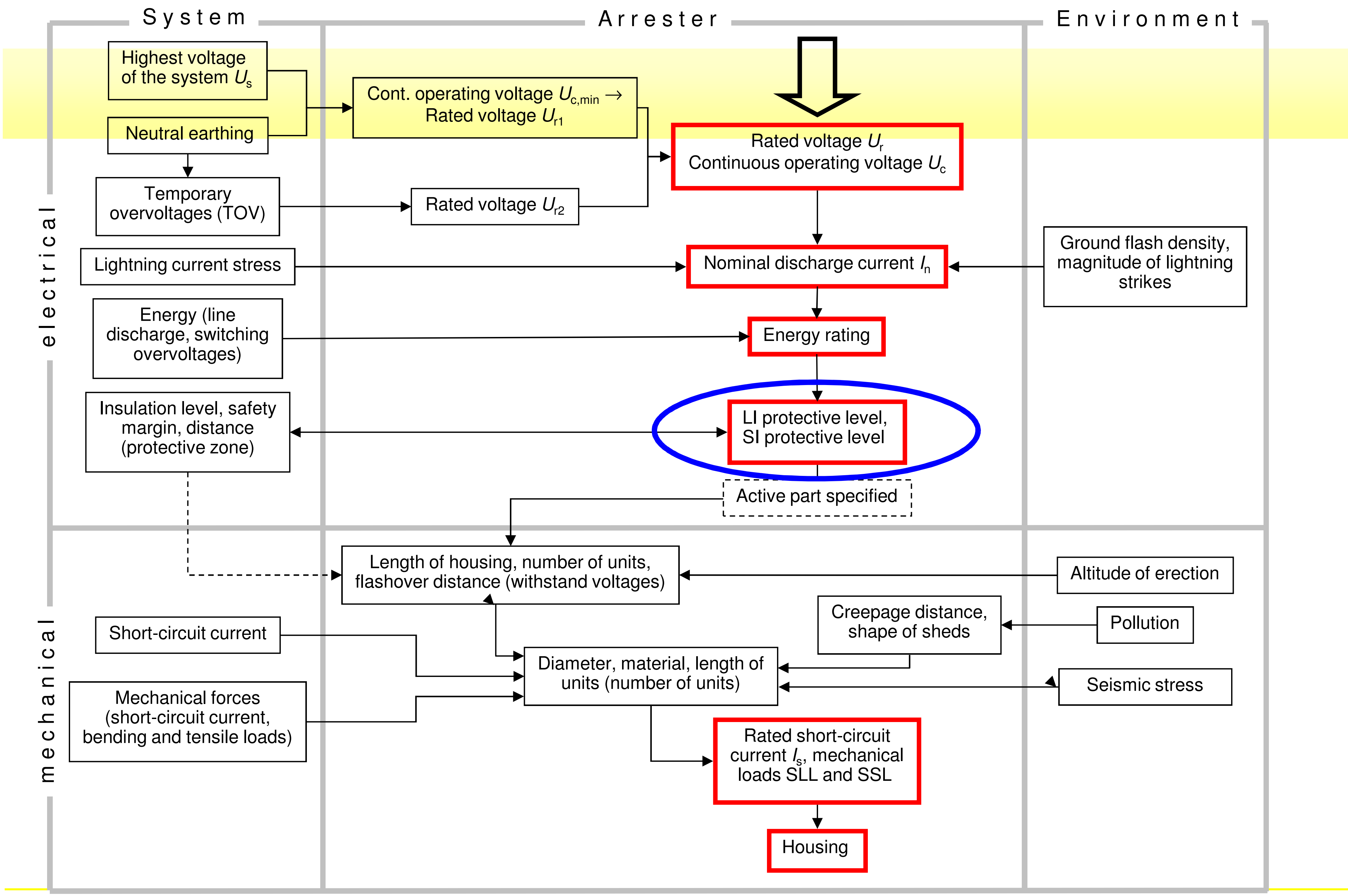
"Old":
LDC = 3

"New":
W_{th} = 7 kJ/kV
Q_{rs} = 1,6 C

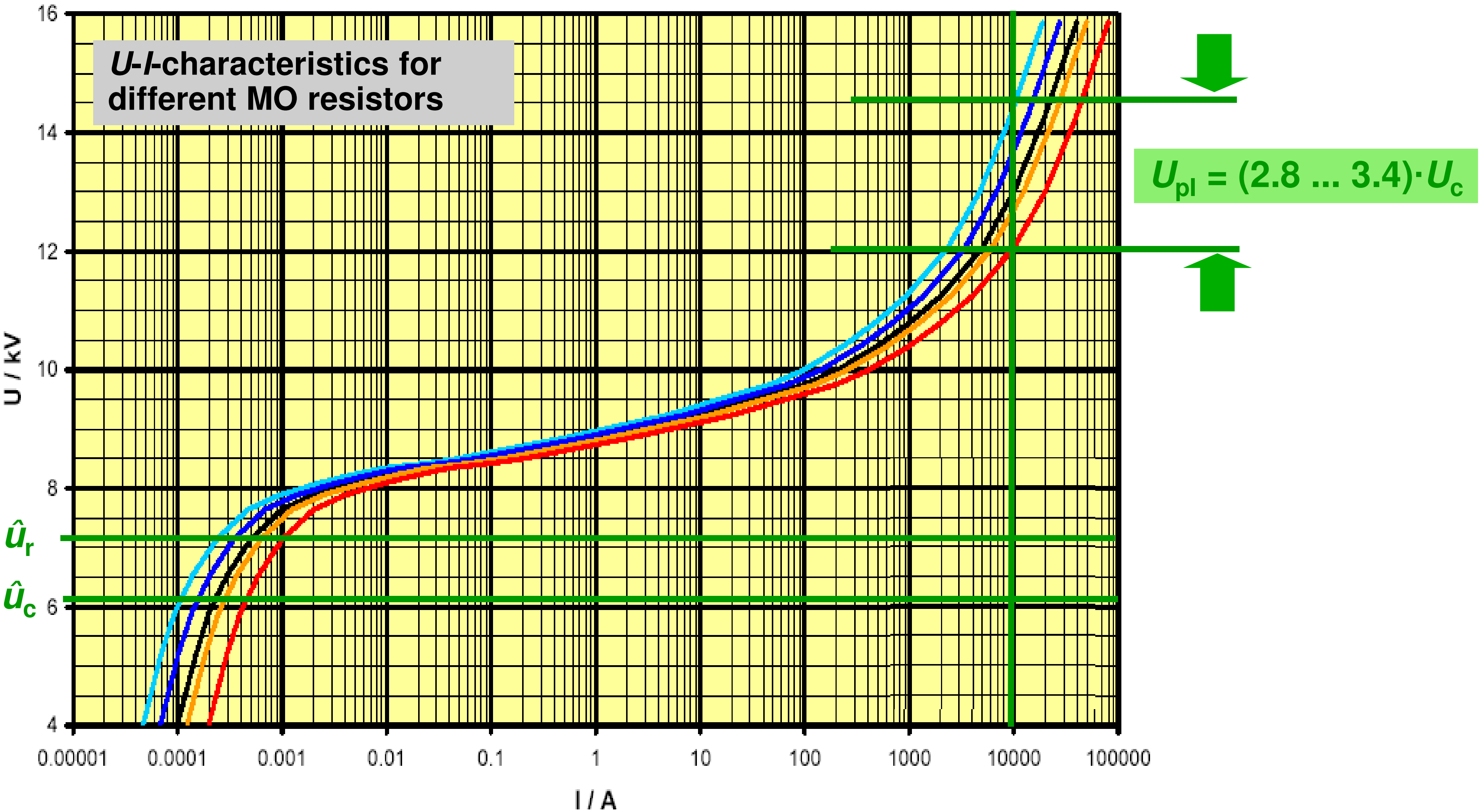
UHV 1200 kV:
W_{th} = 66 kJ/kV
Q_{rs} = 14 C

LDC → $\boldsymbol{W_{th}}$ + $\boldsymbol{Q_{rs}}$

[IEC]


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 strikes
Energy (line discharge, switching overvoltages)
Energy rating
Insulation level, safety margin, distance (protective zone)
LI protective level, SI protective level
Active part specified
Length of housing, number of units, flashover distance (withstand voltages)
Altitude 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)
Rated short-circuit current I_s, mechanical loads SLL and SSL
Housing

LI protection level from *U-I*-Characteristics



Calculation Examples ($U_s = U_m$ = 420 kV)

1) U_s = 420 kV **$U_{10sec} = 1.4 \cdot U_s/\sqrt{3}$ = 340 kV** **(LIWV of equipment = 1425 kV)**

Rated voltage: **$U_{r,\,typ}$ = 336 kV**

LI protection level:

$$U_{10kA} = 336\ \text{kV} \cdot \mathbf{2.4}^{*)} = 807\ \text{kV} < \frac{1425\ \text{kV}}{1.4} \quad \left(\frac{1425\ \text{kV}}{1.4} = 1018\ \text{kV} \right)$$

***) Typical value for former LD class 3, but manufacturer dependent**

Typical Values of Protection Level

$U_s = U_m$ kV	Neutral earthing	Standard lightning impulse withstand voltage LIWV kV	Lightning impulse protective level u_{pl} kV	Factor LIWV/u_{pl}
24	Resonant earthed	125	80	1.56
123	Resonant earthed	550	370	1.49
145	Solidly earthed	650	295	2.2
245	Solidly earthed	950	485	1.96
420	Solidly earthed	1425	825	1.73
550	Solidly earthed	1550	960	1.61

As a rule of thumb (!), a factor LIWV/$u_{pl} \geq 1.4$ offers sufficient protection against lightning overvoltage:

$$\boldsymbol{u_{pl} \leq \frac{\text{LIWV}}{1.4}}$$

The voltage at the terminals of the equipment to be protected must not reach values above LIWV/1.15
(K_s = 1.15 = **safety factor** for non-self restoring insulation, acc. to IEC 60071-2)

For more detailed information see IEC 60099-5, IEC 60071-1 and IEC 60071-2

Reduction of Protection Level

What can be done if the protection level is too high?

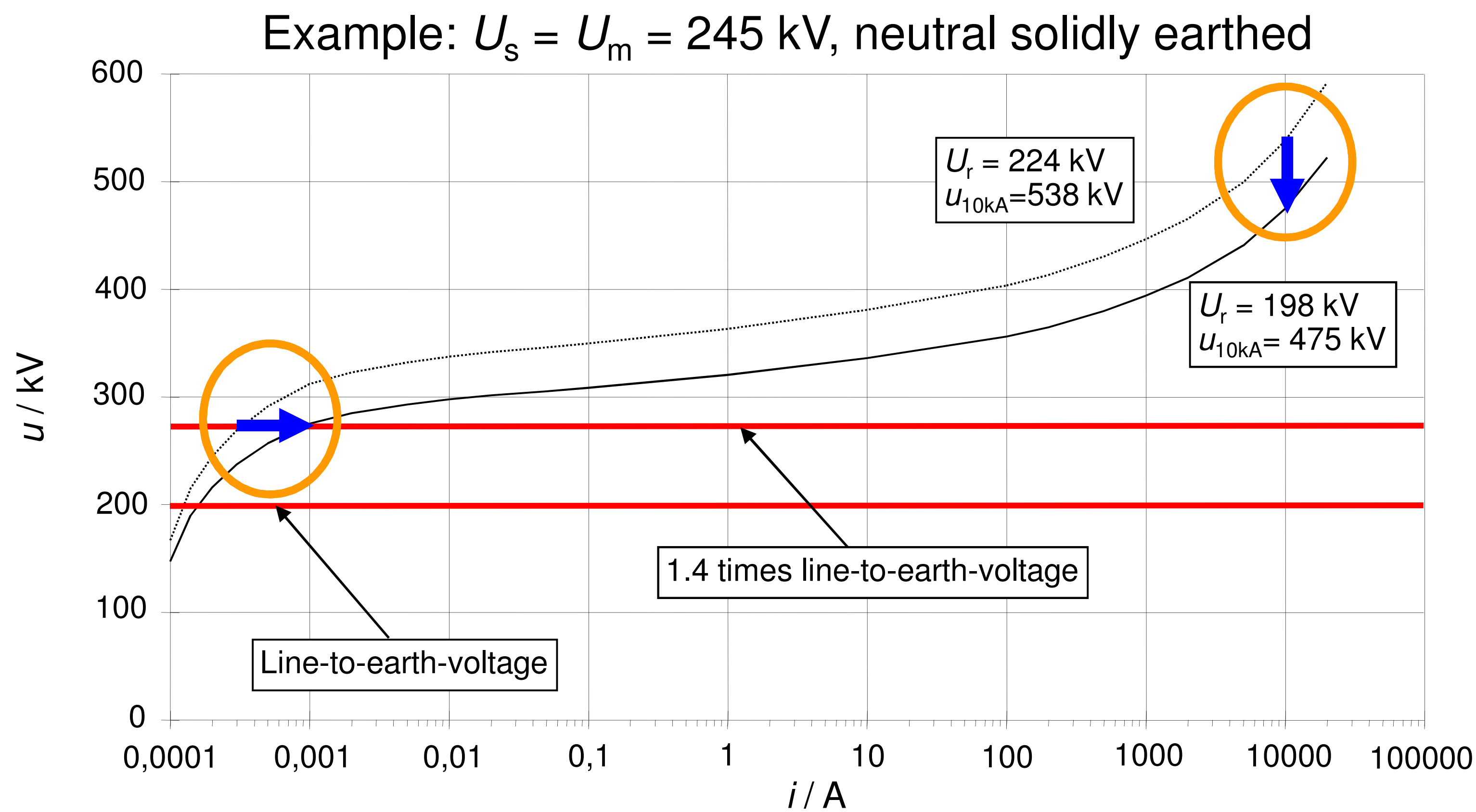
a) Choosing a lower residual voltage

b) Increasing the cross sectional area of the MO resistors

c) Using MO resistors of higher degree of non-linearity

Reduction of Protection Level

a)



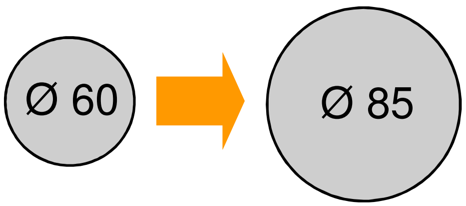
Lower LI protection level → higher specific power-frequency stress

→Reduction of protection level may affect stability under continuous operating and particularly under TOV conditions

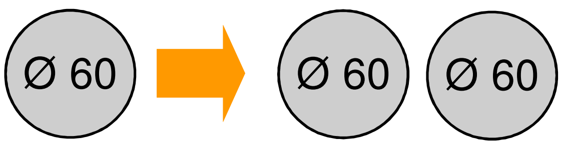
→Protection level should be set to *<u>reasonable</u>* (not necessarily the lowest) values!

