Application Guidelines

Overvoltage Protection

Dimensioning, testing and application
of metal oxide surge arresters in medium voltage systems

ABB

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4th revised and expanded edition: February 2009

RECENT STATE OF TECHNOLOGY AND DOCUMENTATION

The first edition of the application guidelines for the dimensioning, testing and application of metal oxide surge arresters (MO arresters) in medium voltage systems appeared in 1994 and was written by René Rudolph. We were very pleased by the extremely positive reception, which attested to our belief that competent consulting with regard to the application of our products is as important as the quality of the products itself.

The technological progress and the many constructive remarks by our customers now makes it necessary to provide a fourth revised and expanded edition of this brochure. The concept of the brochure remains the same. The dimensioning and the theoretical derivations for the best possible use of the surge arresters have not changed and therefore they were taken as such in the new edition, however some completions were made when considered necessary. The printing mistakes were corrected and the scientific phraseology was improved. The details of the basics were strongly underlined. The state of technological development today demands the use of metal oxyde surge arresters without spark-gaps and with a housing made of synthetic material. That is why we will no longer discuss the surge arresters with spark-gaps and porcelain housing in the present brochure.

The latest state of standards in IEC and CENELEC is taken into consideration. If considered necessary for improved understanding, other standards and publication are also used. The quoted literature is listed, thus offering the opportunity of thorough study.

Bernhard Richter, responsible for product management and quality assurance in the Division Surge Arresters of ABB Switzerland Ltd, gladly took on the task of the general revision of the brochure. He is an active member in various working groups of IEC TC 37 surge arresters (MT 4 and MT 10), CENELEC TC 37A and in the study committee SC A3 high voltage equipment of Cigré, in which he leads the "Surge Arresters" working group.

We hope that you as a reader will be satisfied with our new edition with its new appearance, and that you will find it useful for your purpose. We welcome amendments and suggestions that help us to better meet all possible customer needs.

ABB Switzerland Ltd

Wettingen, February 2009

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1 | INTRODUCTION

Overvoltages in electrical supply systems result from the effects of lightning incidents and switching actions and cannot be avoided. They endanger the electrical equipment because for economic reasons the insulation cannot be designed to withstand all possible cases. An economical and safe on-line system calls for extensive protection of the electrical equipment against unacceptable overvoltage stresses. This applies generally to high voltage systems as well as to medium and low voltage systems.
Overvoltage protection can be basically achieved in two ways:

- Avoiding lightning overvoltage at the point of origin, such as through earthed shielding wires in front of the substation that intercept lightning.
- Limit overvoltage near the electrical equipment, for instance through surge arresters in the vicinity of the electrical equipment.

In high voltage systems both methods of protection are common. The shielding wire protection in medium voltage systems is generally not very effective. Due to the small distance between the shielding wires and the line wires, a direct lightning stroke on the shielding wire leads to an immediate flashover to the line wires as well. In addition, induced overvoltages in the line wires cannot be avoided by shielding wires.

The most effective protection against overvoltages in medium voltage systems is therefore the use of surge arresters in the vicinity of the electrical equipment.

The magnitude of the overvoltage is given in p.u. (per unit), usually related to the peak value of the highest permanent phase-to-earth voltage that occurs. [1]
It is defined as 1 p.u. = $\sqrt{2} \cdot U_s / \sqrt{3}$.
Until now the overvoltages used to be related to the highest voltages of the electrical equipment U_m. This is incorrect because the overvoltages in the system, such as the overvoltages that occur as a consequence of earth faults, do not depend on the electrical equipment, but they depend on the highest operating voltage of the system U_s. That is why the overvoltages, such as those that are decisive for the choice of the continuous operating voltage of the arrester, are related to the operating voltage of the system U_s. The voltages, which are important for the insulation co-ordination and the protection of the insulation of electrical equipment, are derived from the highest voltage of the electrical equipment U_m.
In [1] the differences between the temporary and the transient overvoltages are shown in detail. For the following considerations it is meaningful to distinguish between three types of overvoltages:

Temporary overvoltages occur, for example, during load rejection or because of faults with earth connection. The duration of these overvoltages, mostly with power frequency, can be between 0.1 seconds and several hours. Generally, they are not higher than √3 p.u. and are usually not dangerous for the system operation and the insulation of the equipment. However, they are decisive for the dimensioning of the arresters.

Switching overvoltages (slow front overvoltages) occur during switching actions and consist mostly of heavily damped oscillations with frequencies up to several kHz and a magnitude up to 3 p.u. In the case of inductive switching, the switching overvoltages can reach up to 4 p.u.

Lightning overvoltages (fast front overvoltages) originate in atmospheric discharges. They reach their peak value within a few microseconds and subsequently decay very rapidly. The magnitude of these unipolar overvoltages can reach values well above 10 p.u. in medium voltage systems.

2 | SURGE ARRESTER TECHNOLOGY

The so-called "conventional" surge arresters were almost exclusively employed in medium voltage systems until the middle of the eighth decade of the last century. They consisted of a series connection of SiC resistors with a low nonlinearity and plate spark-gaps. A short circuit to the earth emerges when the spark-gaps come into action during the rising of the overvoltage. The SiC resistors in series limit the follow current from the power supply and thereby enable the arc in the gap to extinguish at the next current zero.
In the final years of the last century, there were two fundamental improvements of surge arresters used in medium voltage systems. On one hand, the series connection of SiC resistors and plate spark-gaps were replaced with the metal oxide (MO) resistors of a very high nonlinearity without series connection of plate spark-gaps, while on the other hand, the housings of the surge arresters made of porcelain were replaced with housings made of polymer material (synthetic material).
A large number of conventional spark-gapped arresters are still installed in medium voltage systems. However, they are no longer produced.
The disappearance of the spark-gaps, which were necessary for the SiC surge arresters, made the design of the surge arresters much easier, especially for the medium voltage systems. Some new designs were only possible due to the development of the MO resistors and the use of polymeric material for the housings. The fundamental advantage is the fact that the surge arrester has now only one "active" element, which is the MO resistor or the so-called active part, consisting of a column of MO resistors. Certainly it goes without saying that the MO resistors have to perform all the functions that were earlier performed by different parts of the SiC surge arresters. For instance, they have to be non-ageing by applied continuous operating voltage, they have to be able to absorb the occurring energy during a discharge and afterwards they have also to be able to reduce the follow current (leakage current) to a small value that is not dangerous for the service. That makes the development, the manufacture and the quality control of the MO resistors a very important task to be fulfilled.

2.1 Arrester design

Generally, an MO surge arrester is made up of two parts: the active part consisting of one or more piled up MO resistors and an insulating housing, which guarantees both the insulation and the mechanical strength.
Fundamentally, there are three different possibilities of construction [2]:

- In a glass-fiber reinforced tube made of synthetic material, which is covered with an insulating material, the active part is installed, similar to the insulators made of porcelain. These so-called hollow insulators have the same disadvantages as the porcelain insulators: they need a sealing and pressure relief system and they can have internal partial discharges.
- The active part is wrapped with glass-fiber material and is soaked with resin, which turns the whole into a rigid body. The insulating polymeric housing is then slipped over the resin block or shrunk on it. This construction has the disadvantage that it forcibly breaks apart when the MO blocks are overloaded. Another disadvantage is the fact that there are different insulating materials, which also means that there are more boundary layers. Therefore, it is necessary to take special measures for sealing.

- The active part is held mechanically together with glass-fiber reinforced loops or bands. The synthetic material (such as silicone) is directly molded on to the MO resistors. This direct molding has the advantage that no gas volume remains in the arrester. Sealing problems and inner partial discharges are thus out of the question. There are no interfaces among the polymeric materials in which humidity can penetrate. The danger of an explosion or a shattering of the housing is very small.

2.2 Metal oxide resistors as arrester elements

MO resistors are made of different metal oxides in powder form which are compressed and sintered in the form of round blocks [3]. Figure 1 on the following page shows the principle of the manufacturing process. The diameter of the MO resistors produced by ABB Switzerland Ltd lie between 38 mm and 108 mm. The height of the blocks is typically between 23 mm and 46 mm. For special applications, the MO resistors can be sliced to a height as small as 0.8 mm. The diameter of the MO resistors determines the current; the height of the MO resistors (or resistor stack) determines the voltage in continuous operation and the volume of the blocks determines the energy handling capability. The diameter of the MO resistors correlates with the line discharge classes corresponding to IEC 60099-4, as shown in Table 1. The current and energy values for the type tests arise directly from the line discharge classes and the nominal discharge current.

Line discharge class IEC 60099-4	-/-*	1	2	2	3	4	5
Nominal discharge current I_n in kA	5	10	10	10	10	20	20
High current impulse I_{hc} in kA	65	100	100	100	100	100	100
Switching impulse current I_{sw} in A	-/-**	125 / 500	125 / 500	125 / 500	250 / 1000	500 / 2000	500 / 2000
Operating duty test, performed with	$1 \times I_{hc}$	$1 \times I_{hc}$	$2 \times I_{ld}$	$2 \times I_{ld}$	$2 \times I_{ld}$	$2 \times I_{ld}$	$2 \times I_{ld}$
W' in kJ/kVU_c	2.6	3.0	**5.2**	**5.5**	**9.0**	**13.3**	**21.0**
W'_{hc} in kJ/kVU_c	2.1	3.6	3.5	3.4	3.3	3.2	3.0
Rectangular wave I_{rw}, 2 ms in A	250	250	500	550	1000	1350	2700
Diameter of MO resistors in mm	38	38	42	47	62	75	108

* Without line discharge class
** In IEC 60099-4 not specified

Table 1: Correlation of diameters of the MO resistors made by ABB with the line discharge class and the nominal discharge current, and the directly related parameters according to IEC 60099-4. The figures in the last four rows are manufacturer-dependent values. The specific energy W' refers to the operation duty test of the corresponding arrester (bold printed), i.e. it refers to the energy of two long duration current impulses. See also Table 2. The specific energy W'_{hc} is the energy that occurs when a predetermined current is injected in the arrester, e.g. a high current impulse of 4/10 µs wave shape. This data is for informational purposes only. See also Chapter 3.2 energy absorption capability.

The time duration of the long duration current impulse I_{ld} for the different line discharge classes is given in IEC 60099-4. The height of the current results from the calculated energy that has to be injected.
The contact areas of the MO resistors are metalized up to the edge of the block with soft aluminum, the surface of the housing is passivated with glass. In this way, the MO material of the MO resistors produced by ABB Switzerland Ltd is completely covered. Figure 2 shows a selection of MO resistors. Figure 3 shows in an enlarged form the inner structure of the MO material. It is absolutely necessary to obtain a very homogeneous structure of the material in order to reach the high specific energy handling capability of the MO resistor.
The energy handling capability of a MO resistor and of a MO arrester respectively, depends on the volume of the active part and on the design (heat transfer) and the electrical dimensioning.

Metal oxide resistors have an extreme non-linear current voltage characteristic, which is described as

$$I = k \times U^{\alpha}$$

α is variable between $\alpha \leq 5$ and $\alpha \approx 50$. An exact value for α can only be provided for a very restricted range of the current in the characteristic curve.
The U-I characteristic of such an MO resistor is shown in figure 4. I_n is the nominal discharge current, U_{pl} is the lightning impulse protection level of the surge arrester. It is defined as the maximum voltage between the terminals of the surge arrester during the flow of I_n. U_c is the maximum permissible continuous operating voltage with the power frequency of the surge arrester, and is given as an rms value; in IEEE/ANSI standards also called MCOV (Maximum Continuous Operating Voltage).

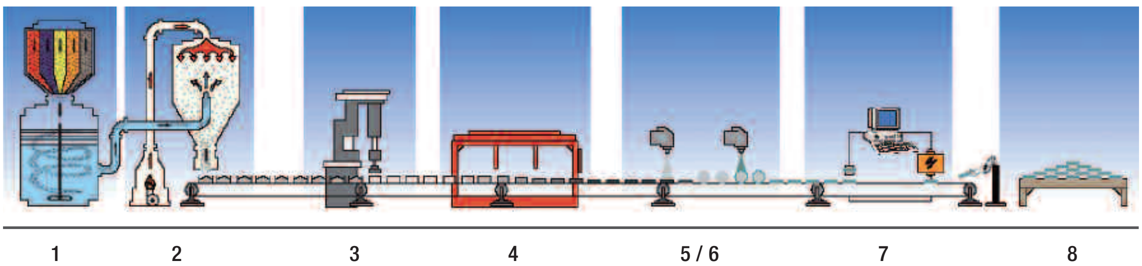


Figure 1: Manufacturing process of MO resistors.
1 Mixing of the metal-oxide powders
2 Spray drying of the powder mixture
3 Pressing of the MO resistors
4 Sintering
5 Metallization of the contact areas
6 Coating of the surface
7 Final tests of the MO resistors
8 MO resistors ready to be installed in the arrester

Figure 2: MO resistors (choice), produced by ABB Switzerland Ltd

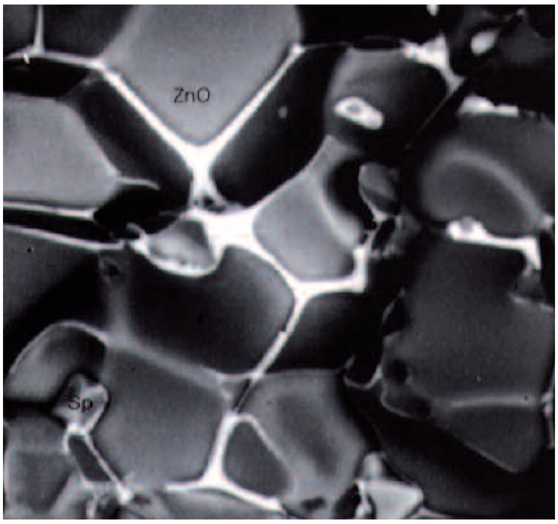


Figure 3: Surface electron microscope image of the MO structure. Fracture surface, 2,000 times enlarged. The MO grains and the boundaries between the single grains can clearly be seen.

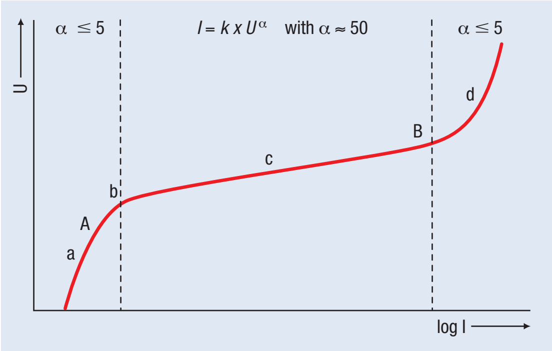


Figure 4: Non-linear voltage-current-characteristic of a MO resistor

a. Capacitive linear area, current ≤ 1 mA
b. Knee point of the characteristic curve, transition from the almost insulating to the conducting condition
c. Strongly non-linear area
d. Ohmic, linear area, high current area
A. Area of continuous operating voltage U_c
B. Residual voltage U_{res}, protection area

2.3 Arrester housing made of silicone

Silicone rubber (usually simply referred to as "silicone") is an excellent insulating material for high-voltage insulators. In high-voltage technologies, silicone has been successfully used since about 40 years for long rod insulators and bushings, for example. The first MO arresters with the typical ABB direct molding were used in 1986. Millions of these arresters are since being used trouble free all over the world and under all climate conditions.

The basic Si-O-Si-O matrix with the additional CH3-groups (Methyl) is characteristic for silicone. The filling materials and special additives cause the arcs and creep resistance necessary for use in high-voltage technology. The qualities of silicone include very high elasticity and resistance to tearing, high temperature stability, very low combustibility (silicone is a self-extinguishing material) and high dielectrical withstand strength. Besides all these qualities the most remarkable one is hydrophobicity: water simply rolls off the silicone surface. The silicone insulators are water-repellent even if they are polluted. This means that the hydrophobicity is also transmitted into the pollution layer on the surface. All this provides excellent performance properties for high voltage equipment insulated with silicone.

The hydrophobicity of the silicone can be diminished under the influence of a long period of humidity or electrical discharges on the surface; it is however completely restored in a short period of time (from a couple of hours to a couple of days). As much as we can say today this mechanism works for an unlimited duration.

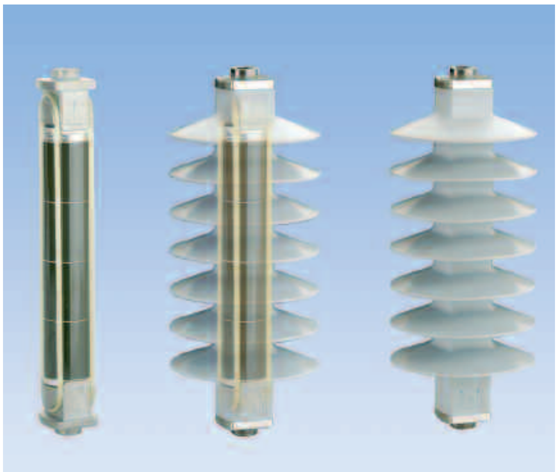


Figure 5: MO arrester Type POLIM-D
Left: active part before molding. Middle: schematic design.
Right: complete arrester.

2.4 MO arresters produced by ABB

All MO arresters produced by ABB Switzerland Ltd used in medium voltage systems are designed according to the same principle. This construction concept of silicone direct molding, which is patented by ABB, consists of two electrodes connected together through two or more glass-fiber reinforced elements. It results a hard cage or frame, which guarantees the mechanical strength. The MO resistors are arranged within this frame. Additional metal cylinders with the same diameter as the MO resistors fill the inside completely, thus forming a uniformly round active part. The MO blocks are pressed together with a bolt in the centre of the lower electrode; the bolt is secured in the end position, thereby providing each arrester with the same contact pressure. The contact pressure with some small sized arresters is achieved through spring elements. The active part is placed into a form and completely sealed with silicone. As a result, the surge arrester, which is completely sealed and tight, has no void inside. Figure 5 shows an MO arrester of type POLIM-D manufactured according to this technique. It is shown before and after being molded in silicone. The flexible method of construction (modular concept) makes it possible to change the form of the arrester to meet any necessity.

The demands on the arresters depend on the operational conditions and the type of the electrical equipment to be protected. ABB offers a selection of different types of MO surge arresters for medium voltage systems and for special applications. Figure 6 shows, as an example, three arresters with the same active part, but with different housings; figure 7 shows an absolutely touch-proof arrester to be used in substations for protecting the cable systems.

Figure 6: MO arrester MWK and MWD
Left: MWK … K4 with alternating sheds and a long creepage path for regions with strong pollution.
Middle: MWK with standard housing.
Right: MWD for indoor applications. The MO active part is similar in all three cases.

Figure 7: MO arrester POLIM-D … PI
Pluggable, touch-proof arresters for use in cable installations.
For all existing switchgear with an inner-cone system, cone sizes 2 and 3.

Table 2 and Table 3 contain the primary technical data for the surge arresters produced by ABB for use in medium voltage systems.
It is to be noted here that this present application guidelines does not take into consideration regular revisions. Therefore it is possible that there might be differences between the technical data given in the tables and the data on the data sheets. Decisive are always the data sheets.

In Table 2 there are four MO arresters with I_n = 10 kA and line discharge class 2 for use in medium voltage systems. The other electrical data differ (except the line discharge class) from one arrester to another and therefore the surge arresters are for different applications.

Table 2: Main electrical data for ABB surge arresters used in medium voltage systems

Arrester type to be used in medium voltage systems	**LD***	I_n kA	I_{hc} kA	I_{rw} 2 ms A	*W'* kJ/kV$_{U_c}$	U_c kV	U_{pl}/U_c
POLIM-D…PI	1	10	65	250	2.6	4 to 42	3.58
POLIM-D	1	10	100	250	3.6	4 to 36	3.5
POLIM-K	2	10	100	500	5.2	4 to 36	3.33
MWK/MWD	2	10	100	550	5.5	4 to 44	3.07
POLIM-I…N	2	10	100	550	5.5	4 to 44	3.07
POLIM-S…N	3	10	100	1000	9.0	4 to 44	3.0
POLIM-H…N	4	20	100	1350	13.3	4 to 44	3.19**
for special applications							
POLIM-C…N	2	10	100	550	5.5	0.9 to 7.5	3.5
POLIM-C…LB	2	10	100	550	5.5	2.3 to 4.8	3.44
POLIM-C…ID***	2	10	100	550	4.3	1.0 to 2.2	3.2
POLIM-R…-1/-2 N	-/-	20	100/200	1350/2400	12/24	0.11 to 0.78	3.38/3.07

* Line discharge class according to IEC 60099-4.
** A lightning current impulse of 10 kA peak value results in U_{res}/U_c = 2.9.
*** Also for d.c. applications. U_c is given here for applications in d.c. systems.

Table 3: Main mechanical data of the ABB surge arresters to be used in medium voltage systems

Arrester type to be used in medium voltage systems	**Admissible bending moment 1 min** Nm	**MPSL*** N	**Torsion** Nm	**Vertical force** N	**Rated short circuit current** I_s**, rms** kA
POLIM-D…PI	-/-**	-/-	-/-	-/-	16
POLIM-D	200	400/690	50	625	20
POLIM-K	200	400/690	50	1000	40
MWK/MWD	500	280/850	68	1200	20
POLIM-I…N	2500	3500	100	2000	40
POLIM-S…N	4000	5700	100	3000	50
POLIM-H…N	6000	8000	100	4000	63
POLIM-C…N	200	690	50	1000	20

* Maximum Permissible Service Load. The definition of MPSL is the force that can be applied on the highest arrester of the same type for 60 s to 90 s without producing any permanent deflection >5 % of its height.
** The arresters without specification of the mechanical data should not be stressed with larger mechanical forces. The information regarding to the mechanical strength can be obtained from the manufacturer.