Reduction of Protection Level

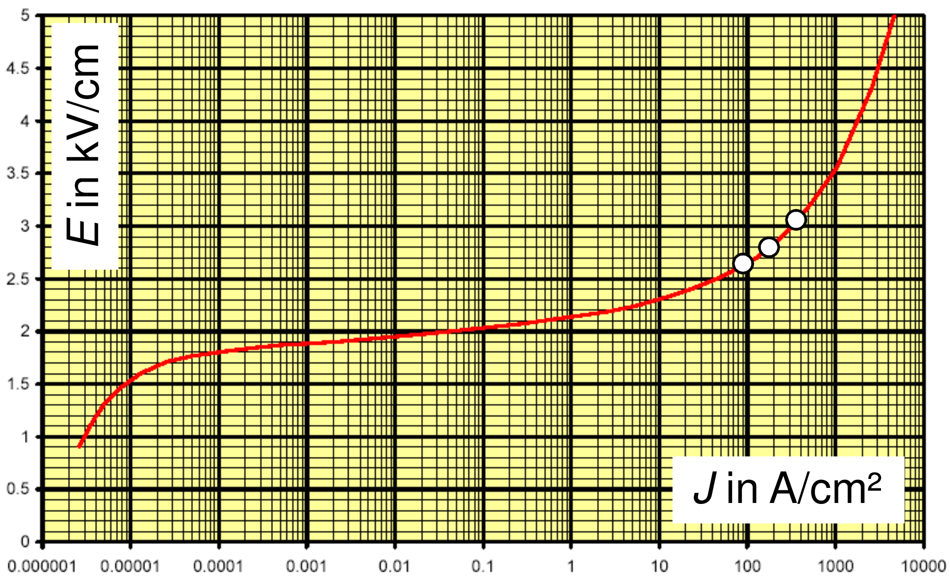
b) Increasing the cross sectional area of the MO resistors in order to **reduce current density**



Increasing diameter by factor √2 **doubles** area



Using two identical resistors in parallel also **doubles** area



Impressed current I = 10 kA

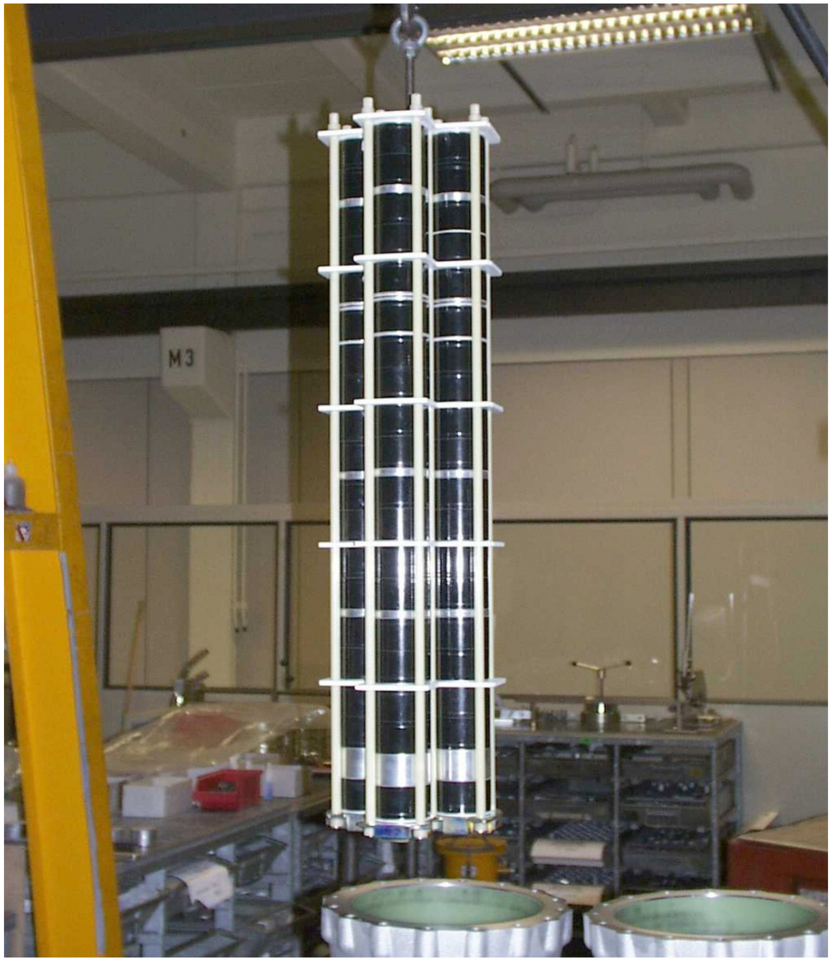
J = 360 A/cm² @ Ø 60 mm
→ $U_{10kA\ reference}$

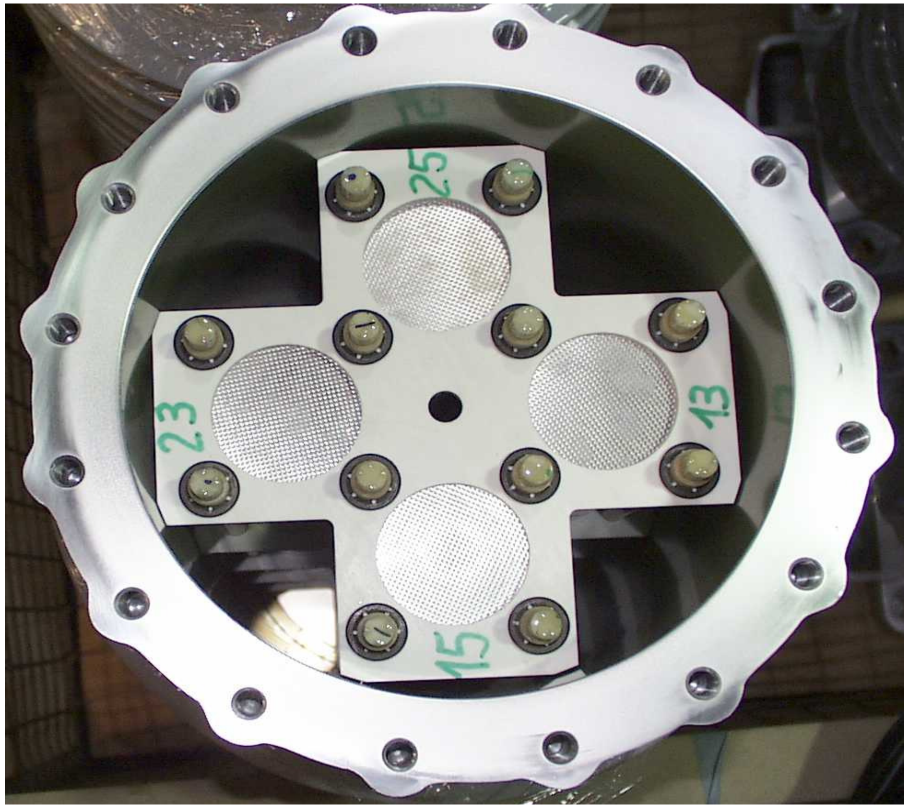
J = 180 A/cm² @ Ø 85 mm or 2 x Ø 60 mm
→ ΔU_{10kA} = **-10%**

J = 90 A/cm² @ Ø 120 mm or 4 x Ø 60 mm
→ ΔU_{10kA} = **-15%**

Reduction of Protection Level

b) Increasing the cross sectional area of the MO resistors in order to **reduce current density**

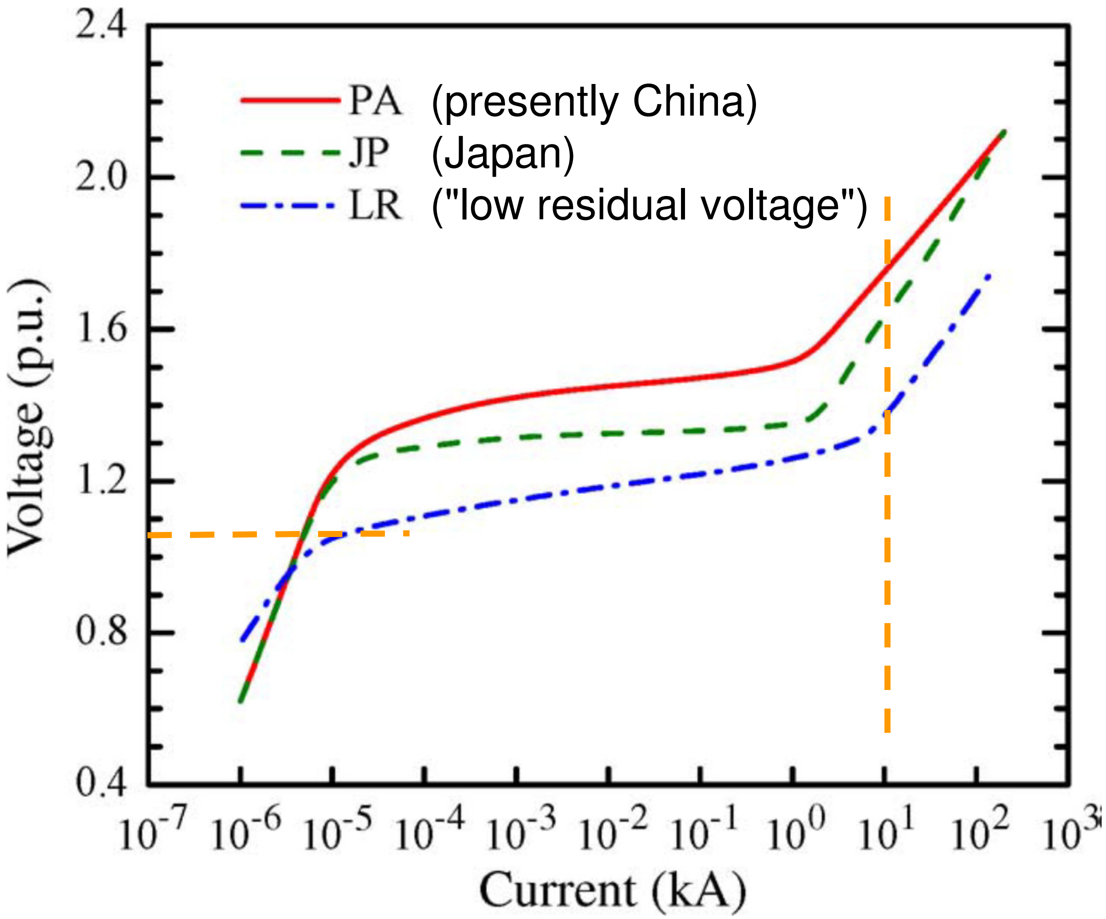




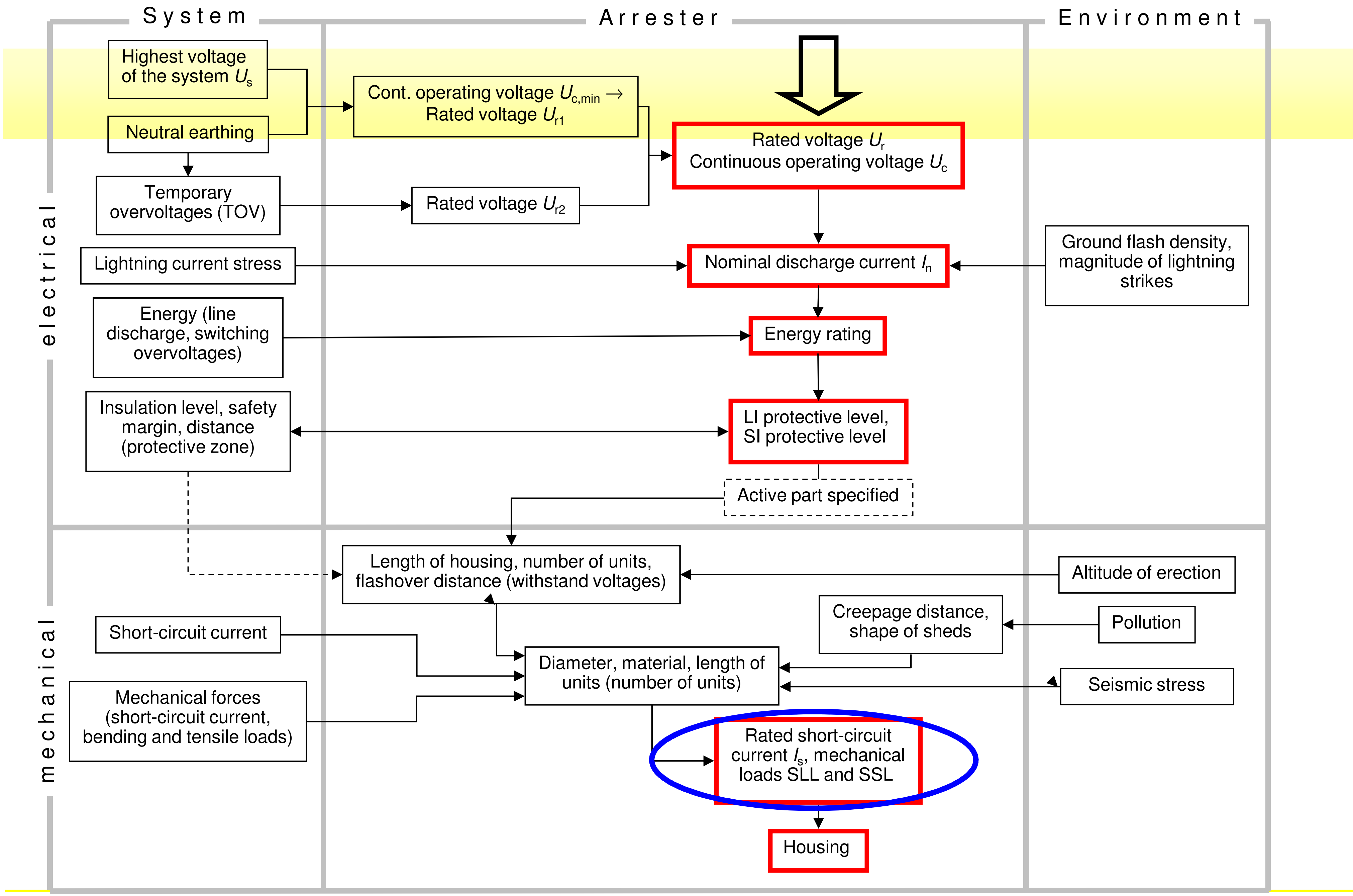
Example: Siemens

Reduction of Protection Level

c) Using MO resistors of a different U-I characteristic (higher degree of non-linearity)



HE *et al.*: DEEP SUPPRESSION OF SWITCHING OVERVOLTAGES IN ACUHV SYSTEMS; IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 26, NO. 4, OCTOBER 2011


System
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Highest voltage of the system U_s
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Cont. operating voltage $U_{c,min}$ → Rated voltage U_{r1}
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Rated voltage U_{r2}
Lightning current stress
Nominal discharge current I_n
Ground flash density, magnitude of lightning strikes
Energy (line discharge, switching overvoltages)
Energy rating
Insulation level, safety margin, distance (protective zone)
LI protective level, SI protective level
Active part specified
Length of housing, number of units, flashover distance (withstand voltages)
Altitude 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)
Rated short-circuit current I_s, mechanical loads SLL and SSL
Housing

Housing Requirements

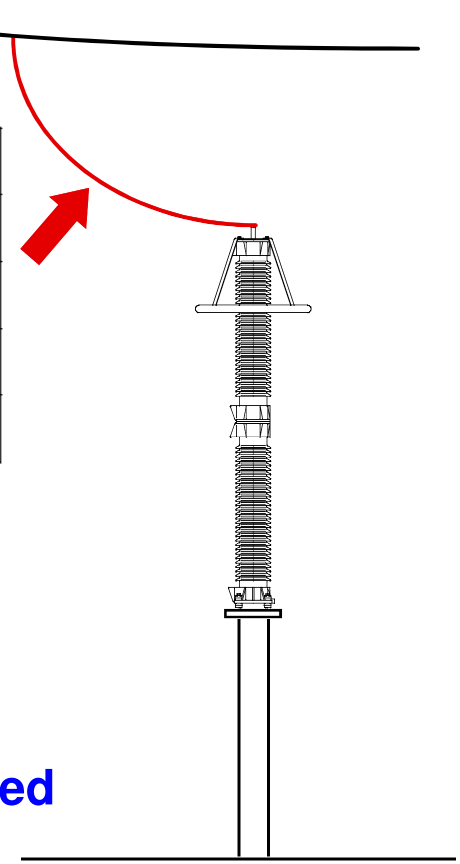
- Mechanical strength
    - **static and dynamic loads by connected conductors**
    - strength against seismic events
- Dielectric strength
- **Short-circuit performance**
- **Performance under polluted conditions**
    - shed profile
    - creepage distance
    - flashover distance
    - partial heating of active parts
    - internal partial discharges
    - hydrophobicity (incl. dynamics of hydrophobicity)

Mechanical Strength of Housing

Minimum recommended strength if there are no further requirements
(given by conductor loads ←→ wind, vibration, short-circuit current forces):

Table 7: Recommended mechanical characteristics for arresters with porcelain housing

Highest system voltage U_s / kV	SLL / N	SSL / N	MBL / N
< 123	350	875	≥ 1050
123 … 420	400	1000	≥ 1200
550	600	1500	≥ 1800
800	800	2000	≥ 2400



SLL … specified long-term load
SSL … specified short-term load
MBL … mean value of the breaking load

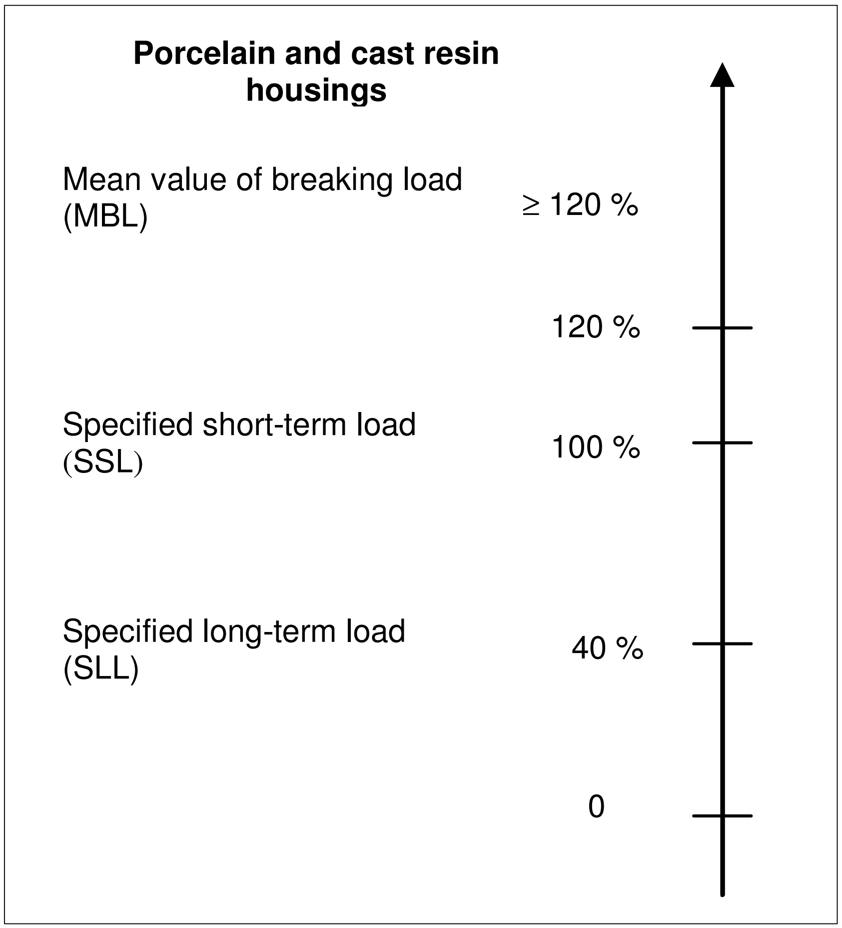
[Hinrichsen: Arrester Book]

- Ratio F_{dyn} / F_{stat} **= 2.5 for porcelain** housings
- Ratio F_{dyn} / F_{stat} for **polymer** housings **not yet definitely established**

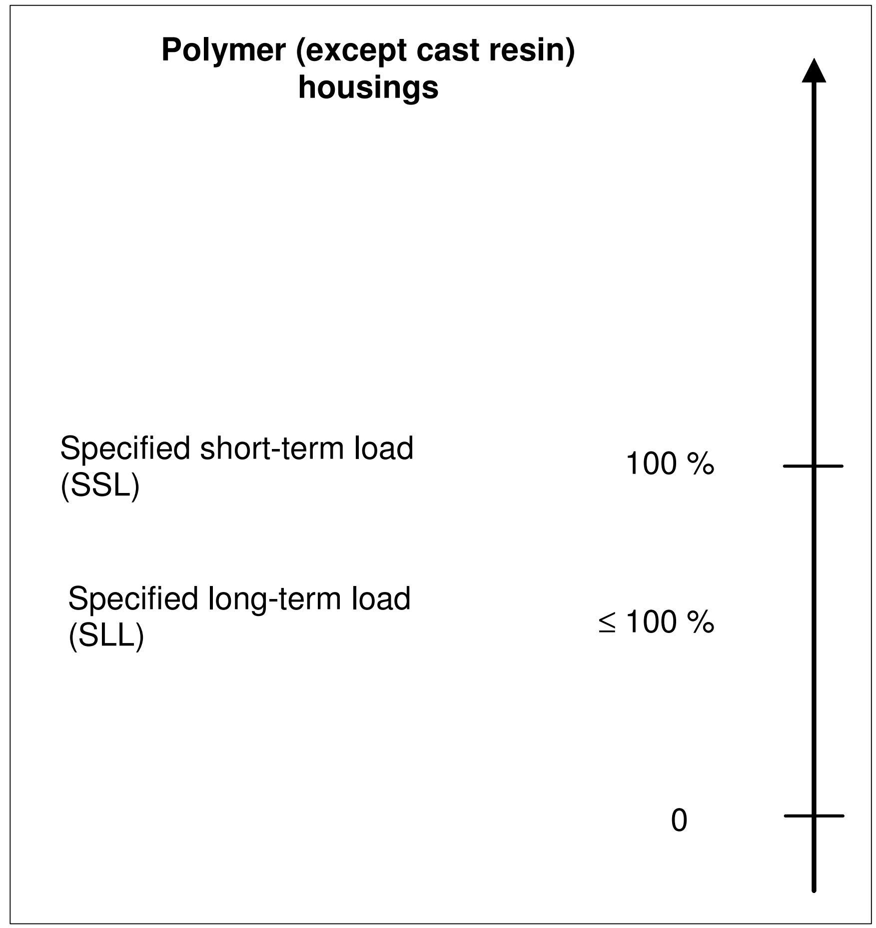
Mechanical Strength of Housing

Mech. testing flow chart

According to latest version of IEC 60099-4 (Edition 3.0):

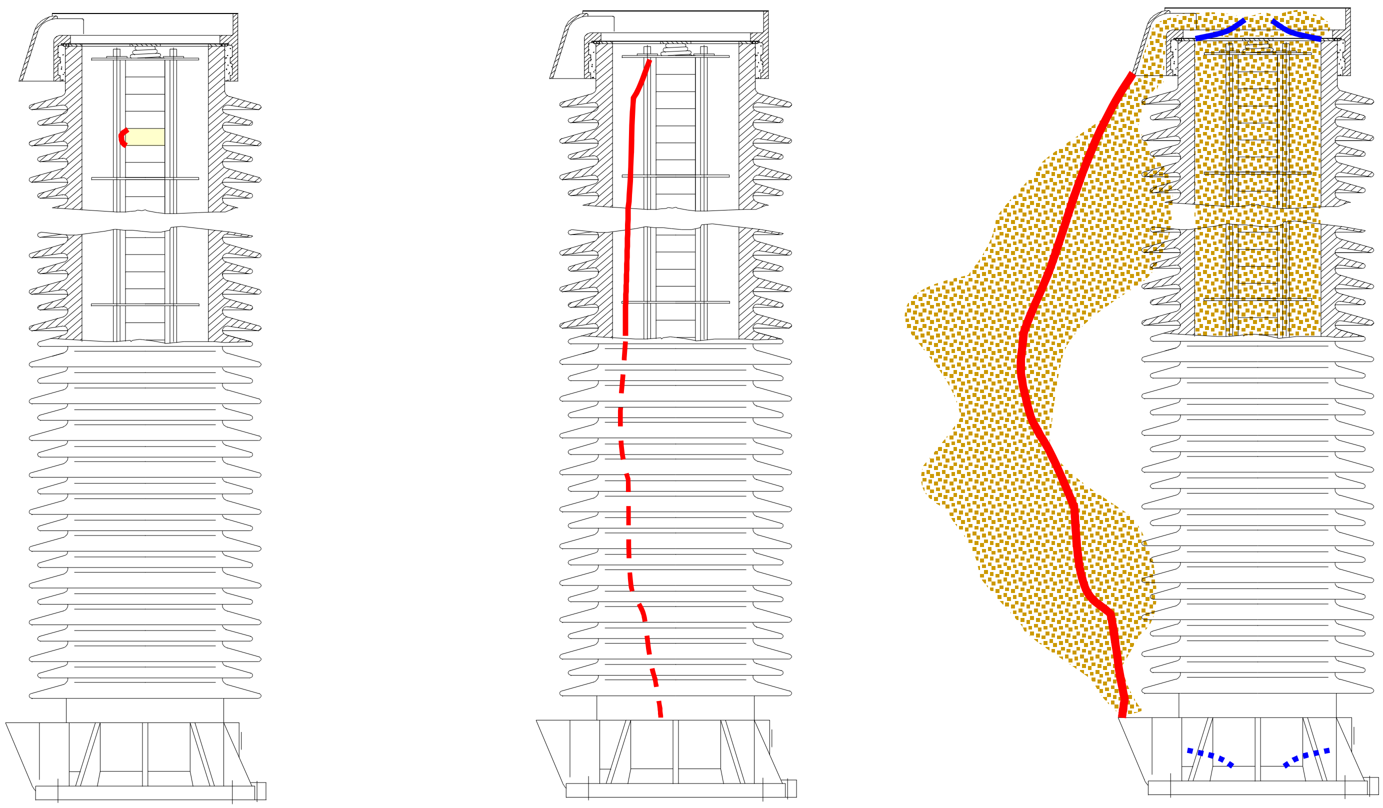


IEC 249/09



IEC 250/09

Pressure Relief of a Porcelain Housed Arrester Unit

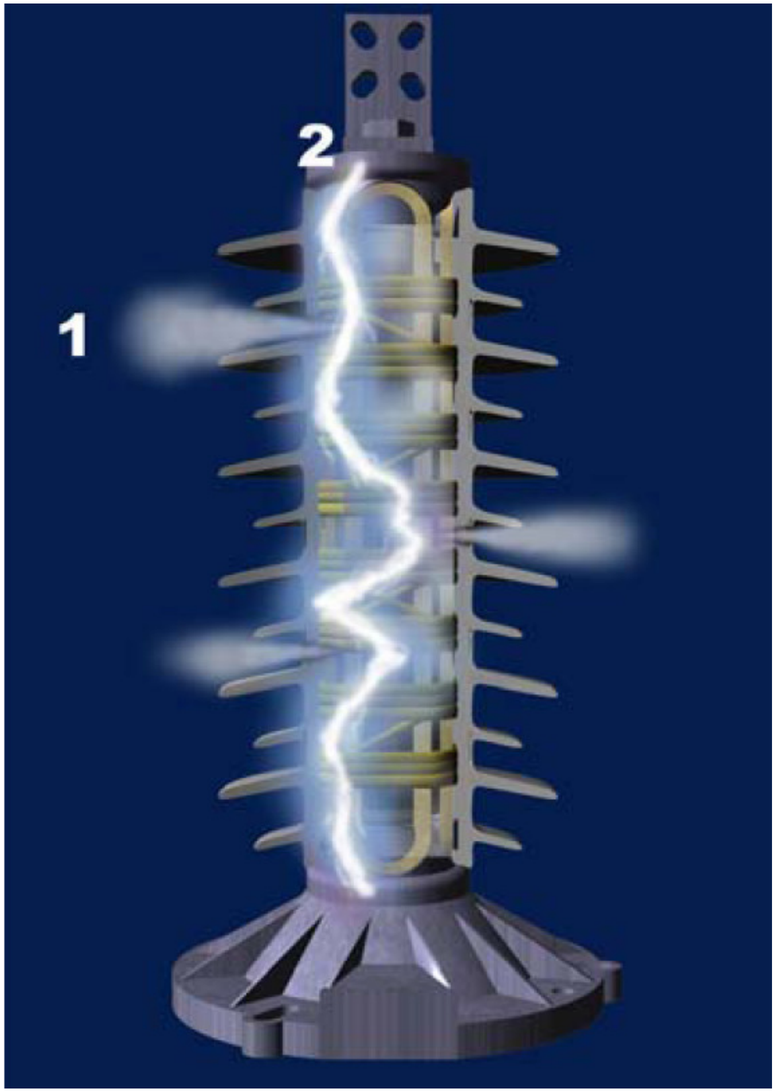


1) Puncture and flashover of individual MO resistor(s)