POLIM-K: Is to be used for protecting overhead lines, transformers in substations and as a line arrester. It has a flexible housing concept for the arrester for optimal use in all the various polluted locations. It is very suitable as a line arrester due to its high short circuit resistance of 40 kA. The POLIM-K is ideal for applications in areas in which arresters of line discharge class 2 are to be used.

MWK/MWD: The classical arrester with the particularly favorable protection ratio of U_{pl}/U_c = 3.07 and high energy handling capability. It is especially suited for protecting SF_6-gas insulated switchgears, as well as for protecting cables and substations. With insulated cable connections, the indoor execution MWD is also suited for installation in narrow switchgears. The MWK is also suitable for protecting generators and motors, as a "riser pole" arrester, and also for protecting capacitors, because of its low residual voltage.

POLIM-I: Has the same favorable electrical data as MWK/MWD, but its mechanical resistance is much higher, which is why these arresters are used in applications that require high mechanical stability. Typical areas of application are use in traction systems and as line arresters, if it is necessary to have very high mechanical resistance.

POLIM-C: The MO arresters of the type POLIM-C also have line discharge class 2. The application lies in the lower voltage range for special applications, such as the protection of cable sheath and the protection of motors.
With this ABB offers a wide range of MO arresters for use in the technical demanding area of class 2 arresters.

3 | TECHNICAL DATA AND FUNCTION OF MO ARRESTERS

The function of a surge arrester with an active part consisting of a series connection of MO resistors is very simple. In the event of a voltage increase at the arrester's terminals, the current rises according to the characteristic curve – Figure 8 – continually and without delay, which means that there is no actual spark over, but that the arrester skips over to the conducting condition. After the overvoltage subsides the current becomes smaller according to the characteristic curve. A subsequent current, such as those that arise with spark-gaps and spark-gapped arresters, does not exist; it flows only the so-called almost pure capacitive leakage current i_c of about 1 mA.

The resistor stack of the surge arrester behaves in an almost pure capacitive manner with applied continuous operating voltage U_c. The stray capacitance of each resistor against the earth causes an uneven voltage distribution along the arrester axis under applied U_c. This unevenness increases with the length of the resistor stack and can be approximately calculated according to **[4]**. High voltage MO arresters therefore need grading elements, such as grading rings, which mostly compensate the unfavorable influence of the stray capacitance. The resistor stack with medium voltage arresters is, however, so short that the uneven voltage distribution can be neglected. Therefore, medium voltage arresters do not require any grading elements. The following paragraph shows and briefly explains typical current and voltage waveforms in different areas of the characteristic curve.

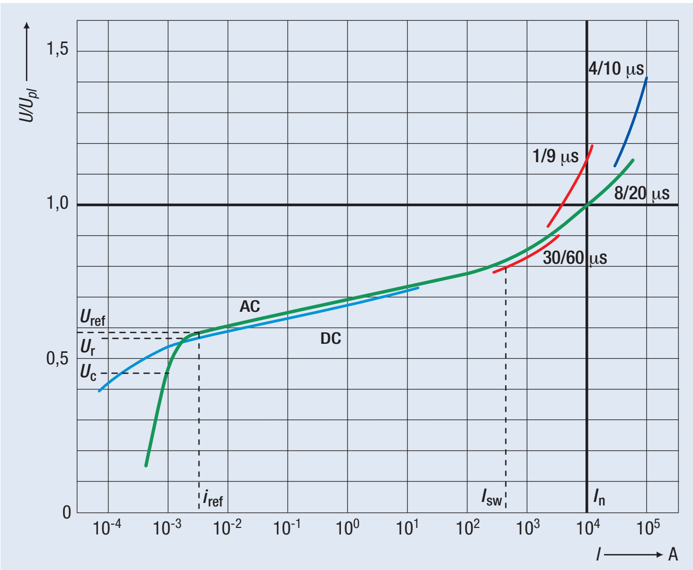


Figure 8: Voltage-current characteristic of an MO arrester with I_n = 10 kA, line discharge class 2. The voltage is normalized to the residual voltage of the arrester at I_n. The values are given as peak values for the voltage (linear scale) and the current (logarithmic scale). Shown are typical values.

3.1 Currents and voltages

In [4] the following arrester related terms are given:

Continuous operating voltage U_c: Designated permissible rms value of power-frequency voltage that may be applied continuously between the arrester terminals.

Continuous current (i_c): Current flowing through the arrester when energized at the continuous operating voltage. The MO arrester behaves in an almost purely capacitive manner in the region of the continuous operating voltage. The current is around 1 mA and almost 90° electrically shifted compared to the voltage. The power losses in this region can be neglected. The continuous current is also known as leakage current.

Rated voltage U_r: Maximum permissible rms value of power-frequency voltage between the arrester terminals at which it is designed to operate correctly under temporary overvoltage conditions as established in the operating duty tests.

Briefly: the rated voltage U_r is the voltage value, which is applied for t = 10 s in the operating duty test in order to simulate a temporary overvoltage in the system. The relationship between the rated voltage U_r and the continuous operating voltage U_c is generally U_r/U_c = 1.25. This is understood as a given fact, but it is not defined anywhere. Other ratios can be chosen. The rated voltage has no other importance although it is often used when choosing an arrester.

Reference voltage U_{ref}: Peak value of the power-frequency voltage divided by √2, which is applied to the arrester to obtain the reference current.

Reference current (i_{ref}): Peak value (the higher peak value of the two polarities if the current is asymmetrical) of the resistive component of a power-frequency current used to determine the reference voltage of an arrester.

The reference current is chosen by the manufacturer in such a way that it lies above the knee point of the voltage-current characteristic and has a dominant ohmic component. Therefore, the influences of the stray capacitance of the arrester at the measurement of the reference voltage are not to be taken into account. The reference voltages, which are measured at single MO resistors, can be added to give the reference voltage of the entire arrester.

Reference voltage (U_{1mA}) and reference current with d.c. voltage: A reference current and the reference voltage for d.c. voltage belonging to it are often also demanded instead of a given reference current for a.c. voltage. It is now common practice to specify the d.c. voltage, which is applied with a direct current of 1 mA to the terminals, no matter what the diameters of the MO resistors are. Both types of information, the reference current and the reference voltage for a.c. voltage and for d.c. voltage, are in principle equal. Both of these types information describe a point on the voltage-current characteristic of an arrester, where the influences of the stray capacitance can be ignored. All the tests per-

Diameter MO resistor in mm	38	42	47	62	75	108
MO arrester	POLIM-D	POLIM-K	MWK/MWD POLIM-I POLIM-C	POLIM-S	POLIM-H	POLIM-X*
i_{ref} in mA sw	1.4	1.6	2.2	3.6	5.0	10.0

Table 4: Reference current i_{ref} for different ABB MO arresters.

* The POLIM-X is used as type POLIM-X…ND only in d.c. traction systems for the time being.

formed according to IEC are always based on the reference current and the reference voltage for a.c. voltage. Reference current and reference voltage with d.c. voltage are additional information, which can be received from the manufacturer.

Residual voltage U_{res}: Peak value of voltage that appears between the arrester terminals during the passage of a discharge current.
The residual voltage of a MO resistor or MO arrester is determined with surges having different wave forms and current heights and it is given in tables or as a voltage-current characteristic on a curve. The measurements are generally performed on MO resistors. As the measurement is mostly performed in regions of the characteristic where the ohmic part of the current is dominant, the capacitive stray influences can be ignored. The residual voltages measured on single MO resistors can be summed up as the residual voltages of the whole arrester.

Lightning impulse protective level U_{pl}: Maximum permissible peak voltage on the terminals of an arrester subjected to the nominal discharge current. Corresponds to the guaranteed residual voltage U_{res} at I_n.

Switching impulse protective level U_{ps}: Maximum permissible peak value on the terminals of an arrester subjected to switching impulses. The higher switching impulse among those in the Table 1 is to be used.

Lightning current impulse: Current impulse with the wave shape 8/20 µs. The virtual front time is 8 µs and the time to half-value on the tail is 20 µs. The lightning current impulse reproduces approximately the current impulse produced by a lightning stroke in a conductor after an insulator flashover. This current impulse travels as a transient wave along the line.

Nominal discharge current of an arrester I_n: The peak value of the lightning current impulse that is used to classify an arrester. The nominal discharge current combined with the line discharge class of an arrester prescribe the test para-

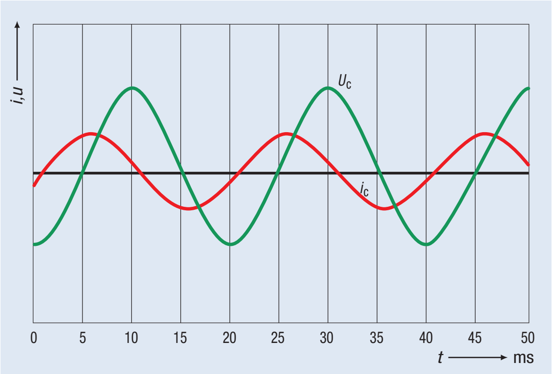


Figure 9: Continuous operating voltage U_c and leakage current i_c of an MO arrester. The current has a sinusoidal waveform form and is almost purely capacitive. The ohmic part of the current at du/dt = 0 at the peak value of the voltage is about 15 % to 20 % of the total current.

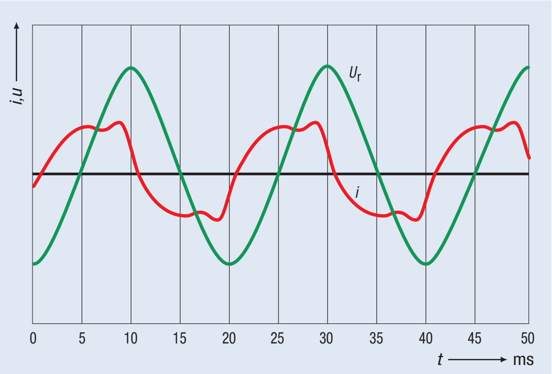


Figure 10: Rated voltage U_r and current i, which flows through the MO arrester with this voltage. The current already begins to distort, an ohmic component in the area of the peak value can clearly be seen. In this example, the rated voltage lies in the area of the knee point of the voltage-current characteristic of the MO arrester.

meters, see Table 1. Recommendations for the choice of the nominal discharge currents and the line discharge classes for different system voltages are to be found in IEC [4], [5].

High current impulse (I_{hc}): Peak value of discharge current having a 4/10 µs impulse shape. The high current impulse should reproduce a lightning stroke close to an arrester and it is used with medium voltage arresters of the line discharge class 1 as a proof of thermal stability. It represents not only an energetic stress but also a dielectric one, taking into consideration the high residual voltage that occurs with a high current impulse with a peak value of 100 kA. However, it is necessary to strongly emphasize that a high current impulse with an amplitude of 100 kA is not the same as a real lightning current of the same amplitude. The real lightning current of this amplitude measured during a thunderstorm possibly lasts longer than several 100 µs. Such strong lightning currents and impulse shapes are very rare and appear only under special conditions, such as during winter lightning in hilly coastal areas.

Switching current impulse (I_{sw}): Peak value of discharge current with a virtual front time between 30 µs and 100 µs, and a virtual time to half-value on the tail of roughly twice the virtual front time. The switching current impulses are used to determine the voltage-current characteristic, and in connection with the line discharge class are also used to determine the energy which has to be absorbed by the surge arrester during the operating duty test. The current amplitudes lie between 125 A and 2 kA, and roughly reproduce the load of an arrester produced by overvoltages, which were caused by circuit breaker operation.

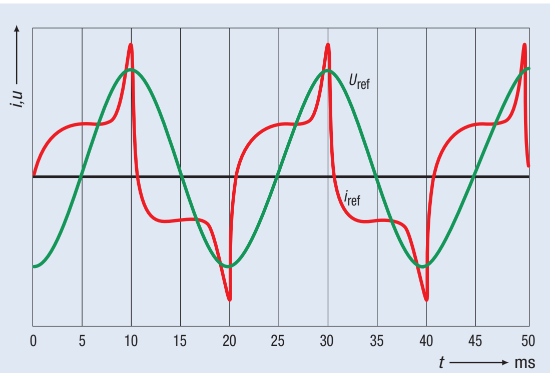


Figure 11: Reference current i_{ref} and reference voltage U_{ref}. The ohmic component of the current in the area of the peak value of the voltage clearly dominates the total current. This means that the current lies above the knee point and the capacitive stray influences during the measurement can be disregarded.

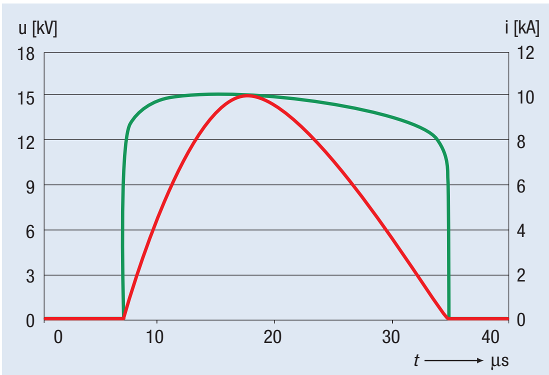


Figure 12: Current and voltage of a nominal discharge current of I_n = 10 kA (wave shape 8/20 µs) injected in a MO resistor. The residual voltage is U_{res} = 15 kV.

Steep current impulse: Current impulse with a virtual front time of 1 µs and a virtual time to half-value on the tail not longer than 20 µs. The steep current impulses are used to determine the voltage-current characteristic. They have amplitudes up to 20 kA and roughly reproduce steep current impulses like those which may appear with disconnector operation, re-striking, back flashes, and vacuum circuit breakers.
All the current impulses described above (except the high current impulse) are used to determine the voltage-current characteristic of a MO arrester. It is to be considered that only the virtual front time and the amplitude of the current impulses are decisive for the residual voltage and not the virtual time to half-value on the tail. That is the reason why the tolerance for the virtual front times is very tight, and contrastingly, the tolerances for the virtual times to half-value on the tail are very broad.

Long-duration current impulse (I_{ld}): Also called rectangular wave (I_{rw}) or square wave. A long-duration current impulse is a rectangular impulse that rises rapidly to its peak value and remains constant for a specified period of time before it falls rapidly to zero. The length of the current pulse duration is correlated to the line discharge class of an arrester. Rectangular impulses are used in laboratories during the type tests with long-duration current impulses, and during the operating duty test of MO arresters having line discharge classes 2 to 5, in order to inject the energy in the arrester. The current amplitudes are up to 2 kA and reproduce the load of an arrester when a charged transmission line discharges into the arrester in case of an overvoltage occurrence.
It is now regarded as a matter of course to use a rectangular wave of 2 ms duration to compare different MO arresters, although there is no norm established for doing so. Specified is either the amplitude of the rectangular wave for a specific MO arrester or the energy transferred into the arrester during the flow of the rectangular current.

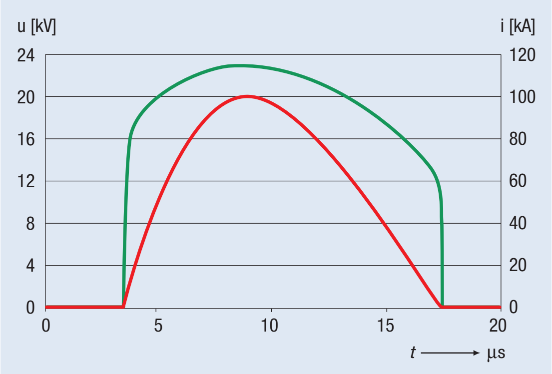


Figure 13: High current impulse of the wave shape 4/10 µs and a peak value of I_{hc} = 100 kA. The residual voltage is in this case U_{res} = 23 kV. An exact measurement is difficult here because of the extreme steepness of the current and the relative high field strength. That is why the measuring of the residual voltage of high current impulses is not generally demanded according to IEC.

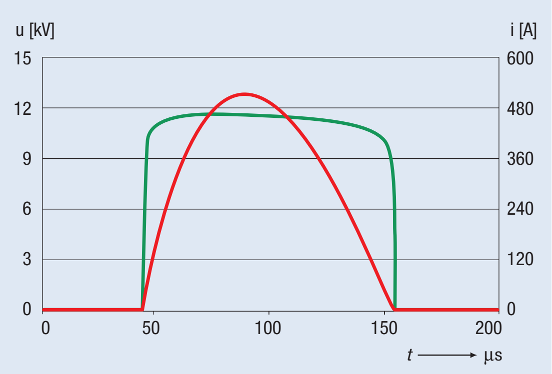


Figure 14: Switching impulse current I_{sw} = 500 A with the wave shape 38/87 µs. The residual voltage is U_{res} = 11.6 kV.

Line discharge class: The line discharge class is the only possible way to specify the energy absorption capability of an arrester provided in IEC 60099-4. The line discharge classes 1 to 5 are defined with growing demands. They differ from one another due to the test parameters of the line discharge tests. The energy W is calculated from the line discharge class in connection with the residual voltage of the switching current impulse. This calculated energy has to be injected with each discharge in a MO resistor during the test with a long-duration current impulse I_{ld} (line discharge test). Two corresponding line discharges are loaded in the arrester during the operating duty test as a proof of thermal stability.

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

U_{res} = Residual voltage of the switching current impulse. Here, U_{res} is the lowest value of the residual voltage measured at the test sample with the lower value of the switching current impulse given in Table 1.

U_L = Charging voltage of the current impulse generator used in test labs for producing the long-duration current impulse I_{ld}

Z = Surge impedance of the current impulse generator

T = Duration of the long-duration current impulse

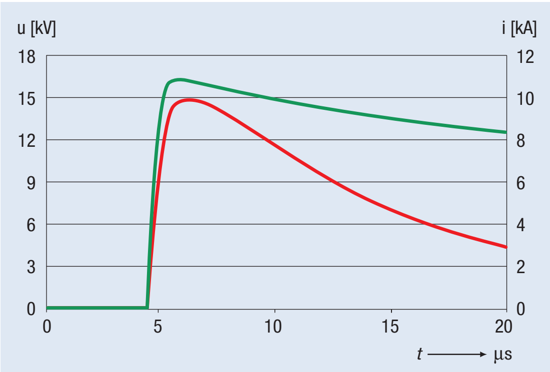


Figure 15: Steep current impulse of the wave shape 1/9 µs. The peak current amounts to 10 kA and the residual voltage is U_{res} = 16.2 kV. This current wave has a very steep rise time, which makes it necessary to compensate the measuring circuit induced voltage $U_i = L \times$ di/dt when evaluating the residual voltage.

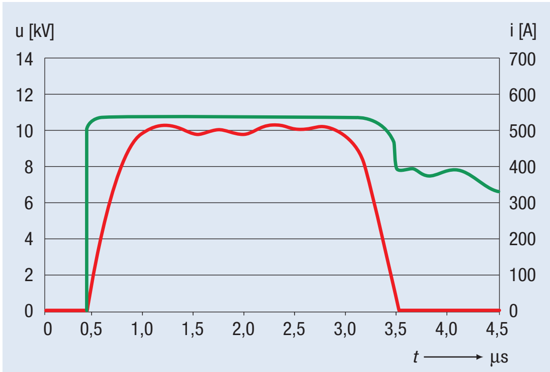


Figure 16: Long-duration current impulse I_{ld} = 506 A with a virtual duration of the current of $t_{90\,\%}$ = 2.15 ms. The residual voltage is U_{res} = 11.1 kV.

The parameter of the line discharge classes are derived from the stored energy of long transmission lines [5], [6], see Table 5.
That is the reason why the line discharge classes have no direct importance in medium voltage systems. They serve here only to distinguish the energy handling capability of different arresters.

I_n kA	LD	U_s kV	L km	Z_L Ω	T ms
10	1	≤ 245	300	450	2.0
10	2	≤ 300	300	400	2.0
10	3	≤ 420	360	350	2.4
20	4	≤ 525	420	325	2.8
20	5	≤ 765	480	300	3.2

Table 5: Correlation between the line discharge class and the parameters of the transmission lines. The duration T of the long-duration current impulse I_{ld} is also given. This specification shows how the duration must be adjusted for the operating duty test and the test with long-duration current impulse according to the line discharge class in the laboratory.
LD = Line discharge class
L = The approximate length of the transmission line
Z_L = The approximate surge impedance of the transmission line

Rated short circuit current I_s: The rms value of the highest symmetrical short circuit current, which can flow after an overload of the arrester through the arc short circuiting the MO resistors without violent shattering of the housing. The proof of the value specified by the manufacturer is conducted in the short circuit test.
The pressure relief class of an arrester, which in the past was specified, as well as the pressure relief test connected to it as found in IEC 60099-1, is no longer applicable.

3.2 Energy absorption capability

The specified or required energy values that are found in technical documentations sometimes lead to misunderstandings, especially when more energy values are given. That is why it is necessary to discuss here the energy absorption capability of the MO resistors and arresters.
The energy absorption capability of MO resistors respectively the MO surge arresters is especially important for the thermal stability of the arresters in the system. The energy absorption capability is tested with different current impulses during the type tests, such as the test with the long-duration current impulse for each MO resistor, the operating duty test and the verification of the TOV-curve with complete arresters.
The energy absorption capability of the MO resistor is tested with a total of 18 long-duration current impulses during the line discharge test. This is a material test of the MO resistor. No power frequency voltage is applied to the test sample during this test. This means that there is no testing of the thermal stability of the MO resistors.
The shape of the current impulse with which the energy is injected into the arrester depends on the line discharge class during the operating duty test. The energy is injected with a high current impulse that has a wave shape 4/10 µs to arresters of the line discharge class 1 (or arresters having no line discharge class).

The energy is injected with two long-duration current impulses to the arresters of the line discharge class 2 or higher. The injected energy with the line discharge class 2 or higher follows the line discharge class and has to be calculated corresponding to IEC 60099-4. The higher the line discharge classes the higher the energy.