2) Internal arc along the full length of the unit

3) Opening of pressure relief devices and venting of the unit

Pressure Relief of a Cage Design Polymer Housed Arrester Unit



1. Arrester has failed and gas begins to be expelled through the housing.

2. The gas streams trigger an external flashover and the internal arc is commutated to the outside

Short-Circuit Test according to IEC 60099-4 Ed. 3.0

skip test details

Test with high current (rated short-circuit current, I_s):

5 10 16 20 31.5 40 50 63 80 kA

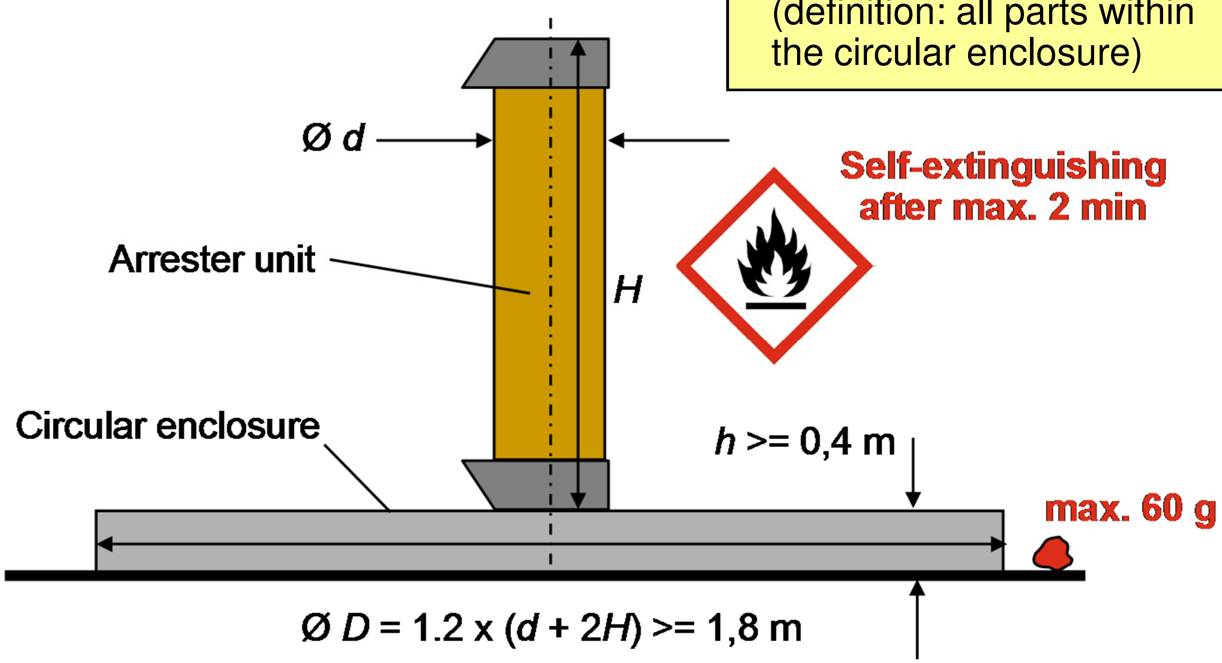
(additionally: tests with ≈ 50% and ≈ 25% of rated short-circuit current)

Test with low current:

600 A ± 200 A

Basic idea:

- Explosion **not allowed**
- Thermal breaking **allowed** (definition: all parts within the circular enclosure)



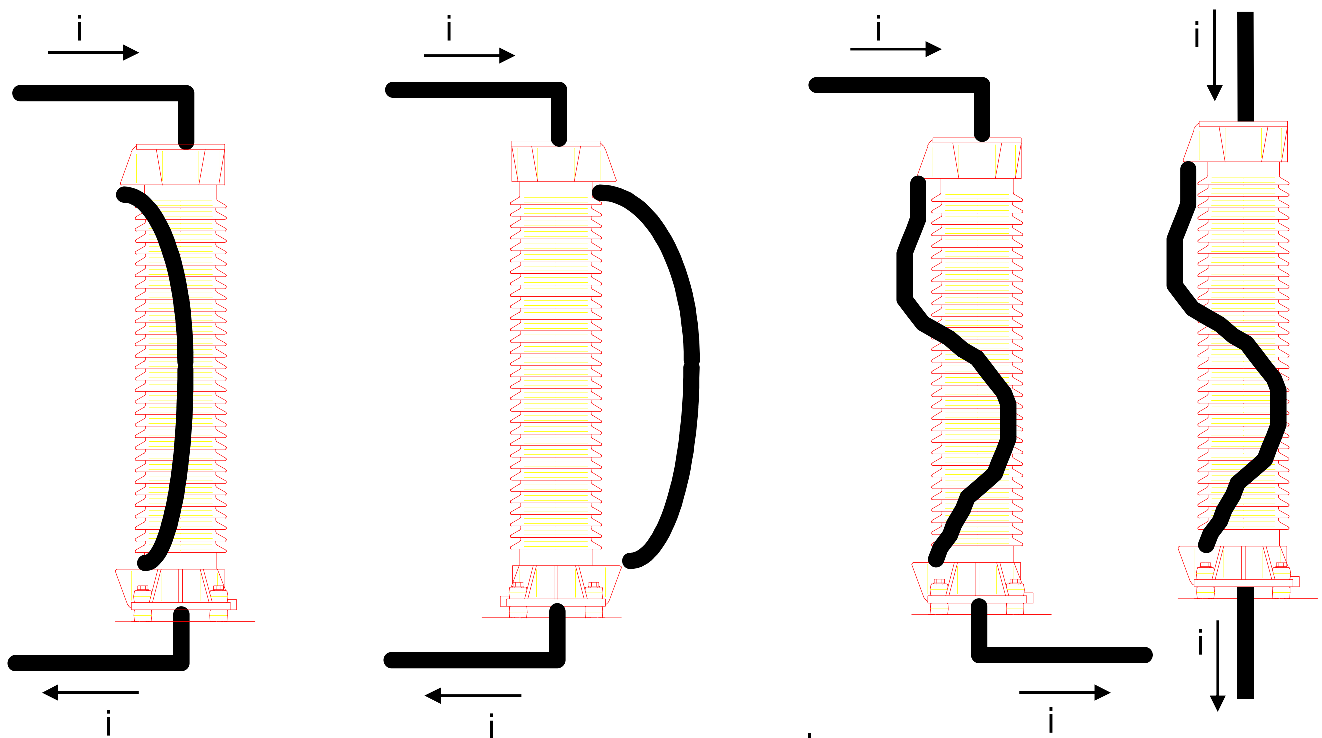
Factors improving pressure relief performance:

- Short housings
- Large gas volume
- Fast opening pressure relief devices
- High mechanical strength (porcelain quality, thickness)
- Favorable short circuit current loop

Short-Circuit Test according to IEC 60099-4 Ed. 3.0

Arrester class = nominal discharge current	Rated short-circuit current I_s	Reduced short-circuit currents ±10 %		Low short-circuit current with a duration of 1 s [a]
kA	100 % kA	≈ 50 %	kA ≈ 25 %	A
20 or 10	80	50	25	600 ± 200
20 or 10	63	25	12	600 ± 200
20 or 10	50	25	12	600 ± 200
20 or 10	40	25	12	600 ± 200
20 or 10	31,5	12	6	600 ± 200
20, 10 or 5	20	12	6	600 ± 200
10 or 5	16	6	3	600 ± 200
10, 5, or 2,5	10	6	3	600 ± 200
10, 5, or 2,5	5	3	1,5	600 ± 200
10, 5 or 2,5	2,5 kA	–	–	600 ± 200
10, 5 or 2,5	1 kA	–	–	Amplitude and time on agreement between user and manufacturer
10, 5 or 2,5	< 1 kA[b]	–	–	Amplitude and time on agreement between user and manufacturer

Influence of the Short-Circuit Current Loop



Porcelain	worst case	most favorable case	neutral case
Polymer (with gas volume included)	favorable case	most favorable case	worst case
Polymer (without gas volume included)	most favorable cases		worst case

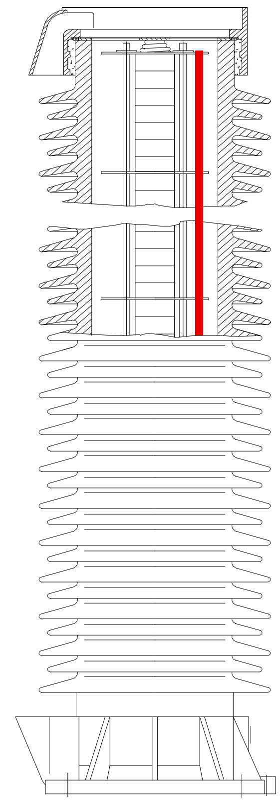
Failure Mode (How to Initiate the Internal Arc)

In brief (!):

- "Conventional" porcelain housed arresters (→ **"Design A"** arresters) shall be tested by the **"fuse wire method"**

- The most common polymer housed arresters ("wrapped" or "cage" design) (→ **"Design B"** arrester) shall be tested by the **"pre-failing method"**

> – "Design A" arresters have a design in which a gas channel runs along the entire length of the arrester unit and fills ≥50 % of the internal volume not occupied by the internal active parts.
>
> – "Design B" arresters are of a solid design with no enclosed volume of gas or having an internal gas volume filling <50 % of the internal volume not occupied by the internal active parts.
>
> NOTE 1 Typically, "Design A" arresters are porcelain-housed arresters, or polymer-housed arresters with a composite hollow insulator which are equipped either with pressure-relief devices, or with prefabricated weak spots in the composite housing which burst or flip open at a specified pressure, thereby decreasing the internal pressure.
>
> Typically, "Design B" arresters do not have any pressure relief device and are of a solid type with no enclosed volume of gas. If the resistors fail electrically, an arc is established within the arrester. This arc causes heavy evaporation and possibly burning of the housing and/or internal material. These arresters' short-circuit performance is determined by their ability to control the cracking or tearing-open of the housing due to the arc effects, thereby avoiding violent shattering.



"A" (External) fuse wire

"B" Pre-failing

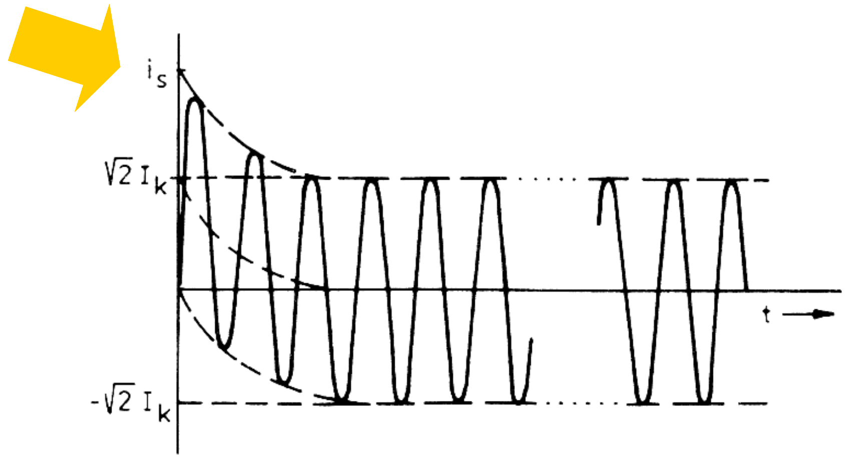
Failure Mode (How to Initiate the Internal Arc)

Problem with the "fuse wire" method

Requirement: $\hat{\imath}/I_{rms} \geq 2.5$ ("asymmetry factor")

→ X/R ratio of test circuit must be ≥ 15

For arrester units of $H \geq 1.5$ m or $U_r \geq 150$ kV the arcing voltage is so high that X/R becomes < 15 (typical test voltages in high-power labs are only 15 kV ... 50 kV).



→ **An asymmetry factor of 2.5 cannot be achieved for tall arresters.**

Solution: as an exception only for tall **polymer** housed arresters of "tube" design, a test with max. achievable asymmetry factor shall be performed on the **longest** arrester unit **plus** an additional test with asymmetry factor of ≥ 2.5 on an arrester unit of $\boldsymbol{U_r \geq 150}$ **kV**

Failure Mode (How to Initiate the Internal Arc)

Problem with the "pre-failing" method

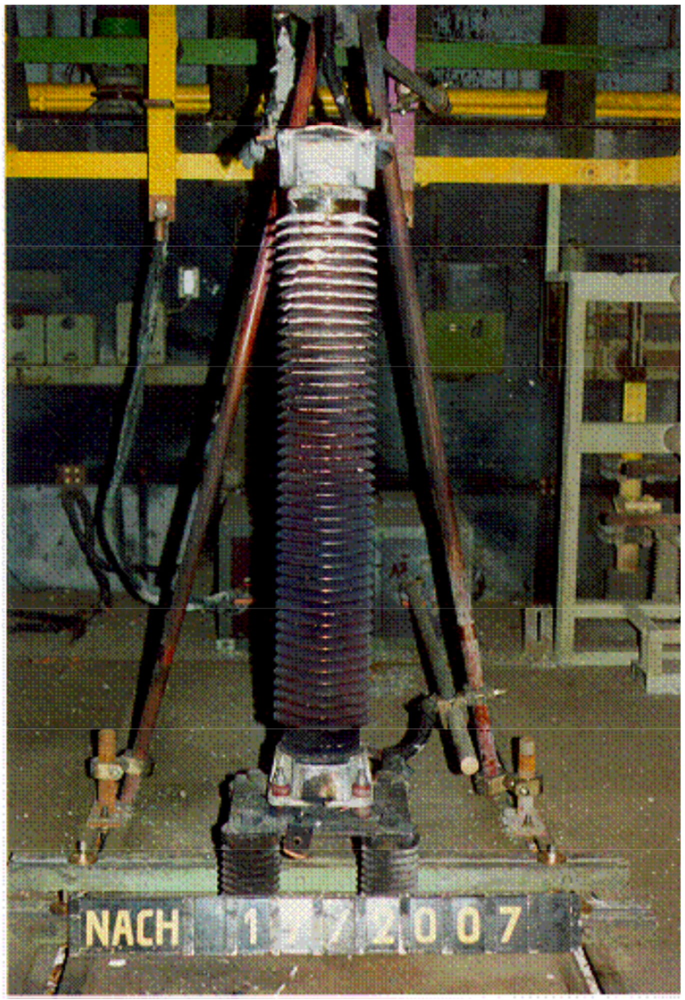
The full asymmetry factor of ≥ 2.5 usually cannot be achieved as the time instant of failure is random

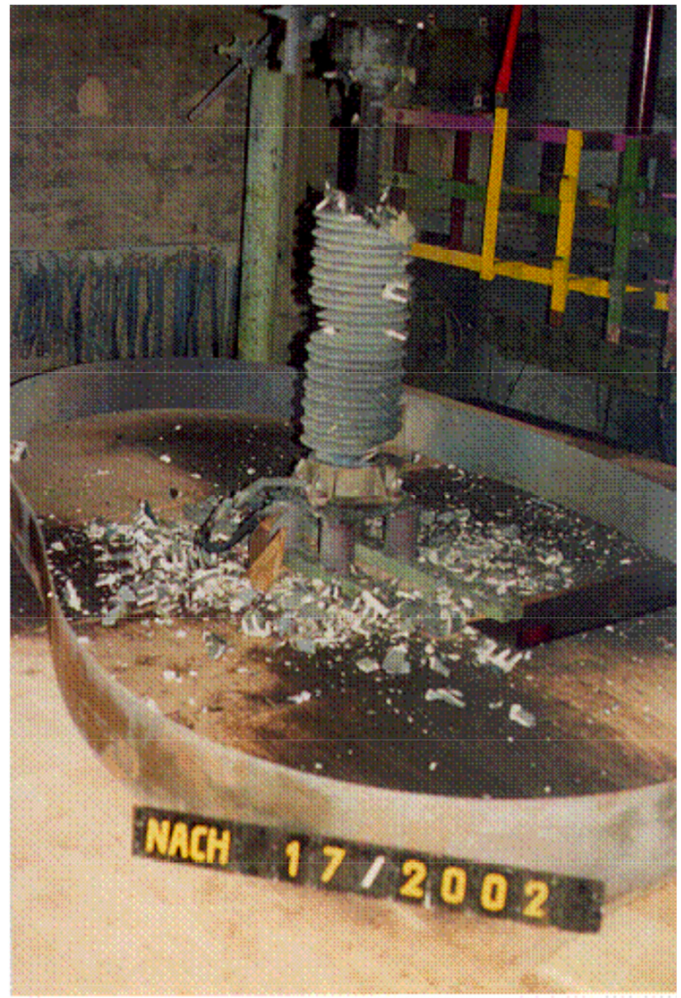
Solution:

- requirement of an asymmetry factor of ≥ 2.5 has been **cancelled** for this type of arrester and been **replaced** by requirement for a factor of ≥ **√2**
- but in any case the test shall be performed **on the longest unit** of the design

Examples of Successful Short-Circuit Tests at High Current

Test with 63 kA/0,2 s on porcelain housed arrester





Examples of Successful Short-Circuit Tests at High Current

Test with 63 kA/0,2 s on polymer housed high-voltage arrester (FRP hollow insulator)

Before test

After test

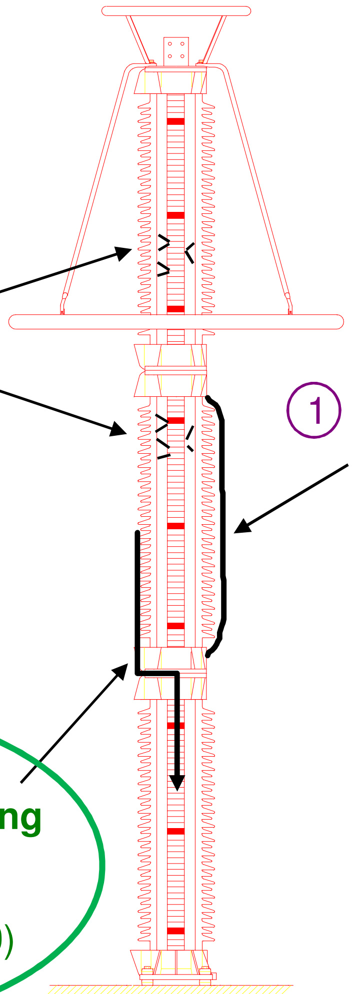
Examples of Successful Short-Circuit Tests at High Current

Test with 63 kA/0,2 s on polymer housed high-voltage arrester (cage design)

Short-Circuit Performance – Wrap-Up

- In general, polymer housed arresters tend to offer a "safer" short-circuit performance.
- But not all polymer housed arresters are intrinsically "safe".
- Design differences play an important role and must still be regarded.

Performance under Pollution Conditions



3 **Radial filed stress:**
- risk of "internal" partial discharges, degradation of the MO resistors and deterioration of the supporting structure

or

- risk of puncture in case of the housing directly applied to the MO column

2 Risk of **partial heating** of the active parts (see **Annex C of IEC 60099-4, Ed. 3.0**)

1 Risk of **external flashover**

Measures against:

1
- Long creepage distance
- Optimized shed profile

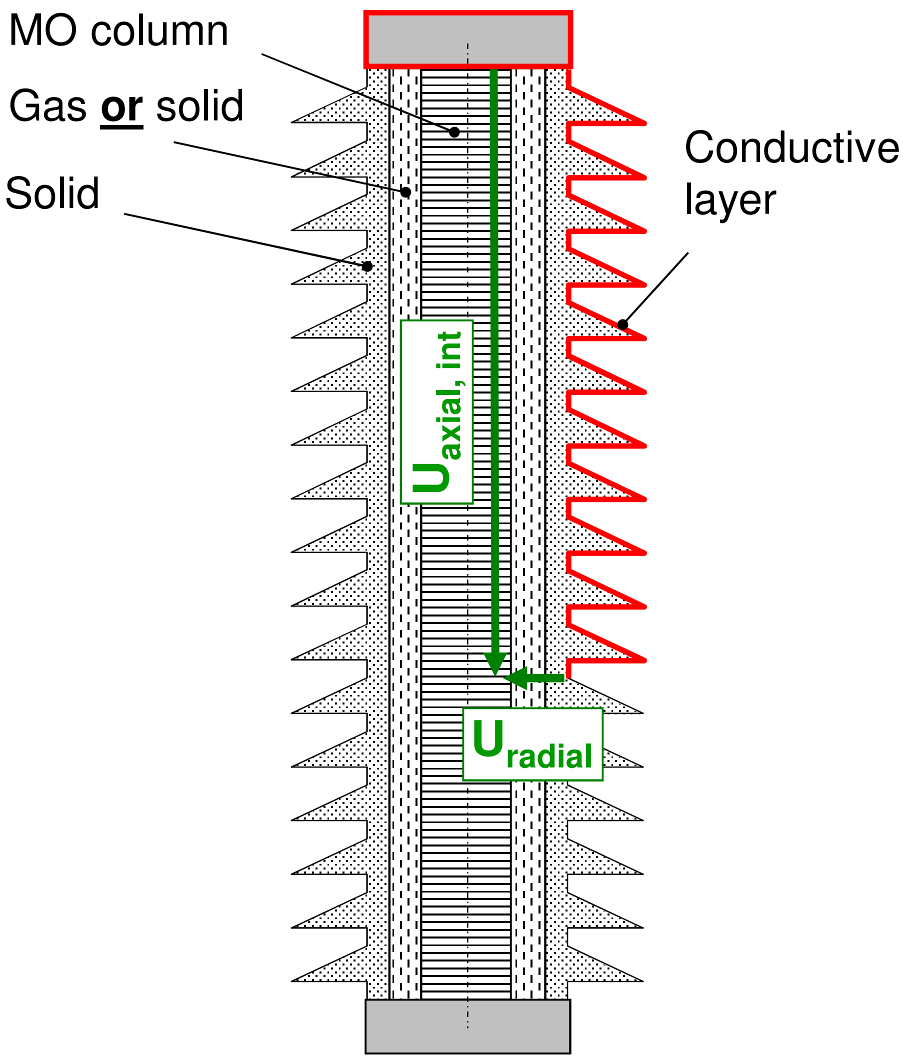
2
- Few number of units (best: single-unit arrester)

3 In case of gas volume included:
- large distance MO column - housing
- no sharp edges at the MO column
- MO blocks with stable aging characteristics
- internal gas volume free of oxygen
- high tracking resistance of supporting structure
- use of desiccants

In case of no gas volume included:
- sufficient thickness of housing
- optimized shed profile
- high tracking resistance of materials

General recommendation: High rated and continuous operating voltage rather than low protection level if possible (leads to moderate electrical stress under continuous operating conditions and improves long term stability)

Performance under Pollution Conditions – Radial Field Stress



For polymer housed arresters: Verified by the „**Weather Ageing Test**“ (1000-h salt fog test
(Test on the longest unit of the design required)

… though main purpose of the test is to check tracking and erosion resistance.

skip UHV

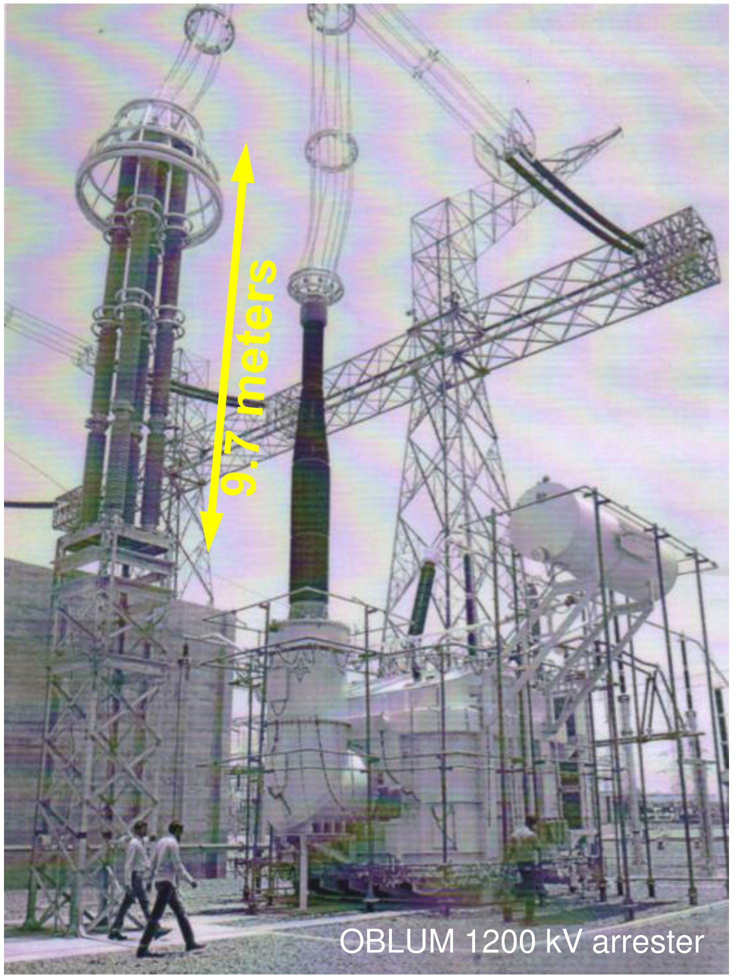
Part 4:
UHV Arrester Considerations

1200 kV Insulation Levels (IEC 60071-1)

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 (2) kV (peak value)
	Longitudinal insulation (1) kV (peak value)	Phase-to-earth kV (peak value)	Phase-to-phase (ratio to the phase-to-earth peak value)	
1200 (5)	1550	1675	1,70	2100
				2250
	1675	1800	1,65	2250
				2400
	1800	1950	1,60	2550
				2700