Provided in Table 1 is the energy for the same high current impulse (100 kA 4/10 µs) for different arresters. This energy decreases when the diameter of the MO resistors increase. If the peak value is the same, the current density and accordingly also the residual voltage become lower. As a result, this leads to a lower energy and accordingly also to a lower increase in temperature of the active part of the arrester. This tendency is favorable because the lower the occurred energy is in the arrester, the safer and the more thermal stable the arrester is in the system.

The energies that are listed in our technical documentations represent no limiting or destructive values, but the energies that occur during the different type tests respectively the occurred energies with different current impulses.

Therefore, a differentiation is to be made between:

- The occurring energy of a specified current such as 100 kA 4/10 µs or a long-duration current impulse of 2 ms. (These data serve only as information.)
- The applied energy, which is used as a proof of the thermal stability of the arrester in a test or in the system
- The energy that destroys a MO resistor or an arrester through cracking, puncture or spark-over.

The energy, which leads to the destruction of a MO resistor or an arrester, is higher than the energy that is applied to an arrester as proof of the thermal stability during an operating duty test. Depending on the type of arrester, the destroying energy is generally much higher than the guaranteed energy for testing the thermal stability.

3.3 Cool-down time

The arresters in the system can work reliably and safe if their energy absorption capability is greater than the energy strain expected in the system operation. In case of multiple surges, one after another, the injected energy is cumulated in the arrester and therefore an intermediary cool-down time can be ignored. But if the energy reaches the guaranteed value, which is applied in the operating duty test, the arrester has to have enough time to cool-down. The necessary cool-down time for the arrester depends on the construction, the ambient temperature and the applied voltage. The cool-down time typically lies between 45 and 60 minutes depending on the arrester type and the ambient conditions.

3.4 Stability of a MO arrester

There are two situations to take into account:

- The thermal stability of the MO arrester after adiabatic energy absorption (sometimes known as short-time stability)
- The long-time stability of the MO arrester in system operation.

3.4.1 Thermal stability

In Figure 17, *P* represents the power losses of the MO resistors in an arrester when U_c is applied. It is evident that *P* exponentially increases with the MO-temperature *T*, which also results in an increased heating of the active component. The cooling-down of the MO resistors occur with the heat flow *Q* from the active part of the arrester to the exterior. *P* is greater than *Q* at temperatures above the critical point. Here the cooling is not sufficient to dissipate the heat produced by the power losses to the exterior. The MO resistors would continue to heat up and the arrester would be destroyed by overheating. This occurrence is called thermal run away or thermal instability.

If the power losses *P* stay under the critical point, i.e. $P < Q$, it is possible to eliminate the warmth faster than it is produced and the active part cools down until it returns to the stable working condition after the cool-down time. This is the area of thermal stability.
As long as the critical point is not exceeded, the arrester can branch off the loaded energy as often as is necessary, which means that it can limit the overvoltage just as often as it is required.
It is possible to raise the critical point to such a level, that even if during the operation the highest energies are likely to occur, this critical point cannot possibly be reached. This can be achieved through suitably dimensioning of the resistors and through design measures that enable the cooling-down of the blocks.

3.4.2 Long-term stability

A MO arrester without spark-gaps in the system can operate absolutely reliably if the voltage-current characteristics curve of the MO resistors under applied continuous voltage do not change. The continuous current i_c should not

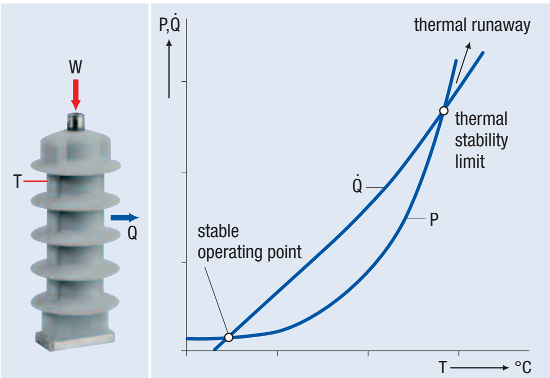


Figure 17: Power losses *P* of the MO resistors and the heat flow *Q* from the active part of an arrester to the exterior, as a function of temperature *T* of the MO resistors at continuous operating voltage U_c.

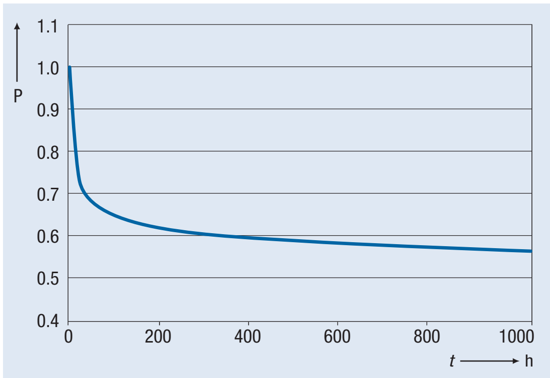


Figure 18: Example of an accelerating ageing test (type test over 1,000 h). The test sample is in an oven with the constant temperature of 115 °C and is stressed with increased a.c. voltage compared to U_c. The power losses *P* are recorded and should decrease constantly or remain constant. A considerable increase over a minimum that was already reached indicates instability and is inacceptable. Test duration of 1,000 h at 115 °C corresponds to an operating time of 110 years in the system at an environmental temperature of 40 °C.

be allowed to shift to higher values to also prevent the increasing of power losses.

A change of the electrical characteristic curve due to applied continuous voltage is not to be expected with MO resistors that are produced by leading international manufacturers considering the present state of technology.

Under certain circumstances, a change (or more precisely: deterioration) of the voltage-current characteristic curve can occur due to extreme stresses, such as very high or very steep current impulses. Another cause that can lead to a change of the electrical characteristics close to the rim may be different components of the materials in which the MO resistors are embedded. This is the reason why the surface area of the MO resistors is passivated, which means that they are coated with a gas-proof glass that is also highly robust.

All these reasons make it indispensable to permanently control the long-term behavior of the MO resistors during the manufacture. This is achieved with the accelerating ageing test according to IEC. In addition the single type tests of over 1,000 hours; there are also accelerated ageing tests according to internal manufacturer instructions to be conducted on each production batch.

It should be emphasized that the accelerating ageing test must be performed with the same kind of voltage that is applied to the MO arrester in the system. Thus, the MO resistors for a.c. systems have to be tested with a.c. voltage and the MO resistors for d.c. systems have to be tested with d.c. voltage. Experience shows, however, that d.c. stable MO resistors are usually also stable under a.c. load, yet on the other hand, a.c. stable MO resistors are not necessarily stable under d.c. load. That is why it is particularly important to use d.c. stable MO resistors with MO arresters in d.c. systems.

3.5 Protection characteristic

The protection characteristic of an arrester is given by the maximum voltage U_{res} at the terminals of an arrester during the flow of a current surge. Generally, a lightning impulse protective level of $U_{pl} \leq 4$ p.u. is considered. This is a value that is generally accepted for the insulation coordination [7]. The real residual voltage with nominal discharge current I_n (thus U_{pl}) can lie above or below that, depending on the type of arrester.

If U_{pl} is set in a relationship with U_c of an arrester, it is possible to get very good information about the quality of the arrester performance with regard to the protective level. The smaller the ratio U_{pl}/U_c, the better the protection.

In addition to the residual voltage at I_n, the residual voltages at steep current impulse and at switching current impulse are also important. The residual voltage increases slightly with the current, but also with the steepness of the current impulse as can be seen from the data sheets of each arrester and also from the voltage-current characteristic in Figure 8. Depending on the usage, the residual voltage at the steep current impulse and at switching current impulse must be taken into account besides the residual voltage at I_n.

3.6 Temporary overvoltages

Temporary (short-time) overvoltages U_{TOV} are power frequency overvoltages of limited duration. They appear during switching operations or earth faults in the system and they can stay in medium voltage systems with insulated transformer neutrals for several hours. Their height depends on the system configuration and the treatment of the star point. The duration is given by the time which elapses until the registration and the switching off of the system failure.

MO arresters are able to withstand an increased operating voltage for a certain period of time. The resistance T of the arrester against such temporary overvoltages is to be seen as an example in Figure 19. T = U_{TOV}/U_c is the extent of the permissible height of U_{TOV}.

The following example should explain the use of TOV curves in Figure 19. An arrester with U_c = 24 kV is operated with U_c in a normally functioning, undisturbed system for a unlimited period of time. At the time t = 0 the arrester is stressed with an energy in relation to U_c of W' = 5.5 kJ/kV$_{Uc}$. Immediately afterwards, the temporary overvoltage U_{TOV} = 28 kV appears. Therefore, it is T = U_{TOV}/U_c = 28 kV / 24 kV = 1.17. For T = 1.17 results a time of t = 400 s according to curve b. That means that the arrester can withstand an increased voltage for 400 s without becoming thermally instable. After 400 s the voltage must go back to U_c, so that the arrester will not become overloaded. If the arrester is not loaded with the energy W' before the appearance of the temporary overvoltage, it is the curve a that counts and the arrester can withstand U_{TOV} for 3,000 s. Therefore, the height and the duration of the admissible temporary overvoltage directly depend on the previous energy load of the arrester.

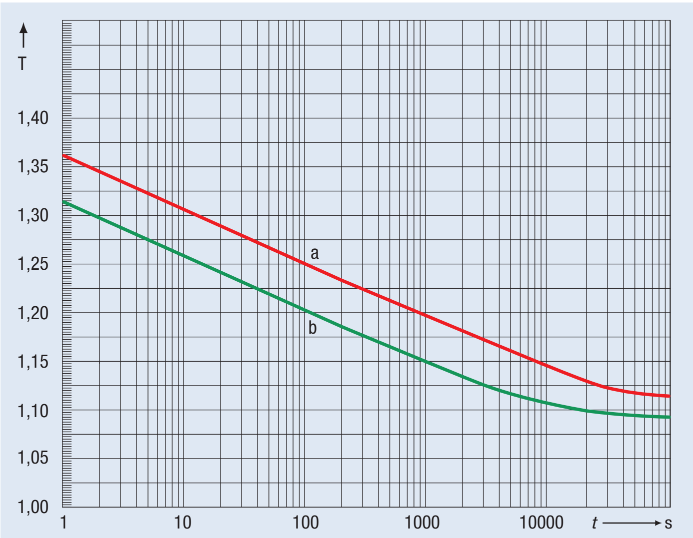


Figure 19: Resistance T = U_{TOV}/U_c against temporary overvoltages depending on the time t. The curve a is valid for an arrester without energy pre-stress, the curve b with a pre-stress of the guaranteed energy W'. t is the duration of the overvoltage at power frequency. The curves are valid for a MO arrester of the type MWK.

4 | SERVICE CONDITIONS

The service life of an arrester can be 30 years or longer under normal operating conditions and if it is correctly chosen according to the system voltages and to the expected electrical and mechanical loads. The normal service conditions for an arrester are listed in [4]:

- Ambient temperature –40 °C to +40 °C
- Solar radiation 1.1 kW/m^2
- Altitude up to 1,000 m above sea level
- Frequency of a.c. voltage between 48 Hz and 62 Hz
- Power frequency voltage at the arrester terminals not higher than the continuous operating voltage U_c of the arrester.
- Wind speed ≤ 34 m/s
- Vertical position

All ABB arresters meet or exceed these operating conditions. The mechanical requirements and the artificial pollution requirements of MO arresters with polymer housing are still in discussion in the international standardization bodies.

4.1 Abnormal service conditions

Some typical abnormal service conditions are:

- Ambient temperature above +40 °C or below –40 °C
- Service at altitudes above 1,000 m
- Gas or steam that can lead to damage to the insulation surfaces or damage to the connections
- Heavy air pollution (smoke, dust, salt fog, other dirt deposits)
- High humidity (condensation water, steam)
- Life line washing
- Areas with risks of explosion
- Unusual mechanical conditions
- Frequencies of the system voltage under 48 Hz or above 62 Hz
- Voltage distortions or voltages with superimposed contents of high frequencies that are caused by the system

The following paragraphs illustrate a few special cases. It is advisable to contact the manufacturer should other abnormal conditions appear that are not mentioned here.

4.2 Overload behavior

Any arrester can be overloaded. The causes can be extremely high lightning currents, lighting currents with a very large charge or a so-called voltage-transition. This is to be understood as a short circuit between two different voltage levels. In all these situation there is in fact an energy overloading. In the case of an overloading, the MO resistors either spark-over or break down and tend to create a permanent short circuit. An arc results inside the arrester and the current in this arc is defined by the short circuit power of the system. With the ABB arresters with silicone housing there is no danger of explosion or shattering in case of an overload. There is no air space between the active part of the arrester and its silicone insulation, thus there is no space for the pressure to build up. The occurring arc (or sparks) escapes the silicon insulation as soon as it occurs and thus is freed. Because of their special construction, the arresters are protected from explosion up to the highest short circuit currents.

4.3 Mechanical stability

ABB arresters are operationally reliable even in areas of high earthquake activity. The arresters may partially take on the support function, or as line arresters, they may have the function of suspension insulators. The manufacturer should be informed about such operational situations. The values listed in the Table 3 are not to be exceeded. The arrester types, which are to be applied on rolling stock, are delivered with a reinforced base plate and are tested under vibration and shock conditions.

4.4 Elevated ambient temperature

ABB arresters (a.c. and d.c. voltage) are guaranteed to function flawlessly up to 40 °C ambient temperature. This also includes maximum solar radiation of 1.1 kW/m² for outdoor arresters. If there are heat sources in the vicinity of the arrester, the increased ambient temperature has to be taken into account, and the value of U_c increased if necessary. If the ambient temperature exceeds 40 °C, U_c should be increased by 2 %, for every 5 °C of temperature elevation. This correction is possible up to maximum of 80 °C ambient temperature.

4.5 Pollution and cleaning

Silicone is the best insulating material in case of pollution. This is mainly because the material is water-repellent (hydrophobic). Silicone arresters behave more favorably under conditions of heavy pollution than porcelain housed arresters or other polymeric insulation materials.
Decisive for the long-term behavior under pollution of an insulation made of a polymeric material is the dynamic behavior of the hydrophobicity, which is originally always very good. Depending on the material, a loss of hydrophobicity can be permanent or temporary. Silicone in contrast to other polymeric materials is able to regain its hydrophobicity after losing it temporarily.
Neither the function nor the properties of the insulation of MO arresters with silicon housing are affected by using environmentally safe cleaning agents. The easiest way to clean silicon surfaces is the use of a soft cloth and clear water.

4.6 Altitude adjustment of arrester housing

ABB arresters can be used without any housing adjustment up to a height of 1,800 m above sea level. At higher altitudes, the air density may be so low that the withstand voltage of the arrester housing (external flashover) is no longer sufficient. In this case, the unaltered active part of the arrester (same protection level) has to be placed in an elongated housing with a longer flashover distance. As a reference value, one may consider that for every 1,000 m above 1,800 m above sea level the flashover distance has to be increased by 12 %. For example, at an altitude of 3,300 m above sea level the flashover distance of the housing has to be 18 % longer than that of a standard arrester.
It is necessary to observe here that the flashover distances of surge arresters for lower voltage levels are initially relatively large, exceeding the minimum requirements of the withstand voltage. Thus, in each individual case it should be checked whether the standard housing possesses the sufficient withstanding voltage for the application in higher altitudes.

5 | TESTS

Arresters manufactured by ABB Switzerland Ltd are tested according to the current international IEC standards. The IEC 60099-4, edition 2.1, 2006-07 [4] is applicable for the MO arresters with polymer housing.

5.1 Type tests

The development of an arrester design ends with type tests. They are the proof that the arrester construction observes the applicable standards. These tests need be repeated only if changes in the construction also cause changes to proved properties or characteristics. In such cases, only the affected tests need be repeated. The type tests that are to be performed on the MO arresters with polymer housing are briefly explained in the following paragraphs.

Insulation withstand tests on the arrester housing

The insulation withstand tests demonstrate the voltage withstand capability of the external insulation of the arrester housing. The withstand values to be proved are calculated from the residual voltages of the arrester. The withstand values of the arresters having a rated voltage lower than 200 kV (this means all arresters used in medium voltage systems) are tested with the lightning impulse voltage (wave shape 1.2/50 µs) under dry conditions, and with a one minute a.c. voltage test. The a.c. voltage test is performed in a rainy environment for the arresters that are intended for outdoor use. The arresters intended for indoor use are tested in a dry environment with the a.c. voltage test.
See also chapter 7.3 Selection of surge arrester housing.

Residual voltage tests

These tests determine the voltage-current characteristic in the high current range. The residual voltage for steep current impulse, lightning current impulse and switching current impulse of different amplitudes is determined and given either in tables or in a curve form. The residual voltage tests are generally performed on MO resistors.

Long-duration current impulse withstand test

This test should prove that the MO resistors withstand the specified energy stress without puncture or flashover. Therefore this is a material test. Each test with long-duration current impulse has 18 impulses, which are divided into 6 groups of 3 impulses. The period of time among the impulses of a group is 50 s to 60 s; among different groups the cooling down of the MO resistors to room temperature is permitted. The test is generally performed at room temperature and on single MO resistors.
The applied currents arise from the requests to the line discharge class test. The higher the line discharge class, the higher is the requested applied energy.

Accelerated ageing procedure

This test determines the voltages U_c^* and U_r^* to be applied during the operating duty tests. In this way, it is possible to perform the operating duty tests with new MO resistors.
The test is performed on MO resistors in the same environmental conditions as are the service conditions of the arresters. Therefore, the MO resistors of the directly molded arresters have also to be molded with the same material during the accelerated ageing test.

The MO resistors have to withstand a voltage higher than U_c in an oven at a temperature of 115 °C for a period of 1,000 h. To be recorded for this period is whether the power losses increase, and if so, by how much. The behavior of the power losses during the accelerating ageing test can indicate the behavior of the power losses of the MO resistors in the systems throughout the entire service life.
MO resistors manufactured by ABB Switzerland Ltd provide stable long-term behavior. That means that they do not show any change of the power losses, which would make it necessary to correct the applied test voltages of U_c^* and U_r^*.

Operating duty tests
The arresters have to withstand the combined stresses during the service, as proved in the operating duty test. These stresses should not lead to any damage or thermal failures.
The high current impulse operating duty test is used for the 10 kA arresters of the line discharge class 1 (and for arresters without line discharge class). The thermal stress is thus applied through a specified current impulse.
The switching surge operation duty test with long-duration current impulse is used for the 10 kA arresters of the line discharge classes 2 and 3 and for the 20 kA arresters of the line discharge classes 4 and 5. The applied energy is calculated according to the line discharge class for each arrester in turn.
The arrester passed the test when thermal stability was achieved; the residual voltage measured before and after the test did not change by more than 5% and the examination of the test samples did not reveal any evidence of puncture, flashover, cracking or other significant damage of the non-linear metal oxide resistors.
The operating duty test is performed on electrical-thermal equivalent models of an arrester. The operating duty test can also be performed on complete arresters with the medium voltage arresters if the labs have the necessary equipment.

Verification of the power-frequency voltage-versus-time characteristic (TOV curve)
The last part of the relevant operating duty test is to be repeated in order to experimentally determine the TOV curve. An a.c. voltage U, having a variable height and duration is applied after the energy input and before the voltage U_c^* instead of the rated voltage U_r^* . It is considered to be sufficient to verify three points on the TOV curve experientially.

Short-circuit tests
Surge arresters are not allowed to explode in case of overloading. This is to be proved with a short circuit test. The way the short circuit is initiated in the arrester depends on its construction. Directly molded medium voltage arresters are electrical pre-damaged, that is they are made low ohmic through applying an increased voltage and afterwards they are connected to the actual test so that the short circuit develops itself inside the arrester. This is a form of an overload, which looks very much alike the one taking place in the arrester under real conditions in service.
The admissible short circuit currents for arresters are specified by the manufacturer.

Internal partial discharge test

The test shall be performed on the arrester's longest electrical unit. Apart from possible internal partial discharges, it is mainly intended to determine whether there is any contact noise in the directly molded arresters.

Test of the bending moment

This test demonstrates the ability of the arrester to withstand the manufacture's declared values for bending loads. As a rule, an arrester is not designed for torsional loading. If an arrester is subjected to torsional loads, a specific test may be necessary by agreement between the manufacturer and the user.

The manufacturer provides information about the admissible mechanical loads for the arrester.

Moisture ingress test

This test demonstrates the ability of the arrester to resist ingress of moisture after being subjected to specified mechanical stresses.

It is a tightness test for the complete arrester. It consists of a thermo-mechanical preconditioning applied to the arrester; the arrester is stressed mechanically in different directions with different temperatures. Afterwards, the complete arrester is immersed in boiling water for 42 hours. After this time, a verification test is performed and the measured values are compared with the initial measurements.

Weather ageing test

This test demonstrates the ability of the arrester to withstand specific climatic conditions. There are two described test series.

- The test series A require a test of 1,000 h under salt fog conditions. This test must be performed on the highest electrical unit with the minimum specific creepage distance.

As a rule, the largest arrester is tested with the medium voltage arresters.

In case of severe environmental conditions, (intense solar radiation, heavy pollution, temperature and humidity fluctuation, etc.) and upon agreement between the manufacturer and the user, a test of 5,000 h according to test series B may be performed.

- Test series B consists of various stresses in a cyclic manner:
  - Solar radiation (UV stress)
  - Artificial rain
  - Dry heat
  - Damp heat (near saturation)
  - High humidity at room temperature
  - Salt fog

A cycle lasts 24 hours; the total duration of the test is 5,000 h.

The tests are regarded as passed if no tracking occurs, if erosions do not occur through the entire thickness of the external coating up to the next layer of material, if the sheds and core are not punctured and if the electrical characteristics did not fundamentally change.