1200 kV Arrester Examples



OBLUM 1200 kV arrester

Siemens 1200 kV arrester

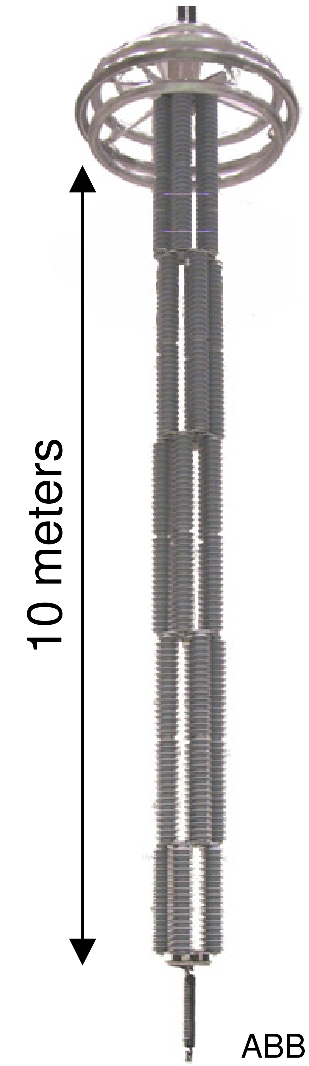


ABB 1200 kV arrester

1200 kV Arrester Examples

Oblum	Siemens	ABB
4 MO columns in individual polymeric tube design housings	**4 MO columns in one common tube design housing**	**5 MO columns in individual polymeric cage design housings**
Ur: 850 kV	Ur: 850 kV	Ur: 850 kV
Uc: 693 kV	Uc: 693 kV	Uc: 693 kV
In: 20 kA	In: 20 kA	In: 20 kA
LIPL at 20 kA: 1716 kV	LIPL at 20 kA: 1700 kV	LIPL at 20 kA: 1700 kV
SIPL at 2 kA: 1496 kV	SIPL at 2 kA: 1500 kV	SIPL at 2 kA: 1500 kV
Energy capability: 56 MJ	Energy capability: 55 MJ	Energy capability: 60 MJ
Is:	Is: 50 kA	Is: 80 kA
LIWV:	LIWV: 2400 kV	LIWV: 2400 kV
SIWV:	SIWV: 1875 kV	SIWV: 1800 kV
Creepage distance: 32800 mm	Creepage distance: 35750 mm	Creepage distance: 30375 mm
SLL: 6 kN	SLL: 8.76 kN	SLL:
	SSL: 12.5 kN	
Overall height: 9.7 m	Overall height: 12.5 m	Overall height: 10 m

Required energy handling capability*):
Total energy = 2 line discharges (LD class 5) + **TOV** + Margins
= 2 · 5 MJ + **35 MJ** + 10 MJ = **55 MJ**

*) R.N.Nayak, M.C.Bhatnagar, B.N.De.Bhowmick, R.K.Tyagi
1200kV Transmission System and Status of Development of Sub-station Equipment/Transmission Line Material in India
2nd International Symposium on Standards for Ultra High Voltage Transmission (IEC/Cigré)

Challenges of UHV Arresters (Indian 1200 kV System)

Design issues
- axial potential and temperature distribution

Insulation coordination issues
- protective distance

Test issues
- dielectric testing
- energy classification and testing

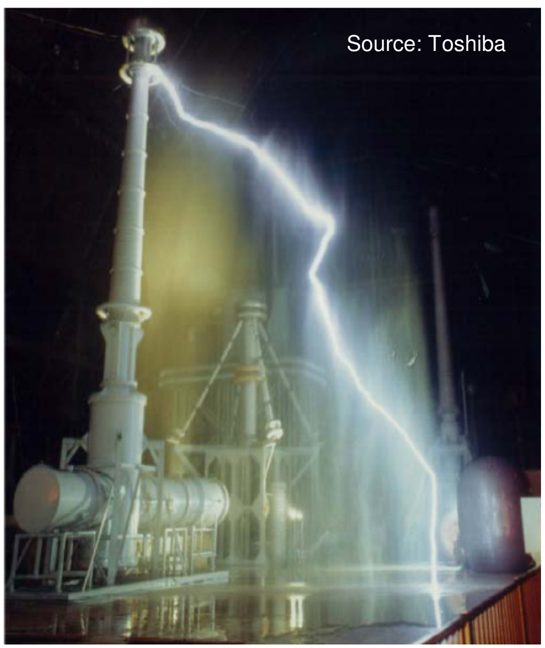
Need for low Switching Impulse Protection Levels

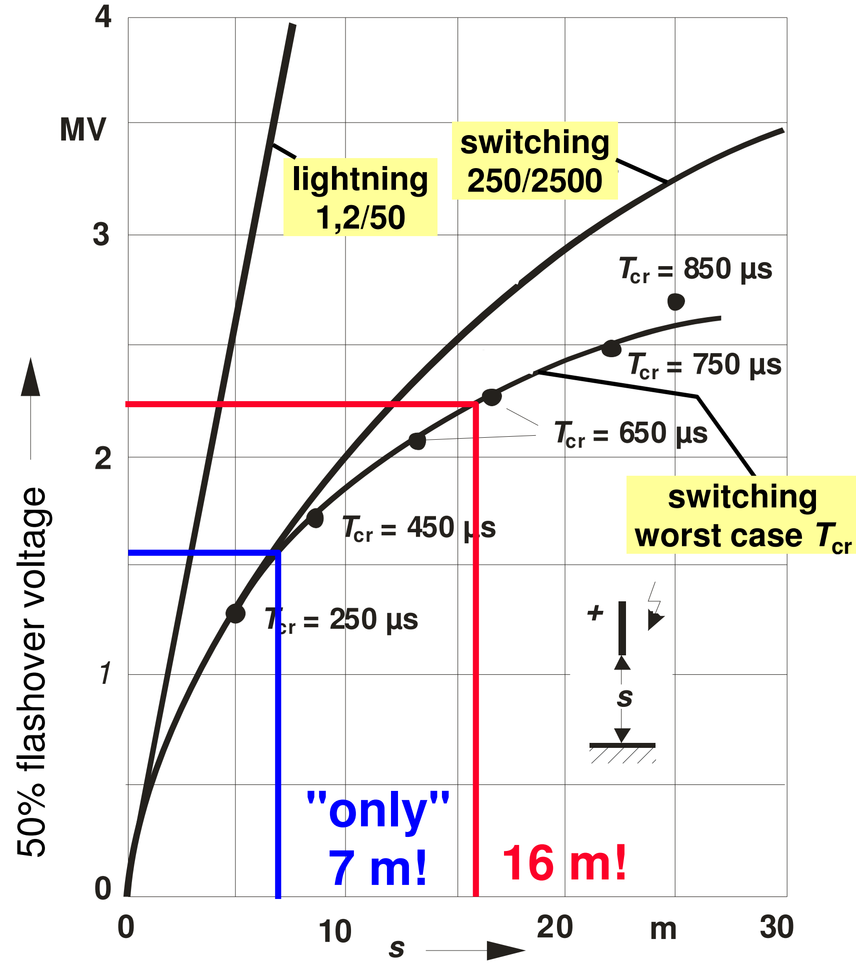
Why do we need so low switching overvoltage levels?

U_s = 1200 kV → 1 p.u. = 900 kV

Slow front overvoltage level of 2,5 p.u.
→ 2.250 kV → **16 m f.o. distance**

Slow front overvoltage level of 1.7 p.u.
→ 1.530 kV → **"only" 7 m f.o. distance**

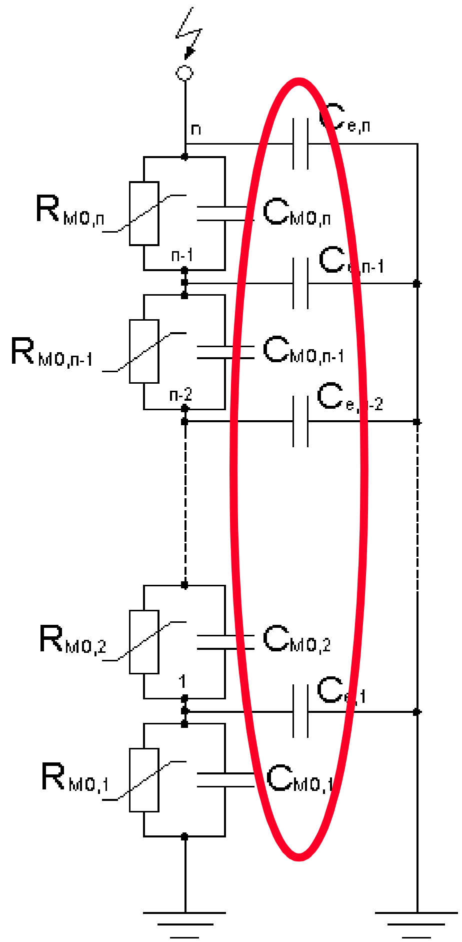


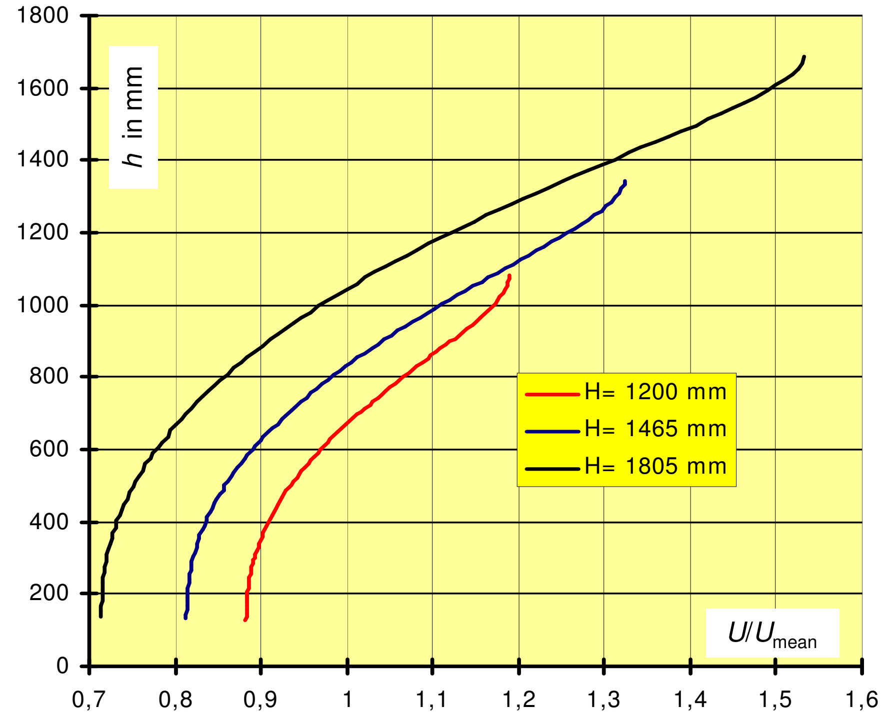


Voltage and Temperature Distribution of MO Arresters

The impact of stray capacitances to ground

$C_{MO} \approx 30$ pF/m → $C_{MO,\,3m} \approx 10$ pF
$C_e \approx 15$ pF/m → $C_{e,\,3m} \approx 45$ pF
For $h = 3$ m → $C_e/C_{MO} \approx 4.5$

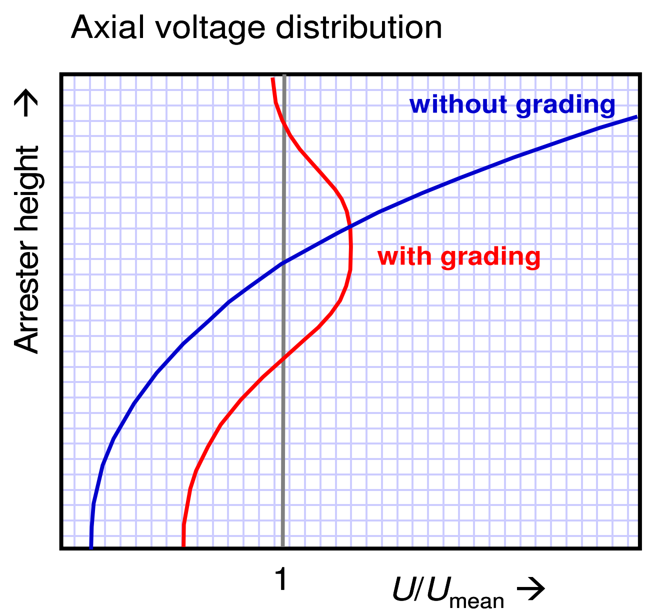


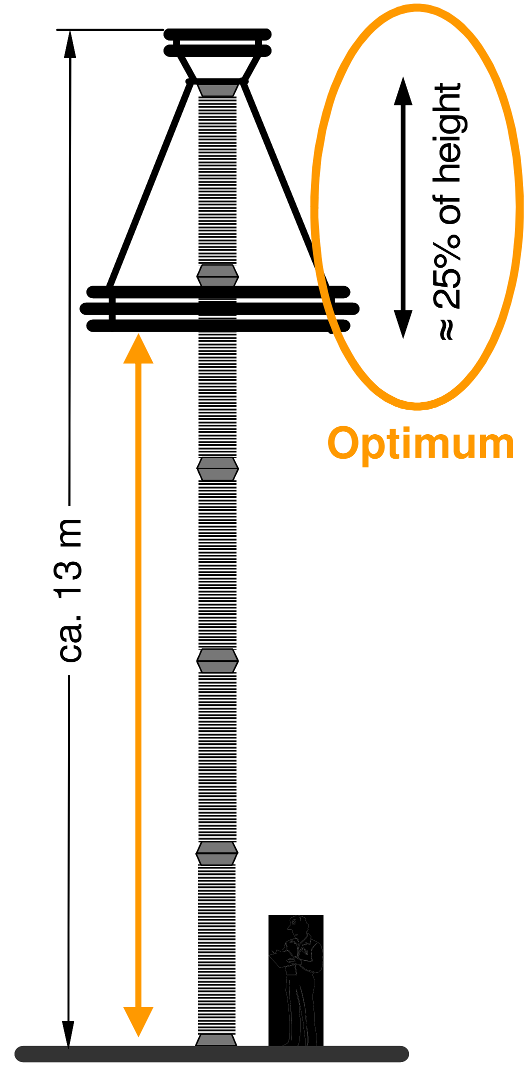


⇒ Grading rings necessary for arrester heights > 1.5 m ... 2 m

Voltage and Temperature Distribution of MO Arresters

- Uneven axial voltage distribution (due to C_e)
- Traditionally controlled by grading ring(s)
- **Cannot be optimized for UHV arresters due to clearance requirements (9…10 m for SIWV = 1800 kV)**