The arresters with silicone housing have no problem passing the 5,000 h cyclic test, because of the dynamical hydrophobicity of the silicone material.

5.2 Routine tests

Routine tests are performed on each arrester or parts of an arrester (for example, on MO resistors). According to the IEC, there are at least the following tests to be performed:

Measurement of reference voltage

The reference voltage is measured with the reference current specified by the manufacturer. The measured values should be within the range specified by the manufacturer. At ABB this measurement is performed on each MO resistor and on each MO arrester.

Residual voltage tests

The residual voltage is measured on each MO resistor at a current value of 10 kA with a current rise time of 8 µs, which is normally a lightning current impulse (or the nominal current). The residual voltages of the MO resistors inside an arrester can be directly added up and they represent the total residual voltage of the arrester.

Internal partial discharge test

This test is performed on each arrester unit. In case of medium voltage arresters, the test is normally performed on each complete arrester. This test is performed at 1.05 × U_c. The measured value of the internal partial discharges is not allowed to exceed 10 pC according to the IEC. ABB Switzerland Ltd's internal guidelines require a value less than 5 pC, which means virtually no partial discharges. During this test the arrester can be screened off from the external partial discharges.

Tightness test (leakage check)

This test demonstrates that the construction of the arrester is tight. The manufacturer has to choose a procedure which is sensitive enough. This test is not applicable for arresters that are completely molded in silicone.

Current distribution test

The current distribution test is to be performed on MO arresters with parallel MO resistors or parallel columns of MO resistors. Arresters with one column only are naturally not to be subjected to such a test.

Apart from the routine tests considered as a minimum request by the IEC, ABB Switzerland Ltd performs additional routine tests on MO resistors and arresters to assure a high quality. This includes:

- Measurement of the total leakage current on each arrester at U_c
- Regular measurement of the power losses on the MO resistors and arresters
- Examination of the energy handling capability of MO resistors with current impulses
- A reduced accelerating ageing test on some MO resistors from each production lot.

5.3 Acceptance tests
Standard acceptance tests include:
- Measurement of the reference voltage on the arrester
- Measurement of the residual voltage on the arrester or arrester unit
- Test of the internal partial discharges

The acceptance tests are to be agreed upon when the products are ordered. The tests are performed on the nearest lower whole number to the cube root of the number of arresters to be supplied.
The proof of the thermal stability of an arrester as part of the acceptance test requires additional agreement between manufacturer and purchaser and it is to be explicitly specified in the order. This is necessary, because the proof of thermal stability means that a part of the operating duty test has to be performed. This test is expensive and can be performed only in laboratories that have the necessary equipment and they have to be booked in advance.

5.4 Special tests
As part of the development of the arresters, additional tests were performed in cooperation with users and research institutes. These tests were performed to examine the behavior of MO arresters with silicone housings under special conditions [2].

Temperature cycles
The construction and also the materials used for the MO arresters manufactured by ABB Switzerland Ltd tolerate temperatures up to –60 °C and extreme changes in temperature between –40 °C and +40 °C without any changes to the mechanical and the electrical qualities. The construction of the arrester and especially the surface of the silicon were not harmed in any way by ice during cyclic freezing.

Humidity tests
The electrical behavior of the directly with silicon molded arresters are not influenced by humidity during long duration tests, which lasted more than 2 years and during which the arresters were subjected to a relative air-humidity of more than 90 % and also to regular rain.

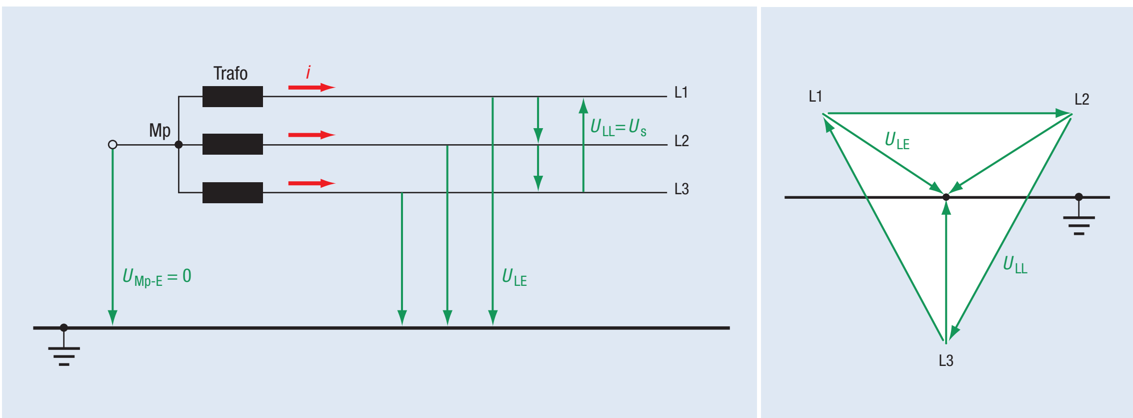
Behavior in fire
Silicon is a self-extinguishing material. If silicon catches fire as a result of a flame or an electric arc and the cause of the fire is removed or switched off, then the burning silicon extinguishes itself in about one minute. To be found on the burnt patch is only non-toxic burnt silicon, which is in fact nothing else but fine quartz sand. Smoke analyses show no toxic gases occur as a result of fire.

6 | NEUTRAL EARTHING METHODS IN MEDIUM VOLTAGE SYSTEMS

The manner in which the star point is treated has a fundamental influence on the height of the current, which occurs in cases of failure with the earth connection, on temporary overvoltages with power frequency and transient overvoltages. Single-phase-to-earth faults (earth fault, earth short circuit) are the most frequent failures in medium and high voltage systems.
Low currents at the failure point tend to be connected with high and long existing temporary overvoltages of the sound phases. This is the case with systems having an insulated star point or earth fault compensation. The single-phase earth fault is registered and quickly switched off by the system protection in systems with low ohmic star point earthing. See also **[12]**.

A system is considered *effectively* earthed if the earth fault factor k does not have a value higher than 1.4 anywhere in the system. This is the case in systems that are described as solid or directly earthed. If the earth fault factor is higher than 1.4 at any point in the system, then this is considered as being *ineffectively* earthed. In such systems, the star point is insulated (also described as open) or compensated. In the following chapters, different star point treatments are briefly explained and the important characteristic values for the choice of the MO arresters are specified.

Figure 20: Basic circuit of a medium voltage transformer with a star connection with open star point (Mp). Specified are the voltages and currents in case of symmetrical load, i.e. in an undisturbed service case. All voltages U_{LE} are equally high. The voltage of the star point U_{Mp-E} relative to the earth is zero. The voltage triangle is provided on the right side for better understanding.



6.1 Systems with insulated star point

As a rule, these are systems of small extension, auxiliary power systems for power stations or station services. A capacitive earth failure current I_{Ce} of about 5 A to 30 A flows in case of failure.
The earth fault factor is:

$$\mathbf{k \approx \sqrt{3}}$$

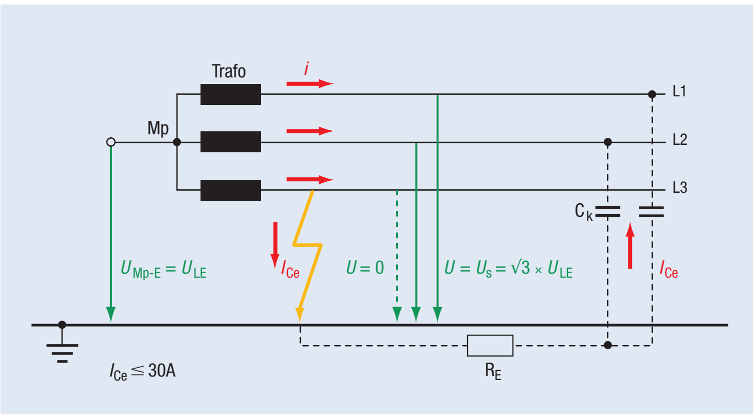
In case of intermittent earth faults, the earth fault factor can reach values up to k = 1.9. The duration of the failure may last up to several hours.

6.2 Systems with earth fault compensation

These are mostly overhead line systems with system voltages between 10 kV and 110 kV. One or more transformer star points in these systems are earthed with high ohmic Peterson coils. An earth fault residual current I_{Rest} of approximately 5 A to 60 A flows in case of a fault.
The earth fault factor is:

$$\mathbf{k \approx (1.0 \dots 1.1) \times \sqrt{3}}$$

The earth fault factor can reach a value of 1.9 in unfavorable situations, such as in the case of intermittent earth faults. As in the systems with an insulated star point, the duration of the failure may last up to several hours.



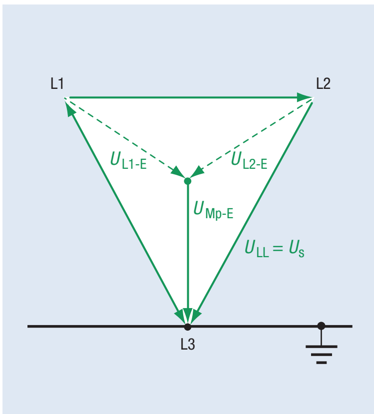


Figure 21: A single pole earth fault occurs in the described system in Figure 20, i.e. the line L3 touches the earth. The voltage $U_{L3\text{-}E}$ moves towards zero, the voltages $U_{L1\text{-}E}$ and $U_{L2\text{-}E}$ move to the value of the system voltage U_s, as it is to be seen in the voltage triangle (right). The voltage of the star point of transformer is $U_{Mp\text{-}E} = U_s/\sqrt{3}$. The earth fault current I_{Ce} is defined through the capacities C_k of the lines L1 and L2 towards the surrounding earth.

6.3 Systems with low ohmic star point earthing

A system with low ohmic star point earthing is provided if the star point of one or more transformers are directly earthed or through current limiting impedances. The system protection is set up so that even a single line-to-earth fault at any place in the system causes an automatic fault clearing.
These are typical cable systems in towns with system voltages between 10 kV and 110 kV. In case of a failure, the earth short circuit current I_k flows, which leads to an immediate automatic clearing of the fault. As a rule, the duration of the failure is limited to $T_k < 0.5$ s. In unfavorable situations, the duration of the failure can last up to 3 s in medium voltage systems.
The earth fault factor is:

k = (0.8 … 1.0) × √3

In case of low ohmic earthing, one has to distinguish between inductive earthing (neutral reactor) and resistive earthing (earthing resistor). In case of single pole earth faults with resistive current limitation earth fault factors of k = 2.0 can appear.

The fault current is in the range of 500 A to 2,000 A. The fault duration is in the range of a few seconds maximum.
A special case of the low ohmic star point earthing is the so-called direct or solid star point earthing. This kind of star point earthing is principally used for all the systems with system voltages of 220 kV and above, but it can also be found in medium voltage systems.
The earth fault factor is:

k = (0.75 …≤ 0.8) × √3, that is k ≤ 1.4

In medium voltage systems the short circuit current can be as high as I_K = 20 kA, and consequently the failure has to be cleared in less than 0.5 seconds.

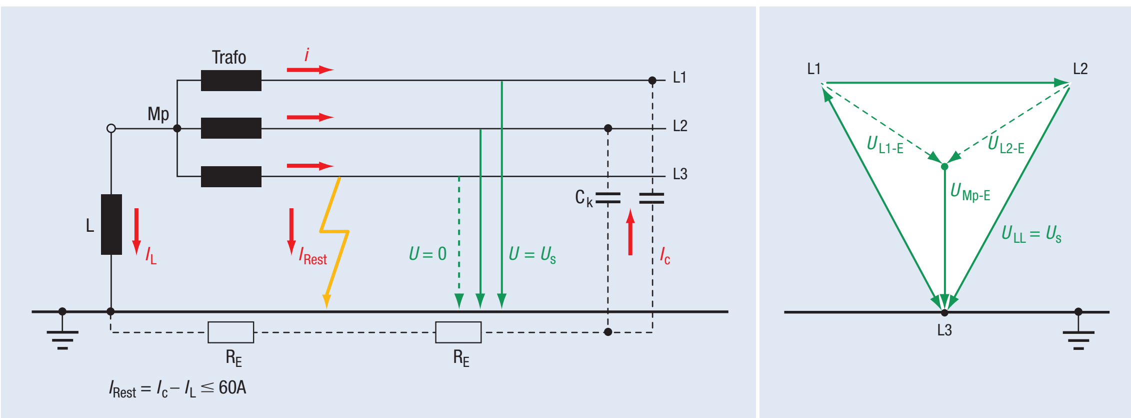


Figure 22: A system with earth fault compensation is described here. The star point Mp of the transformer is earthed high ohmic through a Peterson coil L. If a single pole earth fault occurs, then this results in the voltage relationship shown in Figure 21. The fault current can flow back into the system in this case through the inductance L. The earth fault residual current I_{Rest} arises from the currents I_C and I_L, which have opposite directions.

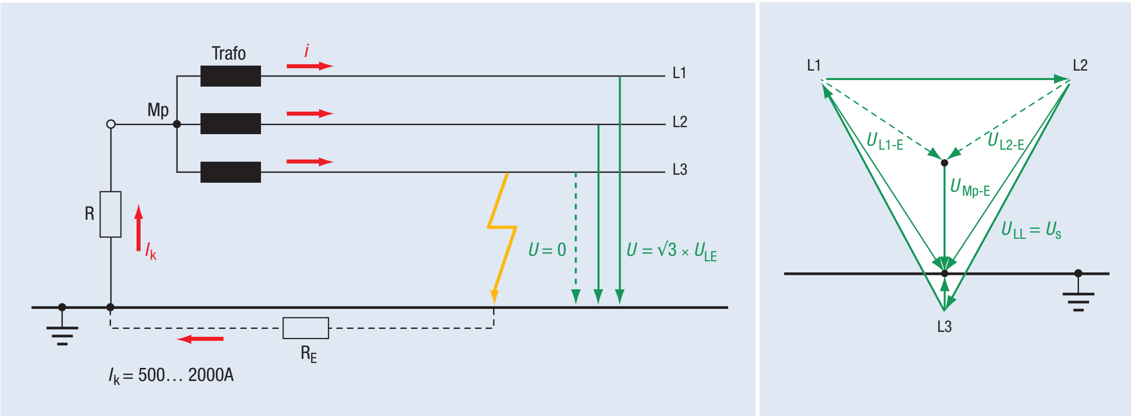


Figure 23: The star point of the transformer is low ohmic earthed through an ohmic earthing resistance. The earth short circuit current I_k can flow directly into the system through the ohmic resistance in case of an earth fault.

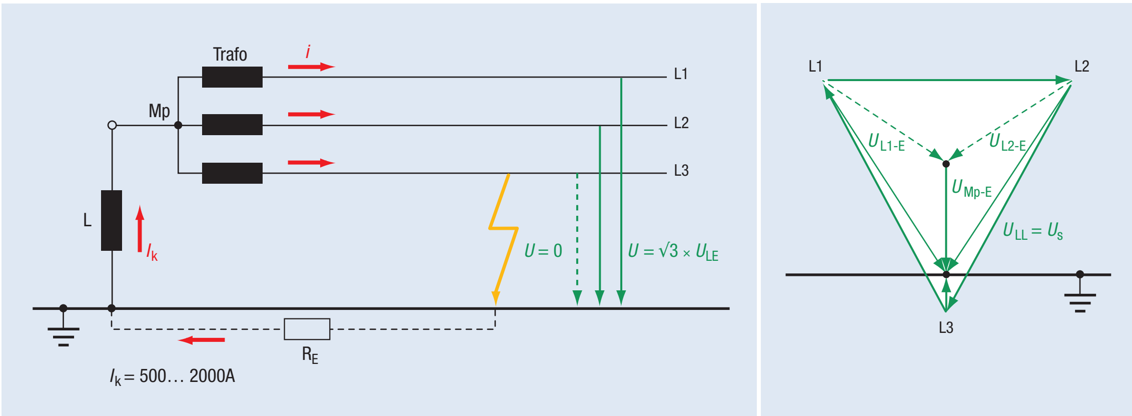


Figure 24: Another option for low ohmic earthing of the star point is the use of an inductive neutral reactor. The fault current I_k flows directly into the system through the neutral reactor, similar to the case described in Figure 23. Neutral reactor coils can be loaded at most 3 s, which is the reason why the system must be switched off after 3 s in case of a low ohmic inductive earthing.

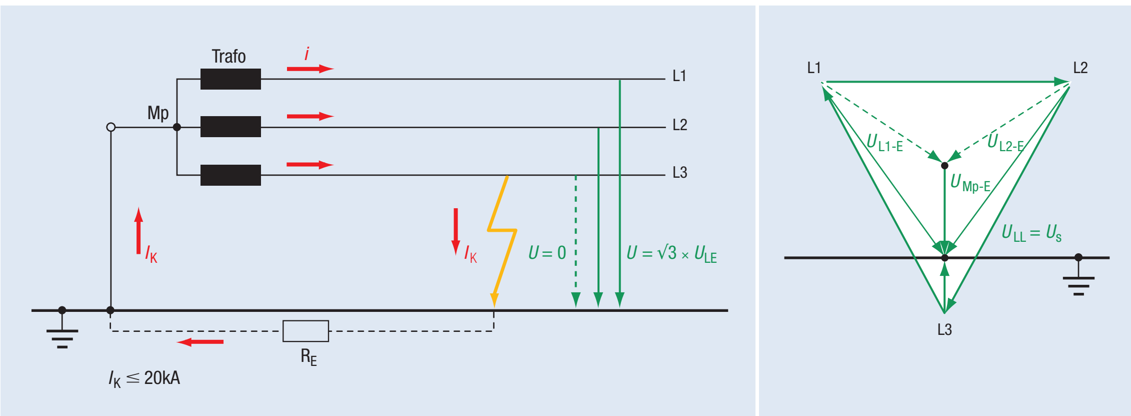


Figure 25: If the star point of the transformer is directly (or solid) earthed, a very high short circuit current flows at once, in case of a short circuit, and the failure is immediately switched off ($t \leq 0.5$ s).

7 | SELECTION OF THE ARRESTER

7.1 Determination of the continuous operating voltage U_c

While choosing the continuous operating voltage U_c, it is necessary to ensure that under no circumstances can the arrester be overloaded due to the voltage with power frequency. In this way, the arrester meets the requirements of the operating system. Therefore, the continuous operating voltage U_c of the arrester is to be chosen in such a way that the arrester cannot become instable either through the continuous applied voltage coming from the system, or through temporary overvoltages that may occur.

In selecting the U_c of an arrester in a three-phase system, the location of the arrester plays the deciding role: between conductor and earth, between the transformer neutral and earth or between two phases.

The maximum operating voltage at the arrester terminals can be calculated with the help of the maximum system voltage U_s.

In medium voltage systems, special attention must be paid to potential temporary overvoltages U_{TOV}. They occur during earth faults and they depend on the treatment of the star point of the transformers and the system management.

Thus results generally the demand for the continuous operating voltage:

$$U_c \geq \frac{U_{Tov}}{T(t)}$$

As a rule, in medium voltage systems the withstand voltage values of the insulation are rather high in relation to the system voltage; see Table 7. This means that the distance between the lightning impulse withstand voltage LIWV and the residual voltage U_{res} of a MO arrester is always sufficient. On the other hand, the system conditions and the maximum system voltage U_s are not always clearly known.

That is why it always makes sense to set the continuous operating voltage U_c of a MO arrester somewhat higher than the calculated minimal value that is required. This “safety margin” contributes to a secure and reliable operational system. A safety margin of 10% or more is recommended when choosing the U_c unless there are explicit technical reasons for not doing so.

The thermal stability of the surge arrester in the system is always to be preferred over a fully optimized protection level.

The examination of the residual voltage of the chosen arrester and eventually the examination of the resulting protection distance are necessary in any case.

7.1.1 Systems with insulated neutral or with earth fault compensation

The voltage increases at the “healthy” phases to a maximum of U_s under earth-fault conditions. This results in

$$U_c \geq U_s$$

for the arrester between phase and earth.

The voltage at transformer neutral can reach a maximum of U_s / √3. This results in

$$U_c \geq \frac{U_s}{\sqrt{3}}$$

for the arrester between transformer neutral and earth.

In every system there exist inductances and capacitances which produce oscillating circuits. If their resonant frequency is close to that of the operating frequency, the voltage between the phase conductor and earth could basically become higher than that of U_s in single-pole earth faults. The system management should avoid the occurrence of such resonances. If this is not possible, then the U_c should be correspondingly increased.

In systems with earth fault compensation the earth fault factor can reach a value of 1.9 in unfavorable conditions. This is to be taken into account by increasing the continuous voltage by 10%.

7.1.2 Systems with high ohmic insulated neutral system and automatic earth fault clearing

The same voltages occur as described in section 7.1.1 in case of an earth fault. However, an immediate automatic fault clearing enables a reduction of U_c by the factor T. Naturally, it is decisive to know the level of the possible temporary overvoltage as well as the maximum time for the clearing of the earth fault. Making use of the TOV curve this results in

$$U_c \geq \frac{U_s}{T}$$

for the arrester between phase and earth,

$$U_c \geq \frac{U_s}{T \times \sqrt{3}}$$

for the arrester between transformer neutral and earth.

7.1.3 Systems with low ohmic insulated star point, or with solidly earthed star point (k ≤ 1.4), respectively

In these types of systems there are so many transformers in low ohmic neutral earthing that during an earth fault the phase voltage in the complete system never exceeds 1.4 p.u. (earth fault factor k ≤ 1.4). The result is therefore $U_{TOV} \leq 1.4 \times U_S / \sqrt{3}$. It can be assumed that the clearing time of the earth fault is t = 3 s at the most. In Figure 19 the described TOV curve for the arrester MWK lists T = 1.28 as a result, so that it may be written

$$\boldsymbol{U_c} \geq \frac{\mathbf{k} \times \boldsymbol{U_s}}{\mathbf{T} \times \sqrt{3}} = \frac{\mathbf{1.4} \times \boldsymbol{U_s}}{\mathbf{1.28} \times \sqrt{3}} = \frac{\mathbf{1.1} \times \boldsymbol{U_s}}{\sqrt{3}}$$

for arresters between phase and earth.
This simple equation can be generally used as a rule of thumb for systems with direct earthed neutral.
The voltage of the neutral of the earthed transformers reaches a maximum $U_{TOV} = 0.4 \times U_S$. This results in

$$\boldsymbol{U_c} \geq \frac{\mathbf{0.4} \times \boldsymbol{U_s}}{\mathbf{1.28}} = \mathbf{0{,}32} \times \boldsymbol{U_s}$$

for arresters between transformer neutral and earth.

7.1.4 Systems with low ohmic neutral transformer earthing that do not uniformly have k ≤ 1.4

For arresters in the vicinity of neutral earthed transformers, U_C can be chosen according to Section 7.1.3, because k ≤ 1.4 is applicable here. Care is required if the arresters are located just a few kilometers from the transformer. This can be the case if, for instance, a cable is connected to an overhead line, and the cable bushing is protected with a surge arrester. In case of very dry soil or rocks (such as in desert regions or mountains) the earthing resistance is very high and it is possible that at the point of the arrester installation the phase to earth voltage comes very close to the system voltage U_S. In this case the procedure described in Section 7.1.2 should be followed:

$$\boldsymbol{U_c} \geq \frac{\boldsymbol{U_s}}{\mathbf{T}}$$

It may also be possible that the fault current in case of an earth fault is so small that no automatic clearing occurs. In such cases, it is better to choose the U_C for the arrester similar to the system voltage, which means:

$$\boldsymbol{U_c} \geq \boldsymbol{U_s}$$

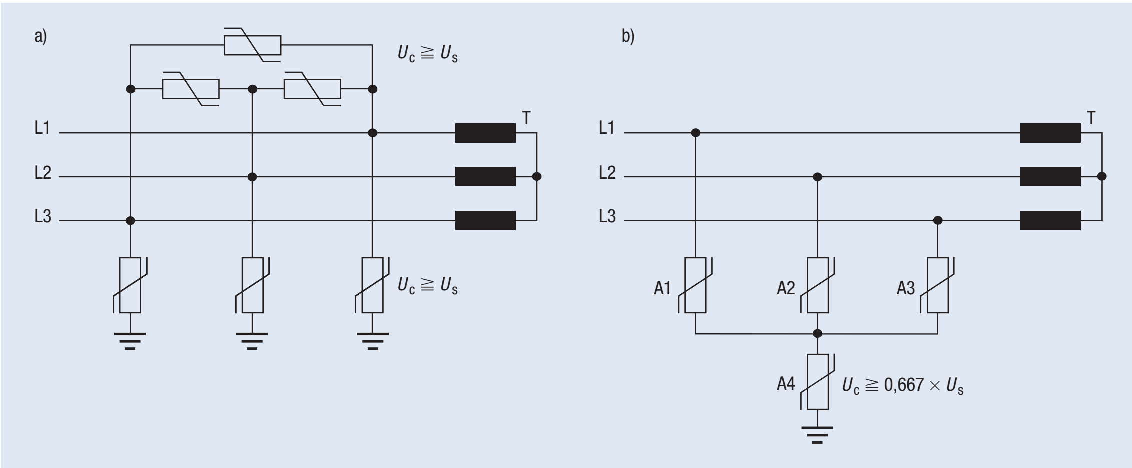


Figure 26: Overvoltage protection between phases and between phase and earth.
a) 6-arrester arrangement with $U_c \geq U_s$ for all arresters.
b) Neptune design. A1, A2, A3 and A4 are 4 similar arresters, each with $U_c \geq 0.667 \times U_s$.
T is the transformer to be protected.

7.1.5 Systems with low ohmic neutral earthing and k > 1.4

This refers to systems that are earthed with impedance so that the fault current may be limited, for example, to 2 kA. In case of an earth fault, the voltage increases in the "healthy" phases up to U_s. With pure ohmic neutral earthing the voltage can also be 5% higher than U_s. Assuming that the automatic fault clearing time is 10 s maximum, it is possible to choose T = 1.25. This results in:

$$U_c \geq \frac{1.05 \times U_s}{T} = 0.84 \times U_s$$

7.1.6 Arresters between phases

7.1.6.1 6-arrester arrangement

In special cases, such as in arc furnace installations, switching overvoltages occur, which are insufficiently limited by arresters between phase and earth. In such cases, it is necessary to install additional arresters between the phases, with

$$U_c \geq U_s$$

for arresters between the conductors.
The protection consists of a total of six arresters, three between the phases and the earth and three between the phases (6-arrester arrangement); see Figure 26.

7.1.6.2 Neptune design

A variation of the 6-arrester arrangement is an arrangement called a "Neptune design" because of its arrangement of the arresters. It consists of four similar arresters. Two arresters in series are fitted between the phases and the earth and also between the phases, as shown in Figure 26. This arrangement permits an overvoltage protection both between the phases and between the phases and the earth. This kind of arrangement however, has a fundamental disadvantage in comparison to the 6-arrester arrangement. For example, in case of an earth fault at Phase 1, the arresters A1 and A4 are connected parallel. Since the arresters behave in a capacitive manner during continuous operating voltage, all 4 arresters now form an asymmetrical capacitive system. The result of this is that the voltage at the arresters A2 and A3 reaches the value 0.667 × U_s. Therefore, all 4 arresters are to be dimensioned for

$$U_c \geq 0.667 \times U_s$$

The protection level of this arrangement, which has always two arresters in series, is therefore similar to the one offered by the arrester with $U_c \geq 1.334 \times U_s$. The residual voltage of this arrester combination is therefore also 33% higher than that of the 6-arrester arrangement.

7.1.7 Operating voltage with harmonic oscillation

Harmonic currents generate harmonic oscillations superimposed upon the power frequency voltage. For this reason it is possible that the peak value of phase-to-phase voltage U_s can be higher than $\sqrt{2} \times U_s$. If this difference is less than 5%, then a correspondingly higher U_c has to be used. On the other hand, if due to the harmonics the voltage increase is higher than 5%, the choice of U_c should be discussed with the arrester manufacturer. The same applies for forms of voltage that can often be seen in the vicinity of thyristor converters: voltage steps, ignition peaks, and asymmetries in the two half cycles.
Commutation overshoots with a high repetition rate, or other voltage spikes, which are common for drives and converters, can generally not be limited by gapless MO arresters. This is not a typical application for MO surge arresters. In case of commutation overshoots and other superimposed voltage spikes, special criteria for the dimensioning of MO arresters have to be considered. This makes a close cooperation and detailed discussion between the user and manufacturer necessary.

7.2 Selection of nominal discharge current and line discharge class

The nominal discharge current I_n is used to classify the MO arrester. In IEC 60099-4 there are five different values, each of them assigned to different areas of the rated voltage U_r. However, the figure alone does not say anything about the operation properties of an arrester. For example, a 10 kA arrester can discharge without difficulty much higher lightning current impulses without getting any damages. The real meaning of this classification lies in the fact that depending on the class there are different demands and test conditions specified.

Primarily, there are the 5 kA and 10 kA arresters that are used in medium voltage systems. The high current impulses I_{hc} are assigned to the nominal discharge currents I_n as it can be seen in Table 1. The line discharge class can also be found in the table. The operating duty test to be performed is now clearly prescribed together with the nominal discharge current and the line discharge class.

The energy used as a proof of thermal stability is applied with a high current impulse of 65 kA, respectively 100 kA, during the operating duty test on 5 kA arresters and 10 kA arresters of line discharge class 1. Therefore, it is a current that is prescribed and injected and not an energy that is specified.

The main difference between 10 kA and 20 kA is the line discharge classes to which they are assigned. The 10 kA arresters are assigned to the classes 1 to 3 and the 20 kA arresters are assigned to the classes 4 and 5. According to the line discharge class, it is necessary to calculate the energy which must be applied with two long-duration current impulses during the operating duty test as a proof of thermal stability. In this case, the applied energy is specified according to a line discharge class.

The higher the line discharge class, the higher the applied energy also is. That makes it clear that the MO arresters with I_n = 10 kA as well as those with I_n = 20 kA can have very different operating properties. Therefore, the classification of a MO arrester is not only dependent on the nominal discharge current I_n, but particularly on the combination of I_n and the line discharge class.

It is therefore enough to mention the nominal discharge current I_n and the line discharge class in order to specify a MO arrester. Other additional requests, such as special energies or currents, can only lead to over definition or even misunderstandings.

Table 6: Correlation of the degree of pollution and the creepage distance.

Degree of pollution	Shortest recommended creepage distance in mm/kV*	Possible reduction of the creepage distance with silicon insulation
I LIGHT	16	30 %
II MEDIUM	20	20 %
III STRONG	25	No reduction recommended
IV VERY STRONG	31	No reduction

* Corresponding to IEC 815, the shortest nominal creepage distance for insulators between phase and earth, related to the maximum voltage for equipment (phase to phase).

7.3 Selection of arrester housing

As previously mentioned, silicone, or EPDM is almost exclusively used today as housing material for medium voltage arresters. Silicone is increasingly gaining acceptance due to its excellent protection behavior especially in regard to pollution.

The choice of the housing for MO arresters in medium voltage systems is not critical. The flashover distance of the arrester housing and the creepage distance along the surface of the housing are to be taken in account.

The minimum flashover distance is determined by the required withstand values of the test voltages which have to be applied in the relevant withstand tests, the lightning voltage impulse test and the a.c. withstand test with power frequency for 1 min.

The height of the test voltage to be applied is related to the protection characteristic of the MO arrester. The test voltage during the test with lightning voltage impulse must be 1.3 times the residual voltage of the arrester at I_n.

The housings for 10 kA and 20 kA arresters with a rated voltage U_r < 200 kV, i.e. all the medium voltage arresters, must withstand for one minute an a.c. voltage test with a peak value of the testing voltage 1.06 times of the protective level for the switching surges.

The resulting values for the arrester housings are as a rule lower than the insulation values for insulations of devices and installations. This is proper because the voltage at the arrester is determined by the voltage-current-characteristic curve of the active part and the arrester naturally protects its own housing against overvoltages.

The real provable withstand values of the housing are generally higher than the demanded minimum values corresponding to IEC, especially with arresters for the lower voltage levels.

The behavior of the external insulation under pollution and applied operating a.c. voltage is important and determines the creepage distance. The pollution classes and the respectively specific creepage distances are specified in IEC 507 [14] and IEC 815 [15], see Table 6. In fact, this table can be used only for glass and porcelain insulators. It is, however, shown here, because the creepage distances are given or demanded in many specifications and there are currently no corresponding values for the polymer insulations.

It is possible, however, to specify the reductions of the creepage distances for synthetic materials, which have a regenerative hydrophobicity such as silicone, towards ceramic insulations [16]. These reductions can also be found in Table 6.

The same creepage distances should be used as a basis for synthetic materials, which have a permanent loss of hydrophobicity, such as EPDM, as for ceramic insulators.

Notice: The creepage distance is often specified in relation to the continuous operating voltage U_c, because pollution problems and flash-overs are always connected to the actual a.c. voltage applied at the arrester. Therefore, it is important to carefully consider the voltage to which the creepage requirements are related.

As a rule, the mechanical loads are low with medium voltage arresters. All ABB medium voltage arresters can be installed in regions where earthquakes occur. Horizontal installation is possible. If the arresters have to bear additional mechanical loads besides their own weight and the normal wind and ice loads, which exceed the guarantee data, then the manufacturer should be contacted.

8 | PROTECTIVE DISTANCE OF THE ARRESTER

The higher its lightning impulse withstand voltage (LIWV) lies above the residual voltage of the arrester at nominal discharge current I_n, the better the equipment is protected against lightning overvoltages.

Note: The acronym "BIL", which is often used for "basic lightning impulse insulation level" is exclusively to be found in the US standards (IEEE/ANSI Standards). It is similar to the "lightning impulse withstand voltage" (LIWV) as used in the IEC definition.

Modern MO arresters with a residual voltage of $U_{res} \leq 3.33 \times U_c$ (VDE recommendation) at I_n maintain a value of $U_{pl} \leq 4$ p.u., even in systems with high-ohmic earthed or insulated transformer neutrals. The U_{pl} is the lightning impulse protection level of the arrester [1].
Table 7 shows a summary of the typical values. It should be noted that the specified residual voltages U_{res} from the data sheets apply for the terminals of the arrester, which means they are valid only for the place where the arrester is installed. The voltage at the devices that are to be protected is always higher than the voltage that is directly at the arrester terminals in view of the reflections of the overvoltages at the end of lines.
Therefore, the overvoltage protection no longer exists if the arrester is placed too far from the device to be protected. The protective distance L is understood to be the maximum distance between the arrester and the equipment, at which the latter is still sufficiently protected.

8.1 Traveling waves

Voltage and current impulses having a rise time shorter than the traveling time of an electromagnetic wave along the line, travel along the line as traveling waves. This means that (disregarding damping) the current and voltage impulse travels along the line without changing its form. Therefore, it is in another place at a later time.
Current and voltage are connected to one another because of the surge impedance of the line. The surge impedance results from the inductance and capacitance per unit length of the line, disregarding the ohmic resistance per unit length and the cunductance of the insulation.

$$Z = \frac{\sqrt{L'}}{\sqrt{C'}}$$

L' = Inductance per unit length in H/km
C' = Capacitance per unit length in F/km

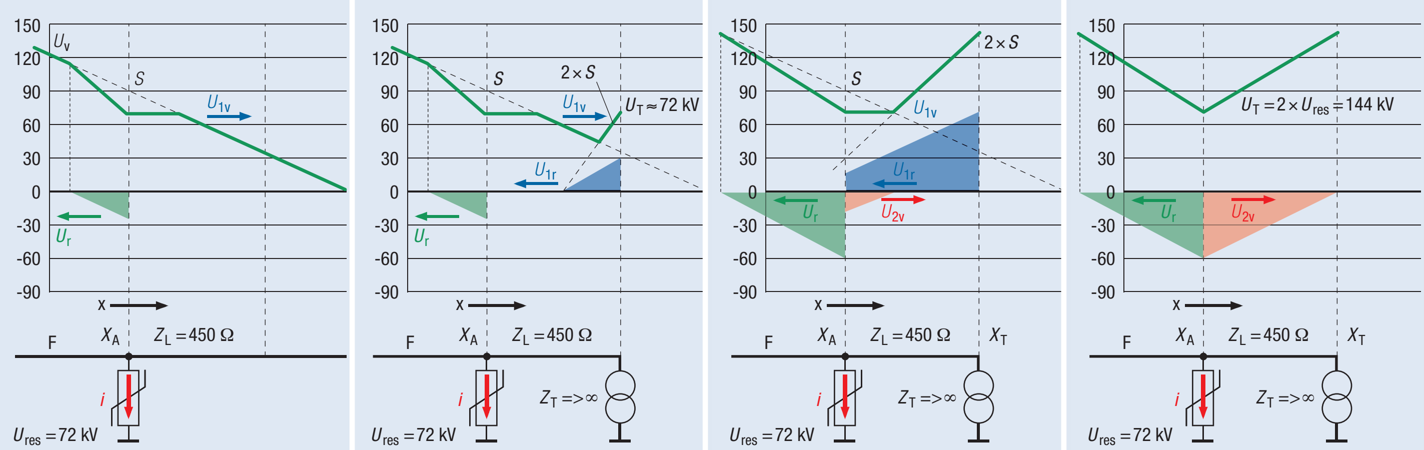
Only the voltage impulses are important when analyzing the overvoltages.
When a voltage traveling wave on a line reaches a point of discontinuity, i.e. a change in the surge impedance, part of the voltage is "reflected" backward and a part is transmitted forward. This means that voltage decreases and voltage increases appear on the connections of the overhead lines to the cable, and at the end of the line. Especially at the end of the line, such as at open connections or transformers, there appear reflections, which lead to a doubling of the voltage. The height of the voltage for each moment and for each place on the line is the sum of the respective present values of all

Table 7: Typical values of the lightning impulse withstanding voltage LIWV according to IEC [1] and the lightning impulse protection level U_{pl} = 4 p.u.

U_m in kV rms	3.6	7.2	12	17.5	24	36
LIWV in kV pv	40	60	75	95	125	170
U_{pl} in kV pv	11.8	23.5	39.2	57.2	78.4	117.6
LIWV/U_{pl}	3.39	2.55	1.91	1.66	1.59	1.45

voltage waves. The principles of traveling wave phenomena are briefly explained in the following figures.
An overvoltage wave travels along the line and is limited to U_{res} at the arrester. The wave, which travels on, is reflected positively at the transformer. A voltage with a double steepness occurs at the transformer. This voltage travels back towards the arrester. The arrester discharges the lightning current towards the earth, therefore it can be considered as a short circuit at this point. Therefore, the voltage is negatively reflected when the voltage wave arrives at the arrester and it is sent towards the transformer. The height and the steepness of the voltage between the arrester and the transformer decline. At the same time, as the arrester starts to limit, a negative voltage wave is sent from the arrester in the opposite direction of the incoming overvoltage.

Figure 27: Traveling waves on an overhead line F with the surge impedance Z_L = 450 Ω. A transformer is connected at the end of the line. In front of the transformer there is a MO arrester.



a) An overvoltage U_v with the steepness S travels along the line with the speed v = 300 m/µs.
An arrester with U_{res} = 72 kV is installed on the spot X_A. If the onward traveling voltage reaches the value U_v = 72 kV, the MO arrester limits and holds the voltage constant at this value. Through the arrester flows the lightning current i, which means that the arrester performs an approximate short circuit now.
In this way, the voltage, which continues to travel onwards, is negatively reflected (U_r) on the spot X_A. The voltage U_{1v} moves on with the same steepness S along the line in the direction of the line end.

b) If the transient wave U_{1v} reaches a transformer with $Z_T = \infty$ on the spot X_T, it is positively reflected. On the spot X_T a voltage U_T with the double steepness S is built up, which reaches about 72 kV at the moment described.
The reflected voltage U_{1r} at the transformer travels backwards in the direction of the arrester.
The arrester on the spot X_A is still conducting and performs an approximate short circuit, which reflects negatively all the incoming voltages.

c) The voltage U_{1r} reached the arrester and is negatively reflected there (U_{2v}) and travels again in the direction of the transformer. The voltage is held at U_{res} = 72 kV on the spot X_A (arrester) and on the spot X_t (transformer) the voltage is still increasing. The voltage U_r travels backwards against the x-direction and reduces the incoming voltage U_v.

d) The voltage U_{2v} arrives at the spot X_T (transformer) again. Meanwhile, the maximum possible voltage $U_T = 2 \times U_{res}$ = 144 kV was built up at the transformer. The voltage U_{2v}, again positively reflected, should travel back in the direction of the arrester, at the same time the voltage U_T should be reduced respectively. This means that the voltage U_T, which appears at the transformer, can be limited by the arrester at the earliest after two traveling times between the transformer and the arrester.
The voltage U_{res} = 72 kV is held constant on the spot X_A (arrester).

Thus, the arrester protects in both directions. To simplify matters, a funnel shaped voltage increase results from the arrester, as it is to be seen in Figure 28.

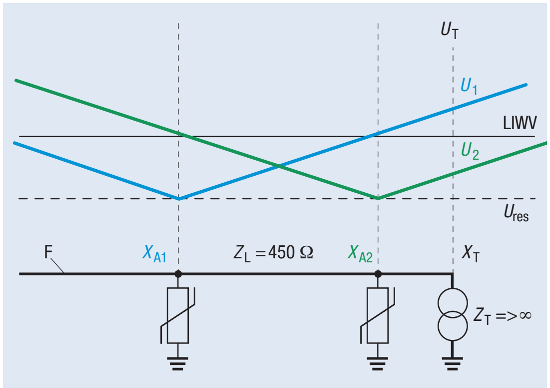


Figure 28: Assuming the simplified transient wave occurrences, as is explained in Figure 27, there appears a funnel shaped voltage increase, which has its lowest value at the installation place X_A. It is possible to immediately check from this that the voltage is similar to the residual voltage of the arrester only at the place of the arrester.
A LIWV of 125 kV for the transformer results with an assumed U_m = 24 kV (like in Figure 27). Therefore the voltage U_1 at the transformer is higher than acceptable taking into consideration the given arrangement. This means that the distance between the arrester (X_{A1}) and the transformer (X_T) is too long.
If the arrester is installed by X_{A2}, the traveling time becomes shorter and consequently the voltage at the transformer is reduced to a value much lower than the withstand value of the transformer insulation (LIWV).

This representation clearly shows that the closer an arrester is installed to the equipment to be protected, in this case a transformer, the better it can protect the device.

8.2 Protective distance *L*

On the overhead line in Figure 29 an overvoltage U travels as a traveling wave with the speed v towards the line end E. At point E there is the equipment to be protected. For the following analysis it is considered that the equipment to be protected is high-ohmic (transformer, open circuit breaker). When the traveling wave reaches E, it is positively reflected and the voltage increases to $2 \times U$. The function of arrester A is to prevent unacceptable high voltage values at the equipment to be protected. Under the simplified assumption that the front of wave steepness S of the incoming overvoltage wave is time constant, the following relationship applies for the maximum value U_E:

$$U_E = U_{res} + \frac{2 \times S \times (a + b)}{v}$$

$$v = 300\ \text{m}/\mu\text{s}$$

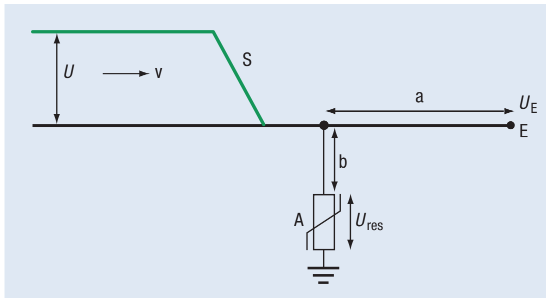


Figure 29: Assumption for the calculation of the voltage at the open end of a line and for the determination of the protective distance *L*.