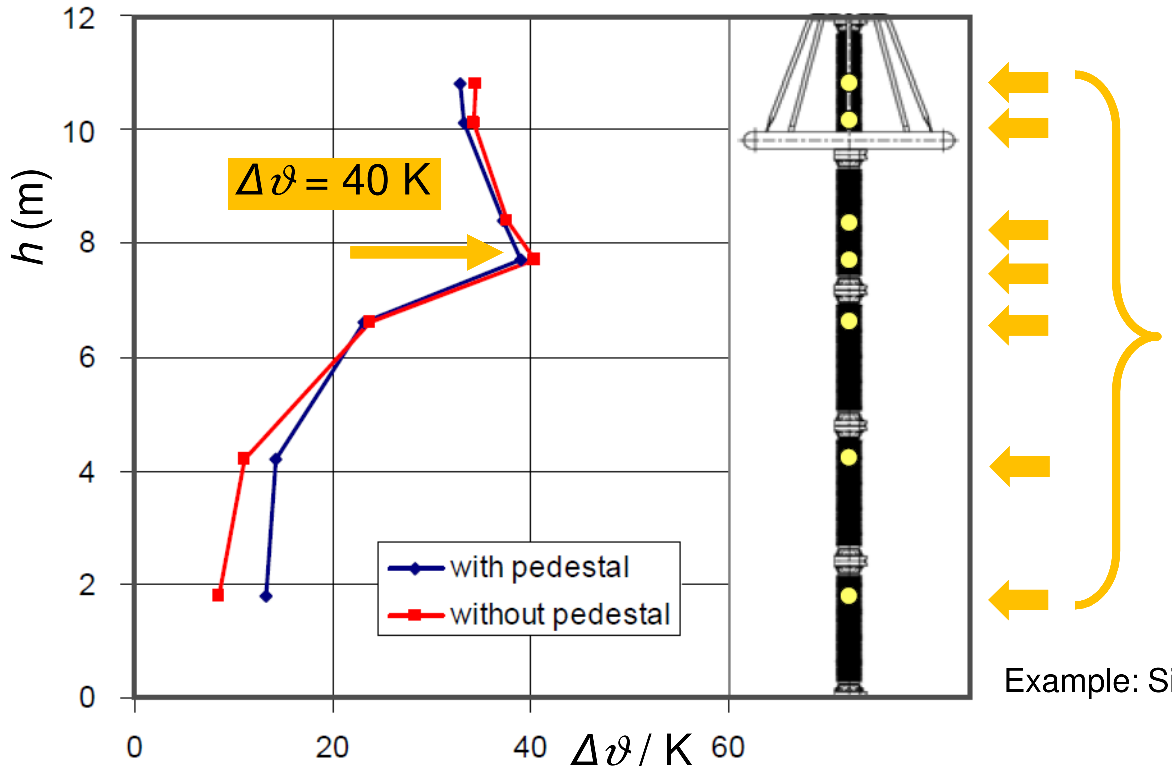


→ **There may be a high overtemperature in the arrester's top part**

- Possibly **higher** for "tube" design due to thermal insulation (overtemperature may reach e.g. 40 K)
- "Tube" design has **high thermal time constants** (may be hours)
  → long cooling time after energy injection

Voltage and Temperature Distribution of MO Arresters

Example of a measured temperature distribution in a 1200 kV arrester:



Calculate **average** temperature from real distributed temperature measurements

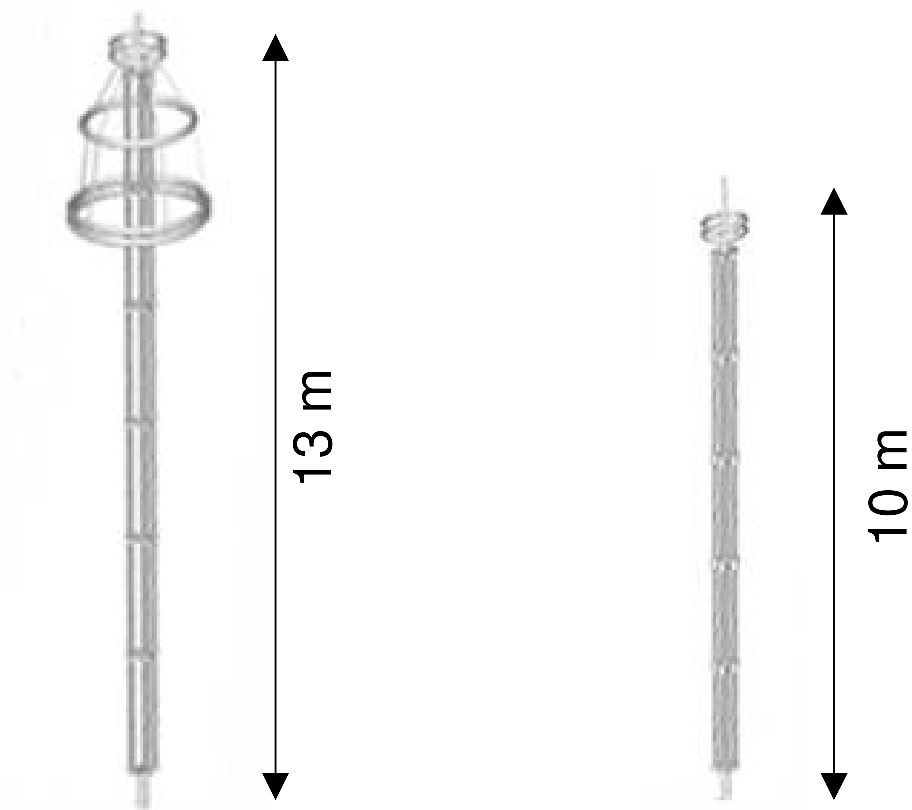
Example: Siemens 1200 kV arrester

Requirement in IEC 60099-4 Ed. 3.0:

Average temperature **= Start temperature in W_{th} test** (for UHV arresters only)

Voltage and Temperature Distribution of MO Arresters

Alternative approach with *external* grading capacitors



Traditional: with grading rings

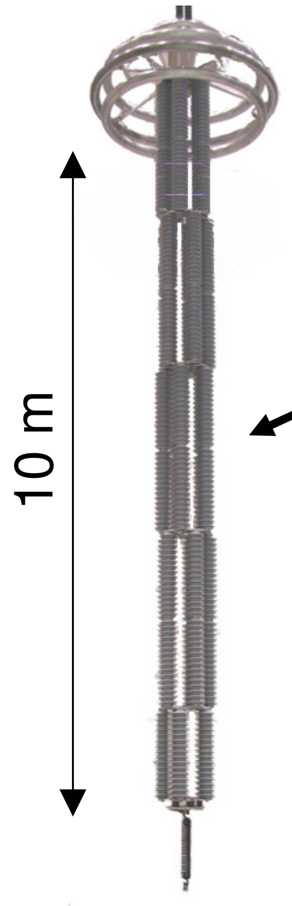
Alternative approach: with external grading capacitors

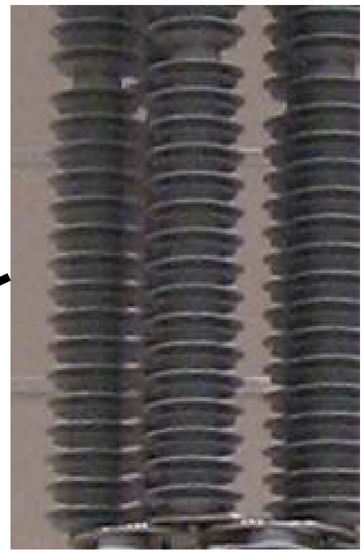
To withstand SIWV of 1800 kV (9…10) m required clearance phase-to-ground, which would be the optimum height of arrester

Example: ABB 1200 kV arrester

Voltage and Temperature Distribution of MO Arresters

Alternative approach with *external* grading capacitors



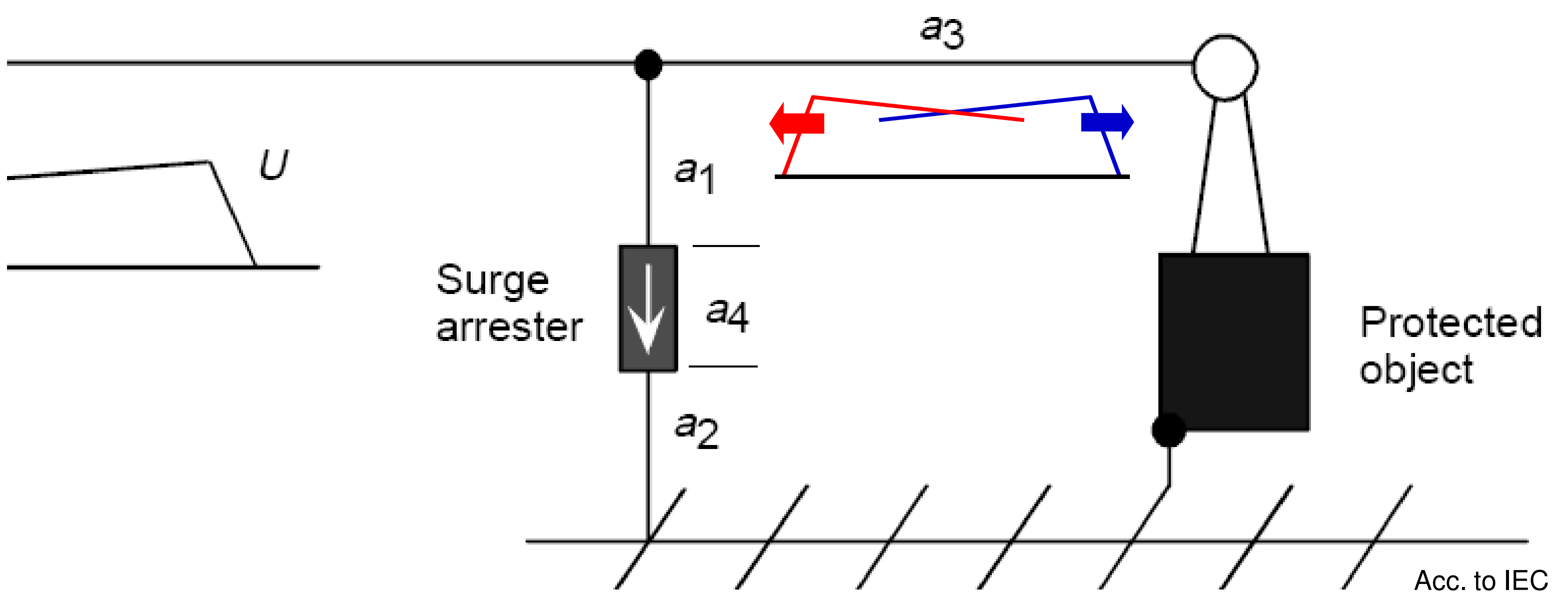


5 parallel polymer units
and a **grading**
capacitor in the center

Example: ABB 1200 kV arrester

UHV Arresters – Protective Distance Considerations

Arresters have a **limited protective distance** (separation effects due to traveling waves) → should be **as close as possible** to the device to be protected against lightning overvoltages



The shorter $\boldsymbol{L = a_1 + a_2 + a_3 + a_4}$ the better the protective performance!

UHV Arresters – Protective Distance Considerations

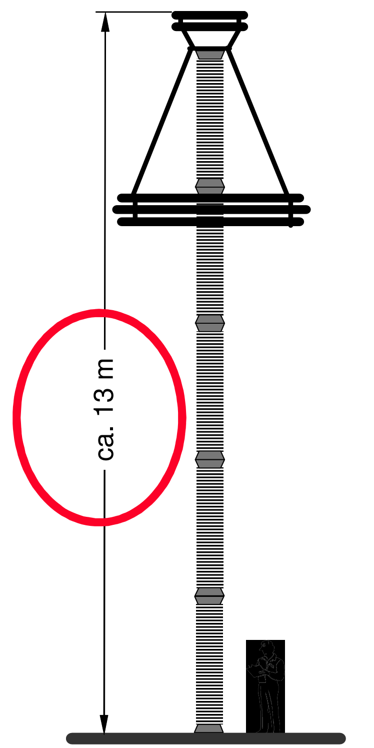
Example: U_s = 1200 kV

Protective distance $$L = \frac{n}{A} \cdot \left(\frac{\text{LIWV}}{1{,}15} - U_{pl} \right) (L_{sp} + L_t)$$ acc. to IEC 60071-2, IEC 60099-5

where $$L_t = \frac{\text{adopted failure rate}}{\text{shielding failure rate}}$$

- U_{pl} = 1700 kV (LI protective level)
- A = 17000 kV for a 6/8 conductor bundle (consideration of corona damping)
- L_{sp} = 500 m assumed (span length)
- n = 2 (n ... number of connected lines; n = 2 if ≥2 lines connected)
- shielding failure rate: 2.5 per 100 km and year = $2{,}5 \cdot 10^{-5}$ $(a \cdot m)^{-1}$
- adopted failure rate: $1 \cdot 10^{-3}$ a^{-1} (one per 1000 years)
- LIWV = 2200 kV

➡ Protective distance **L = 13.5 m** → **too low!**



UHV Arresters – Protective Distance Considerations

Countermeasures

- **Double OHGW** in span field adjacent to substation:
  → shielding failure rate reduced by factor of 10, i.e. to $2.5 \cdot 10^{-6}$ $(a \cdot m)^{-1}$

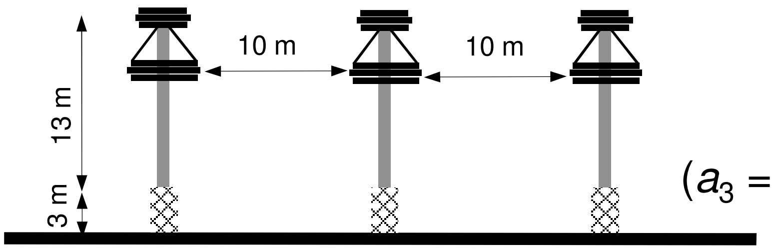
... is **not** sufficient to solve the problem (L = 22.5 m)!

- additional consideration of **CVTs (C = 8 nF)** at line entrance
  → factor A reduced from A = 17000 kV to A = 6000 kV

➡ L = 64 m → **may** be sufficient!

UHV Arresters – Protective Distance Considerations

Installation of **"tube"** design arresters **(self supported)**



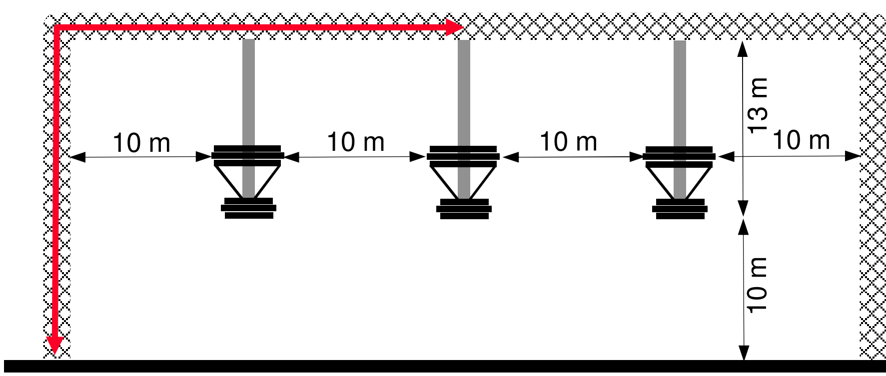
possible if $a_3 \leq \approx 40$ m

(a_3 = distance arrester terminal – transformer terminal)

"Cage" design arresters will require **suspended** installation (for mechanical reasons):

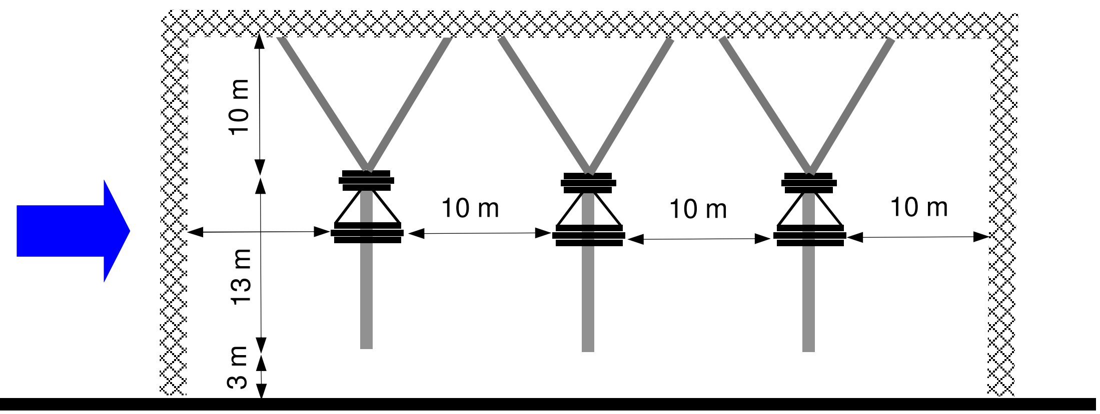
possible only if $a_3 \leq \approx 10$ m!

(≈ 43 m just for grounding connections)



possible if $a_3 \leq \approx 40$ m

(but requires high installation efforts)



UHV Arresters – Energy Handling Considerations

Novel approach of IEC 60099-4, Ed. 3

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

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

- Classification by **application** (similar to IEEE approach)
- Characterized by
  - **repetitive charge transfer rating, Q_{rs}**
  - **thermal energy rating, W_{th}**

UHV Arresters – Energy Handling Considerations

Comparison of "old" and "new" classification

Old LDC	Required minimum test energy* kJ/kV	Corresponding ***new*** thermal energy rating as per **8.7.3** W_{th} kJ/kV	Estimated current at ***old*** LD test ** A	Charge calculated with the same current and duration as for ***old*** LDC to give the required minimum energy C	Corresponding ***new*** repetitive charge transfer rating as per **8.5.4** Q_{rs} C	Approximate range of system voltage kV
1	1,0	2	277	0,56	0,4	
2	2,1	4	538	1,10	1	up to 300
3	3,3	7	721	1,78	1,6	up to 420
4	5,0	10	962	2,75	2,4	up to 525
5	6,9	14	1118	3,75	3,6	up to 800

W_{th} and Q_{rs} can be specified as high as necessary, there is **no upper limit**!

UHV A.C. Arresters – Dielectric Testing

Requirements acc. to "old" IEC 60099-4, Ed. 2.2:

8.2.2 Tests on individual unit housing

The applicable tests shall be run on the longest arrester housing. If this does not represent the highest specific voltage stress per unit length, additional tests shall be performed on the unit housing having the highest specific voltage stress. The internal parts may be replaced by an equivalent arrangement (for example, grading elements) to provide linear voltage distribution along the arrester axis.

8.2.3 Tests on complete arrester housing assemblies

Under consideration.

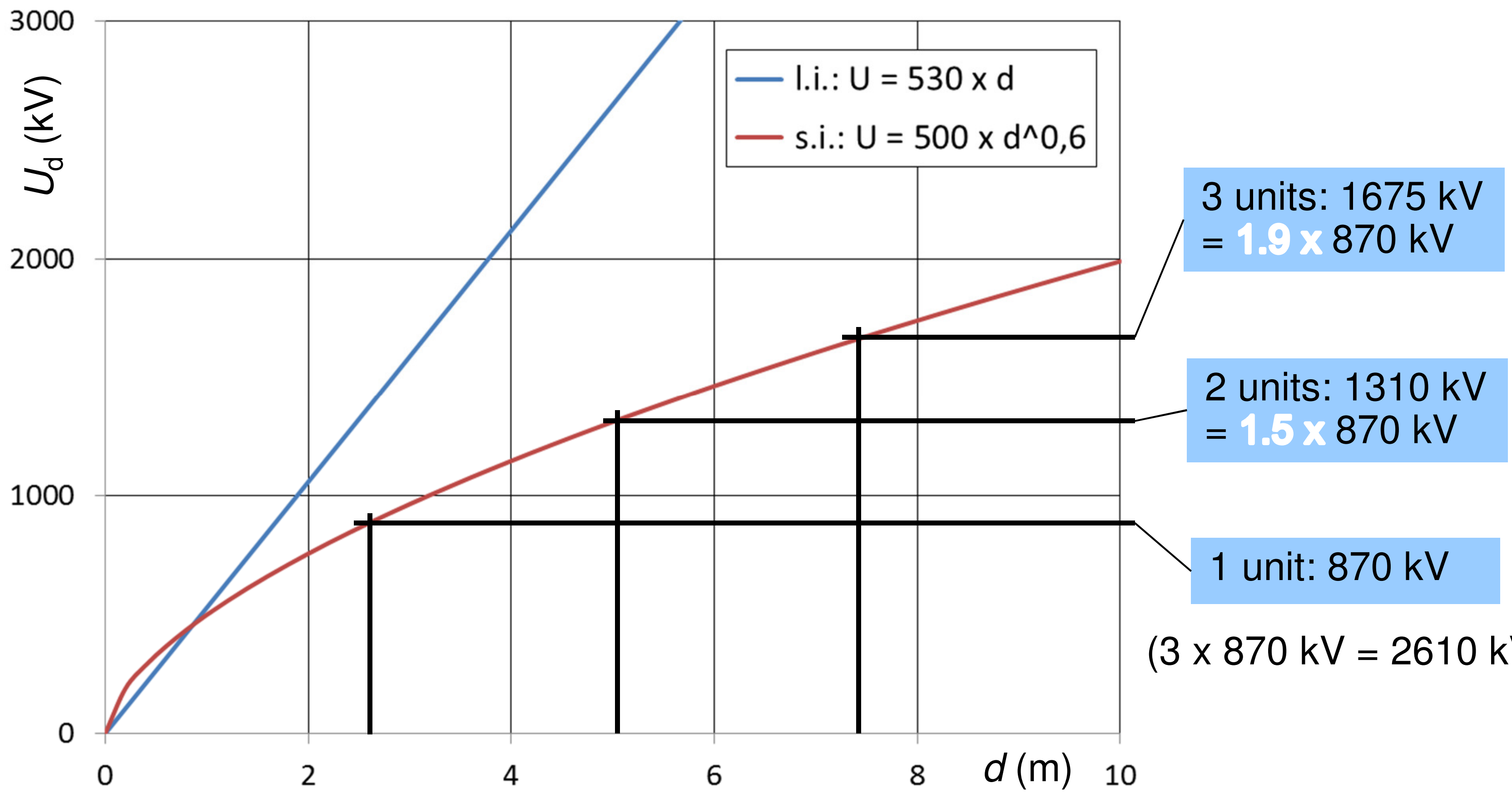
→ Tests on individual unit housings were allowed, even for arresters for highest system voltages.

What was wrong with this approach?

UHV A.C. Arresters – Dielectric Testing

1) Non-linear dependence $U_d = f(d)$ for s.i. voltage

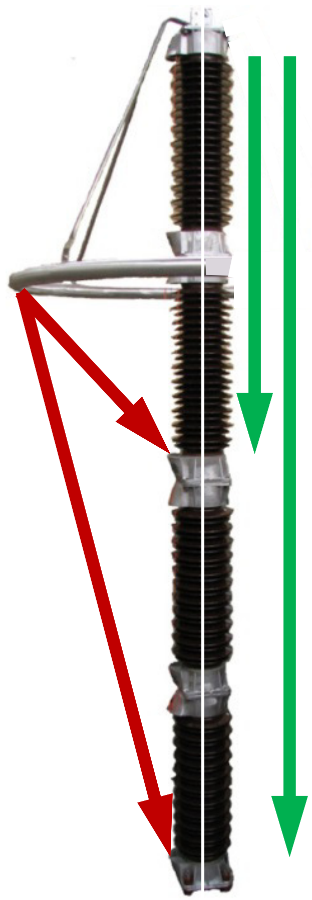
Example: 800 kV arrester; h = 7.5 m; 3 units of 2.5 m each



(3 x 870 kV = 2610 kV)

UHV A.C. Arresters – Dielectric Testing

2) Principally unknown influence of grading rings on dielectric strength

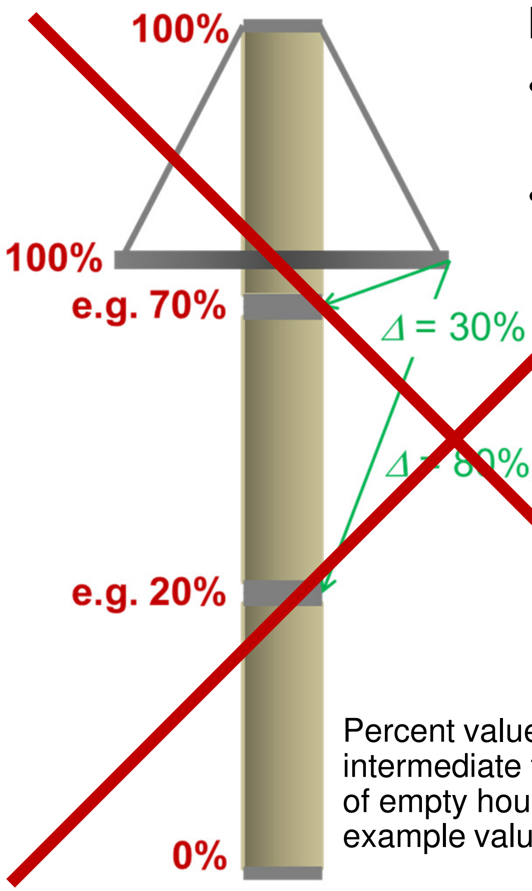


Clearances **with** and **without** grading ring

- All clearances notably affected by grading rings
- Especially “ring-to-flanges” my be critical
  - ➢ Rings must be mounted during tests.
  - ➢ Flanges must be on correct electric potential.

UHV A.C. Arresters – Dielectric Testing

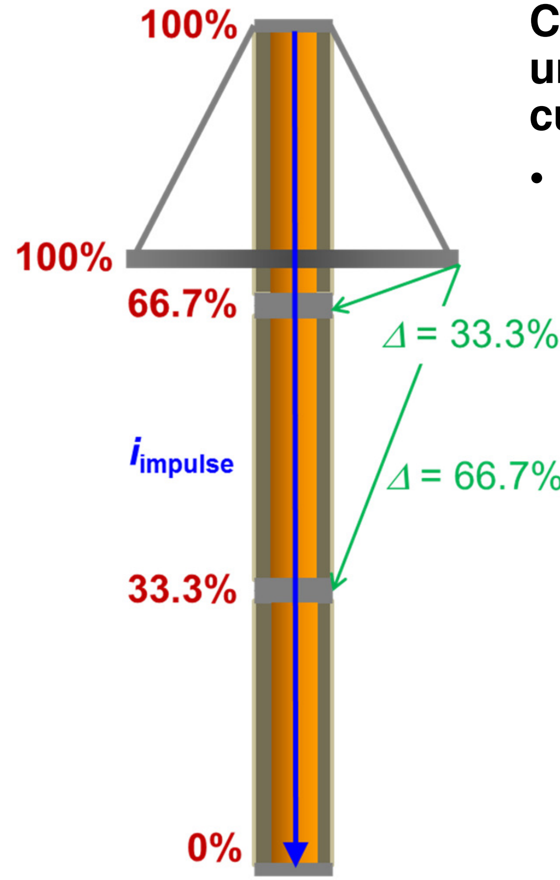
- Dielectric tests on **complete** housing assembly if U_s > 245 kV
- Must be internally graded (to achieve linear voltage distribution)



Empty housing:

- Flanges on floating potential
- Take a potential determined by the external electric field

Percent values at intermediate flanges of empty housing are example values!



Complete arrester under impulse current stress:

- Flange potential controlled by MO resistors‘ resistive voltage distribution

UHV A.C. Arresters – Dielectric Testing

Test levels required acc. to "old" IEC 60099-4, Ed. 2.2 (example: 1200 kV arrester)

– l.i. voltage = 1.3·U_{pl} = 1.3·1700 kV = 2210 kV with U_{pl} ... arrester's l.i. protective level

– s.i. voltage = 1.25·U_{ps} = 1.25·1500 kV = 1875 kV with U_{ps} ... arrester's s.i. protective level

Comparison with requirement on 1200 kV equipment acc. to IEC 60071-1:

- LIWV = 2200 kV
- SIWV = 1800 kV

→ Arrester housings would be tested more severe than other equipment in the system

→ Nonsense, as the arrester housings are the best protected insulators in the system

"New" approach of IEC 60099-4, Ed. 3.0:

– s.i. voltage = 1.1·$e^{m*1000/8150}$·U_{ps} = 1.1·1.06·1500 kV = **1750 kV** → reasonable!

(m = 0.48 in this case, taken from IEC 60071-2, Fig. 9)

Metal Oxide Surge Arresters

The End