U: Incoming overvoltage wave
v: Velocity of the traveling wave
S: Front steepness of the overvoltage
A: Arrester
U_{res}: Residual voltage of the arrester
a,b: Length of the connections
E: End of the line. Connected is, for example, a transformer or an open circuit breaker.
U_E: Voltage at the end of the line

A safety factor K_S is recommended between the LIWV of the equipment and the maximum lightning overvoltage that occurs **[7]**. This protection factor takes into consideration, among other things, the possible ageing of the insulation and the statistic uncertainties in defining the lightning impulse withstanding voltage of the equipment.

In **[7]** K_S = 1.15 is recommended for the internal insulation and K_S = 1.05 for the external insulation. K_S = 1.2 **[8]** is specified for the calculation of the protective distance in medium voltage systems. K_S = 1.2 is used in this application guidelines for all the calculated examples, except where otherwise stated. This results in:

$$\frac{\mathrm{LIWV}}{K_S} \geq U_E = U_{res} + \frac{2 \times S \times L}{v}$$

$$L = a + b$$

The required equation for the protective distance is:

$$L \leq \frac{v}{2 \times S} \times \left(\frac{\mathrm{LIWV}}{K_S} - U_{res} \right)$$

It should be mentioned that the given approximation for L is valid in the strict sense only for $b = 0$, for practice, however, it gives sufficiently precise values.

It is certainly to be assumed that the arrester and the equipment to be protected are connected to the same earthing system. To be observed as a principal rule, the arrester should be installed as close as possible to the equipment to be protected. The connections must be executed on the high voltage side and the earth side short and straight. Especially the connection b should be executed as short as possible. In this way it makes sense to lead the overhead line first to the arrester and from there directly to the bushing of the transformer, for example.

8.3 Expected steepness *S* of lightning overvoltages in MV substations

The steepness S of the incoming overvoltage wave must be known in order to determine the protective distance as it is above described.

The repetition rate of the lightning strokes and the overvoltages related to them can only be taken from statistics. That is why it is not possible to give any generally applicable information about the steepness of the overvoltages that occur. An assumed steepness is always connected to the probability of an event.

Figure 30 shows a lightning stroke on a distribution line conductor. The time aspect of the lightning current is designated by i(t). From the point in which the lightning strikes the conductor, the lightning current i(t)/2 flows out in both directions. If Z is the surge impedance of the conductor to earth, then this current generates a lightning overvoltage u(t) with the steepness of the voltage increase S(t) between the conductor and the earth. As indicated in Figure 30 S(t) is not generally constant. In the following the maximum steepness of the rise of an overvoltage wave will be indicated by S.

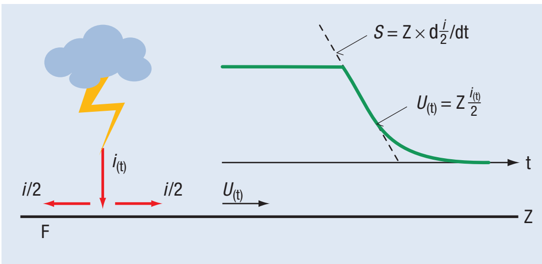


Figure 30: Creation of the lightning overvoltage during a lightning stroke in an overhead line.

F: Overhead line
Z: Surge impedance of the overhead line
t: Time
i(t): Total lightning current in time function
di/dt: Maximum steepness of the lightning current
u(t): Lightning overvoltage in time function
S: Maximum steepness of the lightning overvoltage

In 10% of all cases of lightning, the maximum current rise time di/dt is higher than 32 kA/µs. When Z = 450 Ω, every tenth lightning stroke will cause a maximum voltage steepness S > 7,200 kV/µs. A steepness of this order is to be expected in the substation only if the lightning strikes nearby, for example, within 25 m of the equipment to be protected. The probability of this happening is very small.
Substantially smaller voltage rates of rise are to be expected at the station when the lightning stroke occurs far from the station. Due to corona damping, the front of the overvoltage wave flattens out as it proceeds from the point of the stroke to the station. If S_0 is the steepness at the location of the stroke, the steepness along the length d of the line decreases to the value:

$$\boldsymbol{S} = \frac{\mathbf{1}}{\mathbf{1/S_0 + K \times \boldsymbol{d}}}$$

The constant K is dependent upon the geometry of the overhead line, and it is estimated to K = 5 × 10^{-6} µs/kVm for medium voltage overhead lines [9].
Supposing that the location of the stroke is 135 m distant from the station, a lightning stroke causes an infinitely large voltage rate of rise S_0 at the point of strike. According to the above formula a steepness at the substation of S<1,500 kV/µs occurs due to the corona damping. These two arbitrarily chosen examples specify the order of the voltage rate of rise and should show that large voltage rates of rise occur less often than the small ones.
Of further significance is the fact that the stroke current rise is concave [10]. That is why the greatest steepness of the overvoltage occurs in the range of the voltage maximum, as shown in Figure 30. In voltage waves resulting from high stroke current peak value, a flashover from the line to earth takes place before the peak value has been reached. The upper part of the voltage wave is thereby cut off so that the maximum steepness cannot be reached.

The statistics for faults and damages (e.g. [11]) show that in Central Europe about 8 lightning strokes occur per year and 100 km in overhead lines of medium voltage systems. However, it has to be observed that in regions with unfavorable topographical conditions and especially regions with high thunderstorm activity there may occur up to 100 lightning strokes per year and 100 km overhead lines.
Assuming that 8 lightning strokes occur per year and 100 km in overhead lines in outdoor substation equipment, it can be expected that the steepness reaches

***S* = 1550 kV/µs**
for overhead lines with wooden poles and

***S* = 800 kV/µs**
for overhead lines with earthed cross arms

To be considered here is that overhead lines with wooden poles have a spark over voltage of 3,000 kV and that overhead lines with earthed cross arms have a spark over voltage of 660 kV. These values are valid for outdoor line insulators in a 24 kV medium voltage system which is stressed with steep voltage impulses. The smaller values S for overhead lines with earthed cross arms are the result of lower spark over voltages, and thereupon lower steepness, of the insulators compared to the spark over voltages along the wooden poles.

8.4 Expected lightning currents in medium voltage systems

The lightning parameters are derived from statistical analysis of world-wide measurements [13]. The mostly negative cloud-to-ground flashes that occur have current peak values between 14 kA (95% probability) and 80 kA (5% probability). With a probability of 50% the following values are reached or exceeded:

Current peak value: 30 kA
Rise time: 5.5 µs
Time to half value: 75 µs

Extreme lightning strokes can reach peak values up to 250 kA, with half-time values of 2,000 µs. A peak value of 20 kA with a probability of 80% is often used in standardization work, and for test and co-ordination purposes of surge arresters.

In case of a direct lightning stroke to the conductor of an overhead line, the charge flows in the form of two equal current waves in both directions, starting from the point of striking. The voltage waves are linked with the current waves via the surge impedance of the line.

8.5 Influences on the protective distance through electrical equipment, the arresters and the arrangement of the arresters

If the above mentioned values S are put into the equation listed above (chapter 8.2) the following protective distances result, taking into consideration the LIWV and the U_{pl} from Table 7:

***L* = 2.3 m for overhead lines with wooden poles**
***L* = 4.5 m for overhead lines with earthed cross arms**

This is valid for systems with system voltage from U_s = 3.6 kV to U_s = 36 kV and the assumption that the transformers have an isolated neutral or that they are operated with earth fault compensation, which means that the continuous voltage U_c of the arrester is chosen according to Chapter 7.1.1

In systems which have transformers with directly earthed neutrals the continuous voltage U_c can be chosen according to Chapter 7.1.3. In this case the protective distances are, using the same assumptions, as given in Table 8.

U_s in kV rms	L in m, wooden pole	L in m, earthed cross arms
3.6	2.3	4.4
7.2	3.3	6.3
12	3.5	6.7
17.5	3.8	7.3
24	5.0	9.6
36	6.3	12.2

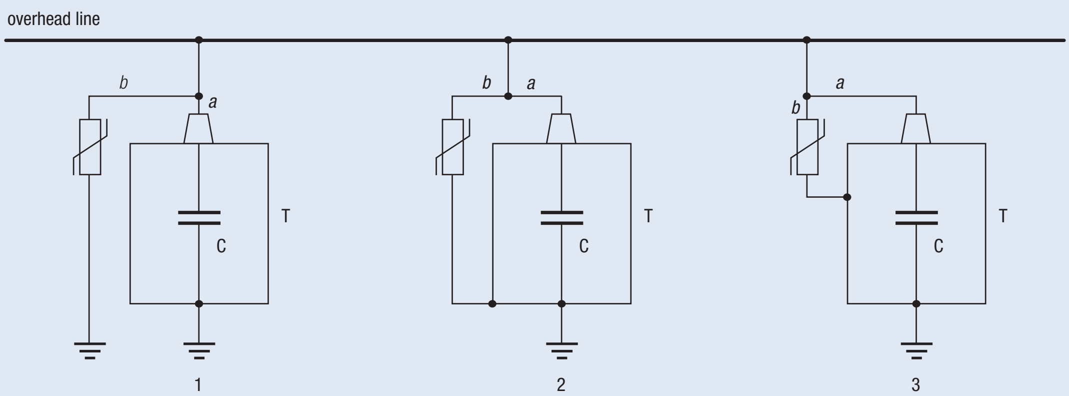
Table 8: Protective distance for MO arresters in systems with directly earthed transformer star points.

In consideration of the TOV, curve U_c can be reduced remarkably. The resulting lower residual voltage of the arrester leads to a greater protection distance. It can be stated as a general rule that arresters with lower residual voltages have also a greater protective distance.

For completeness it must be mentioned that all numerical examples in these guidelines are related to a specific ABB MO surge arrester. Slightly different figures may occur for other surge arresters.
The calculated values are valid for the simplified assumption of Figure 29. All the equipment, such as transformers, voltage transformers and cables, have a self-capacitance towards the earth. The influence of this capacitance on the function of the arrester should be taken into account if detailed calculations must be performed. The capacitance of the equipment produces a voltage oscillation, which can lead to a noticeable increase of the voltage at the transformer. This would result in a decrease of the protective distance.

The parabolic increase of the lightning overvoltage has an opposite influence, due to the fact that a MO arrester without spark gaps limits the overvoltage according to its voltage-current characteristic much earlier and not when the residual voltage U_{res} arrives at I_n.
Therefore, the MO arrester limits the incoming overvoltage at a much lower stage as its peak voltage, so that the maximum steepness of the voltage rise does not affect.
For a quick and simple estimation with sufficient accuracy of the protective distance in practice calculated values above are to be used.

Figure 31: Evaluation of different connection possibilities of a MO arrester at a transformer.



1: Poor. The arrester and the transformer do not have the same earthing point. The incoming overvoltage reaches first the transformer bushing. The connection *b* is too long.

2: Good. The arrester and the transformer have the same earthing point. The connections *a* and *b* are about the same length.

3: Very good. The arrester is earthed directly at the transformer tank. The connection *b* is almost zero. In this way, the incoming overvoltage reaches first the arrester, which limits the overvoltage without delay.

As was previously mentioned above, the arrester should be installed as near as possible to the equipment to be protected. Especially connection *b* should be as short as possible (see Figure 29). The best way is to go first and directly to the arrester terminal with the high voltage side connection and from there straight to the bushing of the transformer in the shortest way possible, as can be seen in Figures 31 and 32. The earth connection should also be short and direct from the bottom of the arrester to the tank of the transformer.

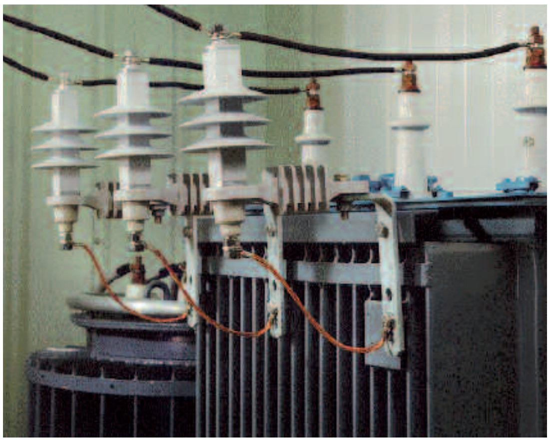


Figure 32: Example of an ideal installation. A MO arrester of the type POLIM-D 12 with disconnector is installed on an insulated bracket directly at the tank of a medium voltage transformer. The flexible earth connection is connected to the transformer tank as shortly as possible. The high voltage connection goes from the overhead line directly to the arrester and from there over the shortest route to the transformer bushing.

9 | SPECIFIC APPLICATIONS

It is sometime insufficient to install only one arrester in the substation, considering the limited protective distance of the arresters and the spatial distance between the equipments in the substation. If the various equipment is installed too far from one another, it is necessary to consider where to find a place for an additional arrester. Some typical cases are described in the following paragraphs.

9.1 Overvoltage protection of cable sections

The essential difference between the electrical data of the overhead lines and cables is the surge impedance of their conductors to earth. For overhead lines in medium voltage distribution systems it lies between 300 Ω and 450 Ω and for cables ranges between 30 Ω and 60 Ω. At first this difference causes a marked decrease of the lightning overvoltage as soon as the traveling wave reaches the cable entrance. The reduced voltage wave travels through the cable and is again positively reflected at the end, so that the voltage increases there. Subsequently, the wave returns to the cable entrance and is again reflected, and so on. In this way, the overvoltage is built up gradually in the cable. The steepness of the overvoltage is in fact lower, but the maximum value lies near that of the lightning overvoltage on the line.

Disruptive breakdowns in cable insulations lead to grave damages and require expensive repairs. Flashovers along the cable bushings can damage them and lead to the same consequences as the insulation breakdowns.

It is well known that repeated overvoltage stresses negatively influence the ageing behavior of the cable insulation, which means that the service life of the cable is shortened. Cables should therefore be treated like station equipment and protected against lightning overvoltage with arresters.

The arresters are to be placed directly next to the cable bushings here as well. The junction lines should be as short as possible. It should be noted that the earth connection of the arrester is directly attached to the cable sheath. Longer cables require arrester protection at both ends. For short cable sections a protection on one side can be sufficient. This is possible because the protective range of an arrester at one end of the cable can still offer sufficient protection at the other end. A cable that connects an overhead line with the substation is often only endangered by lightning on the side of the overhead line.

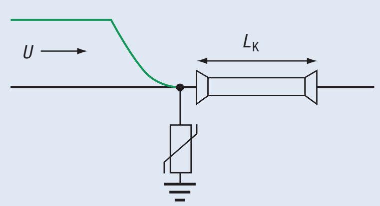
Therefore the arrester has to be installed at the junction between the overhead line and the cable. It is not necessary to protect the other end of the cable as long as the length of the cable L_K does not exceed the values given in Table 9. At first glance, it is clear that L_K is unlimited in 3.6 kV systems. The reason is that the LIWV is relatively high at this system level. Even the reflected overvoltage at the end of the cable lies under the LIWV, so that the insulation is not in danger. This, however, is not valid for the equipment inside the substation. The equipment can be endangered by additional voltage reflections, so that arresters should be planned if necessary.

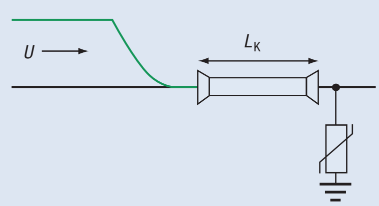
Cables in between overhead lines are naturally endangered by lightning strokes on both sides. With the cables protected at one end only it is necessary to consider that the overvoltage may come from the unprotected end. In this case, the protection offered by the arrester is strongly diminished at the unprotected end. Therefore, the admissible length of cables between to overhead lines should be short, if the arrester protection on one side is to be sufficient. This length is especially short with cables in systems with wooden pole lines, as it is to be seen in Table 9. The specified values are valid for cable sections with constant surge impedance. Otherwise, the voltage reflections produce a shortening of L_K. This is the case, for instance, with cable branches or if two parallel cables are connected with a single one.

9.2 Cable sheath protection

The cable sheath of a single-conductor cable in high voltage systems is earthed on one side only for thermal reasons. This procedure is increasingly used in medium voltage cables to avoid additional losses in the cable sheath **[17]**. If the cable sheath stays open at one side the sheath can take up to 50 % of an incoming overvoltage on the inner conductor at the non-earthed side. The sheath insulation is not able to cope with this overvoltage stress. Flashovers between the sheath and the earth can occur, which damage the external insulation of the sheath.

That is why it is necessary to protect the cable sheath against overvoltages on the unearthed side with an arrester **[18]**. The voltage induced along the cable sheath in case of a short circuit is decisive for the continuous operating voltage U_c. The induced voltage is dependent on the way the cable is installed and can at most amount to 0.3 kV per kA short circuit current





Type of overhead line		Wooden poles	Earthed crossarm	Wooden poles	Earthed crossarm
U_s	Z_K	L_K	L_K	L_K	L_K
kV	Ω	m	m	m	m
3.6	30	∞	∞	8	19
	60	∞	∞	4	13
7.2	30	85	110	11	27
	60	75	100	5	17
12	30	45	50	8	22
	60	33	39	4	16
17.5	30	35	36	6	19
	60	27	30	3	15
24	30	34	36	9	21
	60	27	30	4	17
36	30	30	30	7	19
	60	24	26	4	17

Table 9: The maximum admissible length L_K of a cable if the arrester protection is only on one side. The cable is connected with a lightning endangered line. The connection length between the arrester and the cable should be at most 1 m. The numerical values are valid for an arrester with U_{pl} = 4 p.u. and I_n = 10 kA.

and km cable length [19]. The continuous voltage to be chosen for the arrester which protect the cable sheath results from:

$$\boldsymbol{U}_\mathbf{c} \geq \frac{\boldsymbol{U}_\mathbf{i}}{\mathbf{T}} \times \boldsymbol{I}_\mathbf{K} \times \boldsymbol{L}_\mathbf{K} \text{ in kV, with}$$

I_K: Maximum 50 Hz short circuit current per phase in kA
L_K: Length of the unearthed cable section in km
U_i: Induced voltage occurring along the cable sheath in kV
T: Resistance of the arrester against temporary overvoltages according to TOV curve.

With U_i = 0.3 kV and T = 1.28 for a maximum fault clearing time of t = 3 s of the short circuit current, the result is:

$$\boldsymbol{U}_\mathbf{c} \geq \mathbf{0.24} \times \boldsymbol{I}_\mathbf{K} \times \boldsymbol{L}_\mathbf{K} \text{ in kV}$$

MO arresters, which have at least line discharge class 2 are recommended for the protection of cables in medium voltage systems and also for the protection of the cable sheath. Higher line discharge classes may be used with high voltage cables. The arresters should be matched to one another in terms of specific energy absorption and voltage-current characteristics. Recommended in [5] is the use of MO arresters with the same I_n both for the protection of the cable sheath and for the protection of the cable itself.

9.3 Transformers at the end of a cable

According to the directions in Figure 33, a cable of at least 100 m in length is connected on one end to a lightning endangered overhead line. At the other end, a bus bar consisting of the sections a and b connect the cable end with a transformer. The arrester A1 takes over the overvoltage protection on the line side. Both the cable end and the transformer must be protected with an additional arrester when the connecting distance between the two is very long. The following example indicates under what circumstances the arrester A2 offers sufficient overvoltage protection in addition to the arrester A1.

Table 10: Maximum admissible distance a between cable end and transformer according to Figure 33 with b = 0. The cable is connected to a lightning endangered line and protected at both ends with MO arresters (with $U_c = U_s$). The transformer has no additional protection.

MO arrester with U_{pl} = 4 p.u. at I_n = 10 kA	Overhead line with wooden pole		Overhead line with earthed crossarms	
Z_K Ω	30	60	30	60
U_s kV	a m	a m	a m	a m
3.6	100	100	500	500
7.2	45	40	60	55
12	17	12	22	15
17.5	15	9	20	13
24	13	9	18	11
36	7	6	18	11

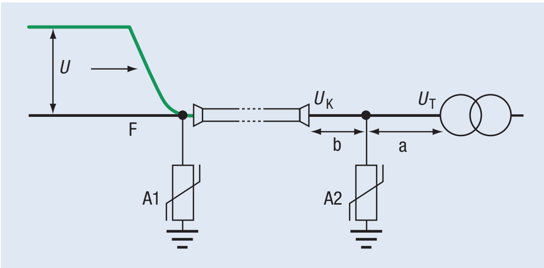


Figure 33: Transformer at the end of a cable

F: Lightning endangered overhead line
U: Incoming lightning overvoltage
K: Cable
A1, A2: MO arrester
a, b: Length of the connection line
U_K: Maximum voltage at the end of the cable
U_T: Maximum voltage at the transformer

The overvoltage reflection *U* at the junction from the line to the cable causes a strong flattening of the voltage steepness in the cable. However, this has practically no influence on the admissible length of the connection *b*, because with the increasing length of *b* the voltage U_K increases very quickly. Therefore, optimal overvoltage protection requires that the arrester A2 should be placed as close as possible to the cable end, in order to shorten the distance *b*.
The line section *a* is different. In this section U_T increases slower with the increasing length of *a*. That is why the transformer is adequately protected even at a relatively far distance from the arrester. The maximum admissible values for *a* are indicated in Table 10. The capacity of the transformer is assumed to be 2 nF. Smaller capacitances result in longer distances of *a*.

9.4 Transformers connected to a lightning endangered line on one side only

Generally, all transformers that are directly linked to lightning endangered lines have to be equipped with arresters between phase and earth. However, if a transformer connects a high voltage system with a medium voltage system, and only the line on the high voltage side is lightning endangered, it is necessary to install an arrester on the medium voltage side as well. Transient overvoltages can be transmitted up to 40 % capacitive from the primary (high voltage side) to the medium voltage side [7]. That is why it is also necessary to install an arrester on the medium voltage side, even though the medium voltage side is not directly endangered by lightning.
The situation is similar with transformers that connect a medium voltage system to a low voltage system. The high frequent overvoltages from the medium voltage side are capacitively transmitted to the low voltage side here as well. Thus, in principle arresters should also be installed on the low voltage side of the medium voltage transformers.
Reported in [20] are failures of medium voltage transformers that had arresters only on the low voltage side. The damages were registered on the medium voltage side with all these cases. The author's opinion is that the overvoltages in this case, as long as they are not transient, are transmitted inductively with the turn ratio.
That is why it is always advisable to install arresters on both sides of all the transformers, particularly in regions with high thunderstorm activity.

The resistive coupling of the overvoltage in a substation is also to be taken into account. Depending on the execution of the earthing at the medium and the low voltage side, overvoltages can be transmitted from one side to the other over the earthing system. In Figure 34 the possible voltage transmissions are depicted in a strongly simplified manner.

The height of the possible transmitted impulse voltage can be roughly estimated with a simple observation.

In a system having a system voltage of $U_s = 24$ kV and an insulated neutral, the MO arrester with a continuous operating voltage of $U_c = 24$ kV is directly connected at the medium voltage bushing of the transformer. This arrester has a typical lightning impulse protection level of $U_{pl} = 78.4$ kV. Therefore, the insulation of the transformer with a lightning impulse withstanding voltage of LIWV = 125 kV is very well protected on the medium voltage side. Though according to **[7]** up to 40% of the voltage that occurs at the bushings is transmitted capacitive to the low voltage side. Thus, a voltage of 31.36 kV can theoretically occur on the low voltage side. The insulation in the transformer is not likely to be endangered, but the bushings on the low voltage side and the connected lines can be destroyed or can spark over.

Let us consider the possible resistive transmission of the overvoltage. The lightning current of $I = 10$ kA peak value flows according to Figure 34 through the arrester and over the earthing resistance R_E to the earth. If we take a typical earthing resistance of $R_E = 10\ \Omega$, a temporary potential increasing of the transformer housing of 100 kV occurs. This potential difference is also to be found on the low voltage side between the conductor and the earthing system. This very simplified examination does not provide an absolute statement about the height of the overvoltages that are transmitted resistively, but explains the problem very well.

Therefore, overvoltages on the low voltage side are to be considered in any case.

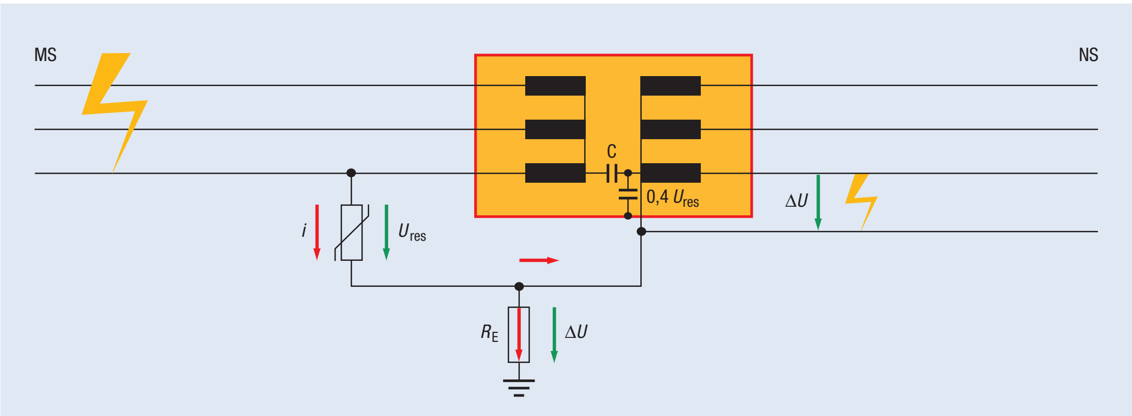


Figure 34: Coupling of a lightning overvoltage through a medium voltage transformer. In addition the coupling in terms of the capacities in the transformer, there is also a resistive coupling through the earthing system of a part of the lightning overvoltage on the respective other side of the transformer. In the described example, the voltage ΔU, which is generated by a part of the lightning current and occurs at the earthing resistance R_E, appears also between the phases and the neutral conductor at the low voltage side.

9.5 Arresters in metal enclosed medium voltage substations

It is often necessary to install arresters in a metal enclosed medium voltage substation. If a cable connects the substation with a lightning endangered line, an arrester with a nominal current of I_n = 10 kA should be installed at the cable bushing.
The conditions are different if the arresters must limit switching overvoltages instead of lightning overvoltages. The former could occur during switching if the inductive current is interrupted before it reaches its natural zero crossing. In addition, vacuum switches can produce high and very steep switching overvoltages. With this kind of switching overvoltages the current load of the arrester is low, so that an arrester with a high current impulse of I_{hc} = 65 kA is sufficient.

9.6 Generator connected to a lightning endangered MV line

If a loaded generator is suddenly disconnected from the system (load rejection), its terminal voltage increases until the voltage regulator readjusts the generator voltage after a few seconds. The relationship between this temporary overvoltage and the normal operating voltage is called the load rejection factor δ_L. This factor can reach a value of up to 1.5. In the worst case, the arrester could be charged with a temporary overvoltage of $U_{TOV} = \delta_L \times U_s$, which must be taken into account when choosing U_c:

$$\boldsymbol{U_c} \geq \frac{\boldsymbol{\delta_L \times U_s}}{\mathbf{T}}$$

The duration t of U_{TOV} determines T and lies in a range from 3 to 10 seconds. The high operational safety requirements for generators make it advisable to use arresters with low residual voltage U_{res} and high energy handling capability W'. That is why the arresters of the type POLIM-H…N are recommended for generator protection.

With the help of an example the U_c of an arrester for the generator protection should be determined.
With U_s = 24 kV, load rejection factor δ_L = 1.4 and t = 10 s results for the type POLIM-H…N:

$$\boldsymbol{U_c} \geq \frac{\mathbf{1.4 \times 24\ kV}}{\mathbf{1.31}} = \mathbf{25.6\ kV}$$

In this way, the type POLIM-H 26 N can be chosen for this case.
Generators have a large capacity between conductor and earth. As a large capacity can lead to a shortening of the protection distance, it is especially important to place the arrester close to the generator terminals.

9.7 Protection of motors

High voltage motors can be over-stressed by multiple restrikes resulting from switching offs during the run-up. This is correct when the cut-off current is less than 600 A. In order to protect these motors, it is necessary to install surge arresters directly at the engine terminals or alternatively at the circuit breaker. The dimensioning of U_c is to be carried out according to the recommendations in Section 7.
It is necessary to use an arrester with a residual voltage U_{pl} as low as possible because of the insulation of the motors, which is generally sensitive to overvoltages, especially if it is aged. That is why arresters should be chosen with an especially favorable U_{pl}/U_c ratio. Under certain circumstances it is possible to use the lowest allowable arrester limit of U_c. However, in no case is U_c allowed to be lower than $U_s/\sqrt{3}$. Typical arresters used for the protection of engines are MWK, or MWD for indoor applications.

9.8 Arresters parallel to a capacitor bank

Normally, no overvoltage occurs when a capacitor battery is switched off. The circuit breaker interrupts the current in the natural zero crossing and the voltage in the capacitors to earth reaches a maximum of 1.5 p.u. As a result of the network voltage varying at the power frequency, a voltage across the open circuit breaker of 2.5 p.u. is caused. A high frequency transient effect takes place between the capacitor voltage and the operating voltage if the breaker re-strikes. During this process the capacitor is charged with a higher voltage [21]. This overvoltage at the capacitor between the conductor and the earth reaches a maximum of 3 p.u.. If the capacitors are connected in a star, then they are discharged by the arrester parallel to battery between conductor and earth. During the discharge up to the voltage of $\sqrt{2} \times U_c$ in terms of power, the arresters are loaded with:

$$W_c = \frac{S_K}{\omega} \times [3\text{-}(U_c/U_s)^2]$$

S_K: 3-phase reactive power of the capacitor battery
W_c: The discharge energy taken up by the arrester

Assuming that the arrester has to carry out this process three times without any cool down phase, it follows with $U_c \geq U_s$:

$$\frac{W_c}{U_c} \geq \frac{6 \times S_K}{\omega \times U_s}$$

The energy consumption capability W of the arrester with U_c has to be thus adjusted to the reactive power of the battery. The maximum admissible reactive power values of the parallel capacitor battery for different arrester types can be found in Table 11.

If the neutral of the capacitor battery is insulated, the arrester cannot discharge the charged capacitor between conductor and earth. This means that the arrester does not get charged. However, it is to be noted that after a re-strike of the breaker, the neutral of the battery increases to 2 p.u. A voltage flashover of the neutral to earth results in the arrester having to discharge the capacitor. Therefore, the arresters parallel to a battery with an insulated neutral have to, in terms of energy handling capability, be adjusted to their reactive power.

If the capacitor battery remains disconnected from the system after a shut-down, the arresters discharge the voltage to zero, not merely to $\sqrt{2} \times U_c$. Below $\sqrt{2} \times U_c$ the discharge current through the arrester is very small, so that the remaining discharge takes a long time. During this time the arrester can cool down. Therefore, it was justified by the above calculation of W_c to take into account only the energy absorbed by the arrester up to the discharge $\sqrt{2} \times U_c$.

If the reactive power of the parallel capacitor battery for a certain arrester type exceeds the limiting values from Table 11, an arrester with higher energy handling capability has to be selected. For systems that are not operated with a standard voltage, the limiting values for S_K are to be found in the column with the lower standard voltage. If the reactive power is very large, arresters connected parallel are to be chosen. In this case, the manufacturer has to be informed in order to take the necessary measures to guarantee a sufficient current distribution between the parallel arresters. The manufacturer should also be consulted when arresters with $U_c < U_s$ are to be used.

9.9 Line traps (parallel protection)

Line traps are air-core coils that are installed in high voltage lines. Their inductivity L is in the range of mH. If no measures are taken, the lightning current in the conductor flows through the trap line. Even relatively small current rates of rise of several kA/µs would produce overvoltages on the line amounting to several 1,000 kV and would lead to a flashover. Arresters are connected to the line trap to prevent this. These arresters take over the lightning currents and limit the overvoltage to its residual voltage U_{res}.

When an earth fault or a short circuit occurs in a high voltage system, the fault current I_K flows through the conductor. This power frequency current would overload the arrester. U_c should therefore be selected so that the short circuit current flows through the line trap. It induces a temporary overvoltage which determines U_c at the line trap:

$$U_c \geq \frac{U_{TOV}}{T} = \frac{\omega \times L \times I_K}{T}$$

I_K: Maximum fault current through the line trap
L: Inductance of the line trap

It may be assumed T = 1.28 for the duration of short circuit current of $t < 3$ s (from TOV curve for the MWK).

9.10 Line arresters

Line arresters are arresters that are installed parallel to insulators on poles along an overhead line. The reason for the use of line arresters is the necessity to avoid short interruptions or outages of the overhead lines due to lightning overvoltages or the necessity to reduce the frequency of their occurrence. As a rule, the line arresters are installed in connection with an additional earthed shielding wire.

Line arresters are used in regions with high thunderstorm activity and a very poor earthing situation.

The continuous voltage U_c for MO arresters that are used as line arresters is to be determined in exactly the same manner as those used for the protection of substations or transformers. Since the line arresters should protect especially against the effects of lightning strokes, it is necessary to dimension them according to the lightning parameters of the respective region (probability, current steepness, charge, a.s.o). As a rule, the line arresters are equipped with disconnectors, so that an arrester that is overloaded can disconnect itself from the system and no earth fault appears.

A special usage of line arresters is the MO arresters with an external series gap. These so-called EGLAs (Externally Gapped Line Arresters) are used in some countries; however, they are not to be found in Central Europe. Figure 35 shows

Arrester type $U_c \geq U_s$	POLIM-D	POLIM-K	POLIM-I MWK/MWD	POLIM-S	POLIM-H
W/U_c in kJ/kV	3.6	5.2	5.5	9.0	13.3
U_s in kV	S_K in MVAr	S_K in MVAr	S_K in MVAr	S_K in MVAr	S_K in MVAr
3.6	0.67	0.97	1.03	1.69	2.50
7.2	1.35	1.95	2.07	3.39	5.01
12	2.26	3.27	3.45	5.65	8.35
17.5	3.29	4.77	5.03	8.24	12.18
24	4.52	6.58	6.90	11.30	16.70
36	6.78	9.81	10.36	16.95	25.05

Table 11: Arrester parallel to a capacitor bank. Maximum admissible reactive power S_K of the capacitor battery for the indicated arrester type. Three discharges of the battery are allowed without a cool down phase for the arrester.
W/U_c: The arrester energy absorption capability in relation to U_c.

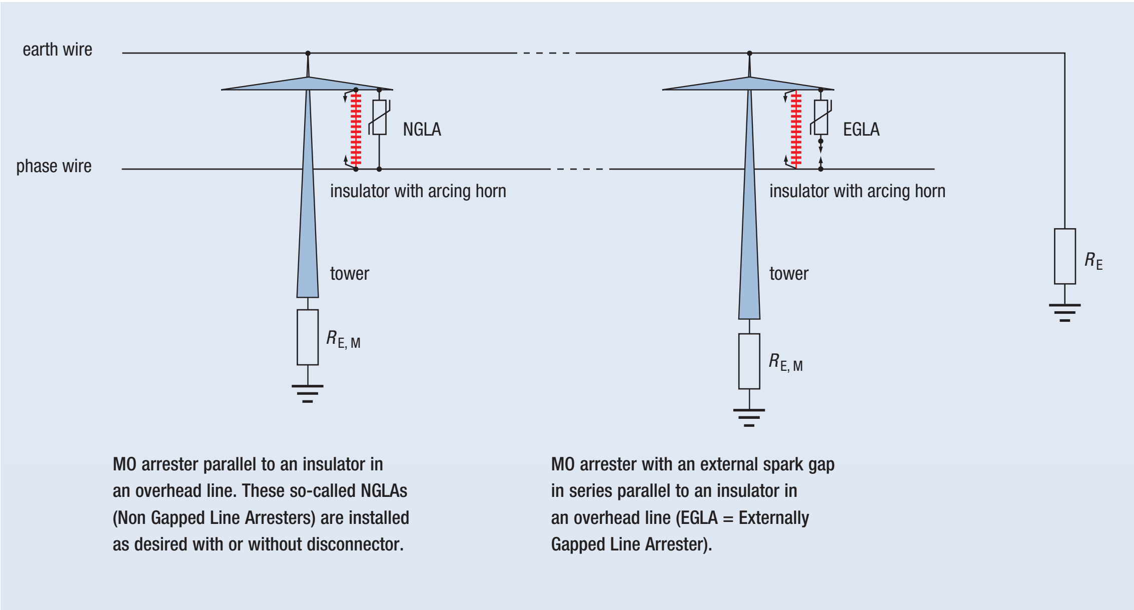
in principle the arrangement of an EGLA. The problem lies in the coordination of the spark-gap in series with the MO arrester and the spark-gap parallel to the insulator to be protected, and also the residual voltage of the used MO arrester. The application guidelines and the tests for the line arresters, especially for EGLAs are still being discussed in the committees.

9.11 High lightning arresters

It is assumed that in high voltage systems the arresters are not stressed by direct or nearby lightning strokes. In medium voltage systems the arresters can be stressed by direct or close strokes under certain circumstances such as on the poles, because these kinds of systems have hardly any earthed shielding wires. In such cases, they must withstand at least a part of the lightning current.

Arresters for high lightning current stresses in the voltage range of 1 kV to 52 kV need to be tested with a special operating duty test according to **[4]**. The required energy used as a proof for the thermal stability is to be injected with switching current impulses instead of long-duration current impulses. The specific energy handling capability of a MO arrester for lightning current stresses in medium voltage systems roughly corresponds to that of a MO arrester of the line discharge class 5 or above it, as it is recommended for transmission systems with a voltage system of U_s = 765 kV **[5]**.

Figure 35: Possible execution of line arresters (description in principal).



10 | ARRESTERS FOR D.C. VOLTAGE

In principle, in d.c. voltage systems there also appear overvoltages produced by lightning or switching activities, which may endanger the equipment and the insulation. In this case, it is also necessary to use an arrester as a protection against overvoltages. The MO surge arresters without spark gaps are particularly suitable, because they do not conduct any follow current after the limiting of the overvoltage, except a leakage current of a few µA, and therefore it is not necessary to extinguish any d.c. current arc. It is to be observed that only MO resistors with long-term stability in case of d.c. voltage stress are to be used for MO arresters in d.c. voltage systems (see Chapter 3.4.2). It goes without saying that all the type tests using continuous voltage should be performed with d.c. voltage.
The typical d.c. voltage stresses are to be found in the high voltage d.c. transmission (HVDC). Comments concerning the choice and the usage are to be found in **[22]**. There is currently no IEC or CENELEC standard for testing MO arresters used in HVDC installations. That is why it is always necessary to get into contact with the manufacturer if MO arresters are to be used in HVDC installations.

The d.c. voltage systems are broadly used for traction systems. The nominal voltages in the public d.c. traction systems lie between U_n = 750 V and U_n = 3,000 V. It is necessary to observe both the high electrical requirements for MO arresters in the traction systems as well as the mechanical and safety relevant requirements. ABB Switzerland Ltd has been certificated according to International Rail Industry Standard (IRIS) since November 2007. The MO arresters produced by ABB Switzerland Ltd also fulfill all requirements of the VDV recommendation 525 **[23]**.
A separate application guideline for MO arresters used in traction systems was written, taking into consideration the importance of an optimal overvoltage protection and the special conditions in traction systems **[24]**.
Additional d.c. voltage applications are to be found in converter stations, drives and in photovoltaic systems. It is absolutely necessary to get into contact with the manufacturer if MO arresters are to be used in such installations.

11 | ARRESTERS FOR DIFFERENT FREQUENCIES

Beside the system frequency of f = 50 Hz and f = 60 Hz, the "railway frequency" of f = 16.7 Hz has also technical importance. MO arresters without spark-gaps can be used without any problem with these frequencies. It is to be noted that the continuous current i_c will change with the frequency because the MO arrester behaves in an almost purely capacitive manner considering the continuous voltage. Because of

$$X_c = \frac{1}{\omega \times C}$$

X_c = Capacitive impedance
ω = $2 \times \pi \times f$ = angular frequency
C = Capacity of the MO arrester

the capacitive impedance becomes smaller with increased frequency and consequently the capacitive current increases with increasing frequency. Table 12 gives as an example the power losses P_V and the continuous current i_c for various frequencies.

Frequency f in Hz	60	50	16.7
Power losses P_V in W	1.32	1.2	0.6
Continuous current i_c in mA, rms	0.44	0.36	0.12

Table 12: Typical power losses P_V and continuous current i_c frequency dependant for a MO arrester with U_c = 20 kV and line discharge class 2.

The dimensioning and application of MO arresters for railway systems with f = 50 Hz and f = 16.7 Hz is precisely described in [24]. The manufacturer should be contacted if the MO arresters are to be used for frequencies higher than 60 Hz.

12 | MO ARRESTERS IN PARALLEL CONNECTION

The arresters are considered generally as single devices, i.e. they fulfill their task in the place in which they are installed according to their specified data, independent of other nearby devices. That is why it is possible in principle to install different kinds of arresters close to one another on a phase wire in the system. However, it is necessary to take into consideration that according to different ways of functioning some arresters may become useless while others may become overstressed, such as in cases when arresters with spark-gaps and without spark-gaps are installed in parallel, or when MO arresters with different voltage-current-characteristics are used in parallel. Deliberate parallel connections of MO arresters are made if the energy absorption should be increased, the residual voltage should become a little lower or if the energy absorption and the residual voltage should be deliberately dimensioned in a different way.

12.1 Parallel connection to increase the energy handling capability

Two or more MO arresters can be connected in parallel in order to increase the energy handling capability if during an application the energy occurring cannot be handled by a single MO arrester. The requirement for an equal current sharing and consequently an even energy sharing between the arresters is the fact that the arresters have to have almost identical voltage-current-characteristics. In view of the extreme non-linearity of the MO resistors, small differences in the residual voltage in the area of switching current impulses bring big differences in current. With a nonlinearity coefficient of $\alpha \approx 30$ in the region of switching current impulses on the voltage-current-characteristic, a difference of 5 % in the residual voltage would lead to a current sharing ratio of 1:4 between the surge arresters.

Therefore, it is absolutely necessary to perform a current sharing measurement on all MO arresters that are to be intended to work in parallel. The manufacturer has to be informed when the order is made if the user intends to connect MO arresters in parallel. It is also to be noted that the arresters are to be installed close to one another and are to be connected together with short connections of low inductance. If this is not taken into consideration, then there may appear separation effects, which lead to an uneven current sharing and consequently to an overstress of one of the arresters.

The parallel connection of MO arresters has, besides the sharing of the current over more arresters, the positive effect of a better, i.e. a lower protection level. This is because the current density per arrester becomes lower in view of current sharing and consequently a lower residual voltage occurs. If, for instance, two arresters having a total current of 10 kA with a wave shape of 8/20 µs are installed in parallel, a residual voltage occurs at the parallel connection, which corresponds to a current of 5 kA with 8/20 µs for a single arrester.

It is to be strongly emphasized that it is always better to use a MO arrester with a larger MO resistor diameter than to connect more MO arresters in parallel with smaller MO resistor diameters.

12.2 Coordination of parallel connected MO arresters

In some cases it is necessary or advantageous to use two arresters in an installation separated from one another in space, but electrically parallel on the same line. This is, for instance, the situation when in view of the distances in a substation one of the arresters is installed at the entrance of the station and another arrester is placed directly in front of the transformer, at a certain distance. In such a case, two arresters of the same type and with the same continuous voltage may be used.

In case of an incoming overvoltage both arresters will discharge a part of the current towards the earth and will provide very good overvoltage protection. However, it is not to be assumed that the energy occurred will be uniformly shared.

MO arresters of different types or of the same type with different characteristics that are matched to one another are used deliberately if an uneven sharing of the energy absorption is intended. This is the case, for example, in stations in which the transformer is connected through a cable to the overhead line, see Figure 36. An arrester is installed on the pole at the junction of the overhead line to the cable and this arrester has a higher energy absorption capability and a lower residual voltage characteristic than the arrester in the station in front of the transformer. The effect of this is that the largest part of the energy is absorbed by the arrester outside on the pole and at the same time the voltage is limited as much as possible. Thus, the arrester in the station has to discharge only a small part of the current and at the same time protects the transformer against overvoltages due to reflections. In practice, this principle can be used by choosing two MO arresters

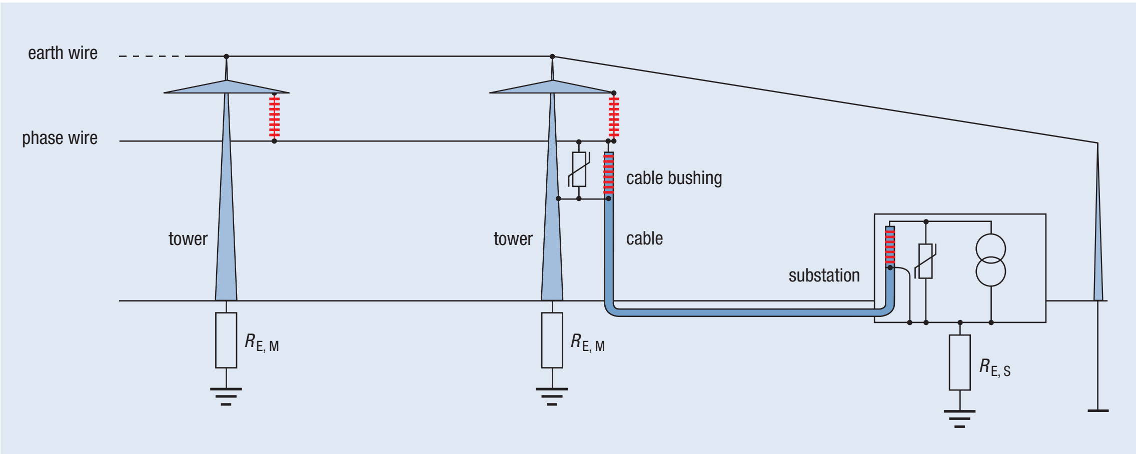


Figure 36: Arrangement of two MO arresters to protect a station with cable entry. The MO arrester on the pole directly at the cable bushing is, for example, a MWK 20 with a U_{pl} = 61,4 kV, the arrester in the station, for example, a POLIM-D 20 with U_{pl} = 70 kV. This coordination of residual voltage and the energy handling capability makes it possible that the larger amount of the current is discharged against the earth on the exterior of the station. In case of an unfavorable ground situation or in extreme lightning endangered regions the installation of an earth wire for some span width in front of the station is recommended.

of the same type, such as MWK with the line discharge class 2; the arrester in the station has a continuous operating voltage U_c of about 10% higher than the arrester outside on the pole.

The same result is reached if two MO arresters with the same continuous operating voltage U_c, but of different types are installed, such as a MWK of line discharge class 2 on the pole and a POLIM-D of the line discharge class 1 in the station in front of the transformer.

Taking into consideration the smaller cross-section of the MO resistors of the POLIM-D compared to MWK, its residual voltage characteristic lies automatically higher than the one of the MWK. In English speaking countries, the arrester on the pole is described as a "riser pole" arrester. This is not a type description for an arrester, but specifies the installation place, which is the place where the cable is rised up on the pole and where it is connected with the overhead line.

12.3 MO arresters and arresters with gaps in parallel

There is no technical reason why MO arresters should be intentionally connected in parallel with SiC arresters with spark gaps. If older SiC arresters with spark gaps were installed in a system and MO arresters are additionally installed in the course of the development of a station or for other reasons, the arresters work independently from one another. However, it is recommended to install in a substation only arresters of one type or at least with the same operational principle. In case of a parallel connection of SiC arresters with spark gaps and MO arresters, there is no current sharing between the two arresters. The MO arrester discharges the current and limits the voltage before the SiC arrester will be activated. Therefore, the MO arrester protects the SiC arrester and takes over the entire energy, the SiC arrester is ineffective.

13 | COORDINATION OF INSULATION AND SELECTION OF ARRESTERS

The coordination of the insulation is the matching between the dielectrical withstand of the electrical equipment taking into consideration the ambient conditions and the possible overvoltages in a system.

For economic reasons, it is not possible to insulate electrical equipment against all overvoltages that may occur. That is why surge arresters are installed to limit the overvoltages up to a value that is not critical for the electrical equipment. Therefore, a MO arrester ensures that the maximum voltage that appears at the electrical equipment always stays below the guaranteed withstand value of the insulation of an electrical device.

In **[1]** and **[7]** the basic principles and the methods of the insulation coordination are depicted in detail; **[5]** lists general guidelines for the selection and application of MO arresters that are used to protect different electrical equipment on all voltage levels.

Described in the following paragraphs are the basic principle of the connections and the most important criteria for choosing the MO arresters in medium voltage systems, see also Figure 37.

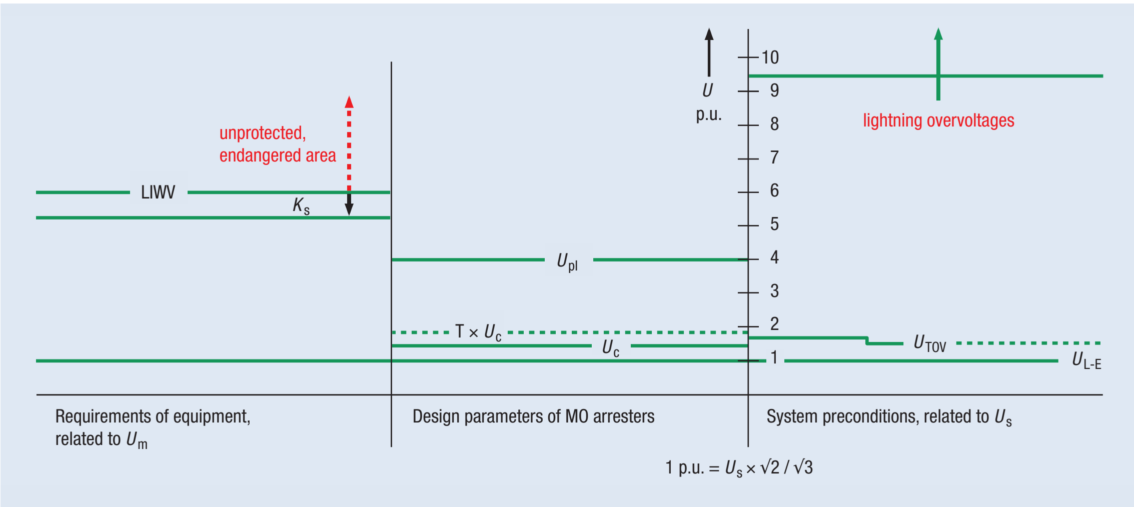
An arrester has to fulfill two fundamental tasks:

- It has to limit the occurring overvoltage to a value that is not critical for the electrical equipment and
- It has to guarantee a safe and reliable service in the system.

The choice of the continuous operating voltage U_c is described in detail in Section 7. The following paragraphs briefly deal with the necessary energy handling capability and the protection characteristic of MO arresters in medium voltage systems.

The continuous operating voltage U_c is to be chosen in such a way that the arrester can withstand all power frequency voltages and also temporary overvoltages without being overloaded in any possible situation. This means that $T \times U_c$ has to be always higher than the maximum possible temporary overvoltages U_{TOV} in the system.

Figure 37: Comparison of the possible occurring voltages in the system, the withstand voltages of the electrical equipment and the parameters of the MO arrester. The lightning overvoltages are decisive in medium voltage systems. That is why are shown only the parameters for the lightning overvoltages.



Comment: Ferromagnetic resonances are the exception. The ferromagnetic resonances can become so high and exist so long that they may not be taken into consideration by the dimensioning of the continuous voltage if the arrester should still be able to fulfill its protection function in a meaningful way. If ferromagnetic resonances appear, then this generally means that the arrester is overloaded. The system user should take the necessary measures to avoid ferromagnetic resonances.

The MO arrester can fulfill its function of protection properly if the lightning impulse protection level U_{pl} lies clearly below the lightning impulse withstanding voltage (LIWV) of the electrical equipment to be protected, the safety factor K_s is also to be taken into consideration. The point is to set the voltage-current characteristic of the arrester in a way that both requirements are met.
The lightning impulse withstand voltage (withstand voltage of the insulation) is relatively high compared to the system voltage, as can be seen in Figure 37, which shows a typical medium voltage system with U_s = 24 kV. This automatically results in a large distance between the maximum admissible voltage at the electrical equipment to be protected and the lightning impulse protection level; see also Table 7.
As mentioned above, it makes sense to choose the continuous voltage U_c a little bit higher than was calculated (for instance 10 %). As a rule, there is enough distance between the maximum admissible voltage at the electrical equipment and the protection level of the arrester.

13.1 Nominal discharge current I_n and line discharge class

As previously mentioned, the lightning current parameters are taken from lightning statistics and the line discharge classes result from the energy that is stored in the loaded transmission lines. As explained above, the line discharge classes have no direct significance in medium voltage systems; however, they are used to specify the energy handling capability that is required for an arrester. Therefore, it is necessary to know the possible energy stores in a system, such as cables, capacitors or capacitors banks and inductivities. If the possible stored energy can be calculated, the value can be assigned to a line discharge class.

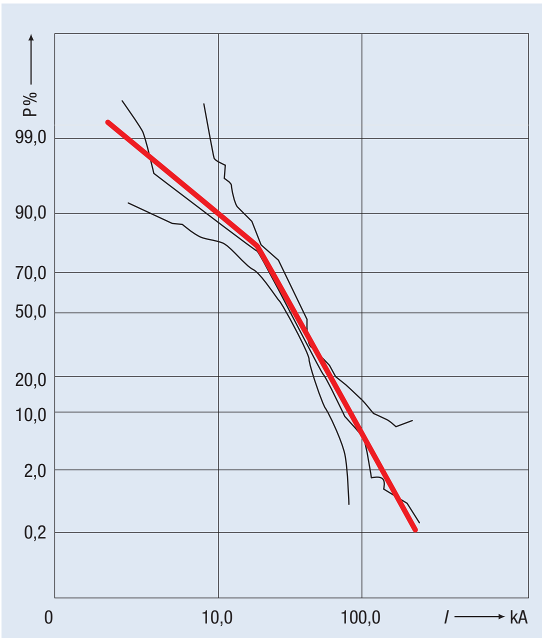


Figure 38: Statistical evaluation of lightning measurements all over the world. Described is the probability of occurrence above the lightning currents' peak values.

Figure 38 shows a statistic evaluation of all the measured lightning currents [10] [13]. The curve of the mean value shows the probability of the occurred lightning current peak values. The probability of reaching or exceeding 20 kA is 80 %, whereas the lightning currents with peak values of over 100 kA are very rare. The specified lightning currents and the high current impulses are derived from these lightning current statistics. Assuming that a lightning current diverts in case of a direct stroke and that half travels along the line in one direction as a traveling wave, one gets the well-known nominal discharge current of I_n = 10 kA. The wave shape of approximately 8/20 µs results for the lightning current if a flashover occurred at one of the insulators.

The nominal discharge current can be chosen according to the thunderstorm activity in a region or the expected threat of lightning to a substation. In this way, the requirements for the defined arresters can be clearly specified together with the line discharge class (see also Chapter 7.2.). MO arresters with I_n = 10 kA and line discharge class 1 or 2 are used in standard applications in medium voltage systems.

Higher nominal discharge currents (I_n = 20 kA) and higher line discharge classes (3 to 5) are chosen only in special cases in medium voltage systems, such as:

- in regions with extreme thunderstorm activities and the danger of direct lightning strikes (arresters for high lightning current stresses)
- with overhead lines at concrete poles or wooden poles and crossarms that are not earthed
- with arresters placed at locations where persons are often to be found (for instance in railway systems and on the electrical traction system)
- in lines, which demand exceptional high safety standards for the working process
- for protection of motors, generators and cables
- with an arc furnace
- with big capacitor batteries.
- with very long cable lengths
- with expensive rotating machines

It also bears mentioning that particularly with negative cloud-earth lightning 3 to 4 single discharges per lightning typically occur, each 30 to 50 ms apart from one another. Research shows that these stresses are not critical for the MO arrester, but in case of inadequate coating of the MO resistors or incompletely molded arresters, some surface problems can appear, such as flashovers along the active part **[25]**. These so-called multi-pulses have no influence over the choice of the nominal discharge current or the line discharge class. An optional operating duty test with multi-pulses is described in the Australian standard **[26]**.

13.2 Protection level

The switching impulse protective level U_{ps} is decisive for the coordination of the insulation in transmission systems of higher system voltages. It is less important in the medium voltage systems discussed here. Of prime importance here is the lightning impulse protection level U_{pl} and if necessary, the protection level at steep current impulse, such as when vacuum breakers are in the system.

Generally speaking, the protection level should be as low as possible to ensure optimal protection. As previously emphasized more than once, the operational safety of the arrester in the system is always to be preferred to the complete exploitation of the protection level. These opposing requirements are mainly uncritical in the medium voltage systems, as explained in Figure 37.

The protection ratio U_{pl}/U_c is fundamentally important. The smaller the ratio, the lower the protection level with the same U_c and the better the protection. If a very low protection level is technically absolutely necessary in a specific case, it is possible to choose an arrester with a better protection ratio. As a rule, this is an arrester with a higher line discharge class, because these arresters have MO resistors with a larger diameter as an active part (see also Tables 1 and 2). The choice of a MO arrester with the same U_c, but a higher line discharge class offers better protection in the system although the operational safety stays the same and it also provides a higher energy handling capability. Moreover, a MO arrester with a lower protection level always provides a larger protection distance.

Therefore, the choice of an arrester or the comparison of different products should also take into consideration the protection ratio U_{pl}/U_c in addition to the nominal discharge current and the energy handling capability. In this context, the temporary overload capability of the MO arrester with temporary overvoltages should also be observed. A high resistance towards temporary overvoltages generally means that the voltage-current characteristic of a MO arrester was set so high that all power frequent overvoltages that occur do not fundamentally exceed the knee point of the u-i characteristic. However, this means that the residual voltage of a MO arrester lies correspondingly high, which causes an unfavorably high protection level.

13.3 Examples

The procedure of the defining of a MO arrester is shown using some typical, but arbitrarily chosen examples:

In [4], Annex G, there are the specifications that are necessary for the definition of an arrester. The most important and the most necessary specifications for the defining of an arrester for medium voltage systems are:

- Highest system voltage U_s
- Power frequency
- Treatment of the transformer star point
- Maximum duration of the earth fault
- The electrical equipment to be protected (transformer, cable, capacitor bank, generator, etc.)
- Insulation level (lightning impulse withstanding voltage) of the electrical equipment to be protected
- Ambient conditions, if they differ from the normal ambient conditions
- Nominal discharge current and the line discharge class

Typical values are assumed for the defining of an arrester if there are none or only a few specifications given.

13.3.1 System with insulated star point

Supplied information

- Overvoltage protection of a substation in an overhead line system
- Medium pollution.
- U_s = 12 kV
- Star point insulated

Without other specifications it is assumed

- U_m = 12 kV
- LIWV = 75 kV
- Duration of earth fault > 30 min, i.e. continuous operation
- Nominal discharge current I_n = 10 kA
- Line discharge class 1
- Short circuit current of the system I_s = 20 kA
- Degree of pollution II (medium)

This results in

The choice of the continuous voltage according to Chapter 7.1.1:

$$\boldsymbol{U_c \geq U_s}$$

With 10 % safety margin for U_c results $U_c = 1.1 \times U_s = 13.2$ kV.
Thus it results an arrester with U_c = 14 kV.

The control of the protection level

It must be

$U_{pl} \leq \text{LIWV}/K_s$

This results in

With K_s = 1.2:
75 kV/1.2 = 62.5 kV as the maximum admissible voltage at the electrical equipment.
Because I_n = 10 kA and line discharge class 1 a MO arrester of the type POLIM-D with U_{pl}/U_c = 3.5 is chosen.

This results in

U_{pl} = 49 kV
The requirement $U_{pl} \leq \text{LIWV}/K_s$ is clearly fulfilled in this way. The demand for a short circuit current of I_s = 20 kA is also met by the type POLIM-D.

20 mm creepage distance per kV system voltage is recommended with a pre-determined degree of pollution “medium”.
Thus, a minimum creepage distance of
U_s × 20 mm/kV = 12 kV × 20 mm/kV = 240 mm results.
The creepage distance can be reduced with 20% with a MO arrester having silicon housing, which results in a necessary minimum creepage distance of 192 mm.
According to the POLIM-D datasheet, this results in a **POLIM-D 14-05** arrester.
The arrester housing has a creepage distance of 460 mm and is absolutely sufficient.

The minimum necessary withstand value of the empty arrester housing is calculated according to IEC:
Lightning impulse voltage 1.2/50 µs:
1.3 × U_{pl} = 1.3 × 49 kV = 63.7 kV
a.c. voltage test 1 min, wet:
1.06 × U_{ps} = U_{test}, sw = 41.1 kV, sw.
This results in a withstand value of
41.1 kV / √2 = 29 kV, rms, 1 min, wet.
The proved withstand values according to the datasheet are:
Lightning impulse voltage 1.2/50 µs: 140 kV
a.c. voltage test:
38 kV, rms, 1 min wet.
Therefore, the housing of POLIM-D 14-05 has significant higher withstand values as the minimum requirements according to IEC.

13.3.2 System with direct star point earthing

Supplied information

- Overvoltage protection in a cable system
- System voltage U_s = 24 kV
- Directly earthed star point

Without other specifications it is assumed

- U_m = 24 kV
- LIWV = 125 kV
- Duration of the earth fault ≤ 3 s, i.e. immediately switching off
- Nominal discharge voltage I_n = 10 kA
- Line discharge class 2, provides a favorable, i.e. a low protection level for a cable with high energy handling capability.
- Short circuit current of the system I_s = 20 kA
- Degree of pollution I (low)

This results in

The choice of the continuous operating voltage according to Chapter 7.1.3:

$$\boldsymbol{U_c} \geq \frac{\mathbf{1{,}1} \times \boldsymbol{U_s}}{\sqrt{\mathbf{3}}}$$

With 10% additional safety margin for U_c,
this results in: U_c = 15.2 kV × 1.1 = 16.8 kV.
Which results in arrester with U_c = 17 kV.

Control of the protection level

This must be

U_{pl} ≤ LIWV/K_s.
With LIWV = 125 kV and K_s = 1.2 this results in
U_{pl} ≤ 125 kV / 1.2 = 104.2 kV.
A lower protection level is especially important for the protection of cables (slowing down of insulation ageing, etc.). That is why a MO arrester of the type MWK with U_c = 17 kV with U_{pl}/U_c = 3.07 is chosen.
According to the datasheet, U_{pl} = 52.2 kV results for the **MWK 17.**
Therefore, the MWK 17 has an outstanding low protection level, which is especially important for the protection of cables.
The MWK meets the demands for a short circuit current of 20 kA.

According to the assumption there is only low pollution to be taken into account, the creepage distance is 16 mm/kV. This results in a minimum requirement of 384 mm creepage distance. With a silicon housing and a low pollution (degree of pollution I), the creepage distance can be reduced by 30 %. This ultimately results in a creepage distance of 269 mm. The MWK 17 has a creepage distance of 492 mm according to the datasheet and offers large reserves here as well.
The withstand values of the empty housing required, according to IEC and proved for the MWK 17, are:
Lightning voltage impulse 1.2/50 µs:
67.9 kV => tested 152 kV
a.c. voltage test 1 min, wet:
31.4 kV => tested 50 kV
Therefore the **MWK 17** meets all the requirements with large safety margins and guarantees a safe system operation and an outstanding protection.

13.3.3 System with earth fault clearing

Supplied information

- Transformer protection in an outdoor station
- Height of installation 3,600 m
- High thunderstorm activity, seasonally dependent
- System voltage U_s = 24 kV
- Star point high ohmic insulated with earth fault clearing after a maximum of 60 s

Additional assumptions

- U_m = 24 kV
- LIWV = 125 kV
- Duration of the earth fault t = 60 s
- Nominal discharge current I_n = 10 kA
- Line discharge class 2, because of increased thunderstorm activity
- Short circuit current of the system I_s = 20 kA
- Degree of pollution I (low)

This results in

The choice of the continuous operating voltage according to Chapter 7.1.2:

$$\boldsymbol{U_c \geq \frac{U_s}{T}}$$

The type POLIM-K is chosen with the assumption of line discharge class 2 on the basis of increased thunderstorm activity. For t = 60 s, this results in a factor of T = 1.225 out of the TOV curve.
The continuous voltage is thus calculated as:

$$\boldsymbol{U_c \geq \frac{24\ \mathrm{kV}}{1{,}225} = 19{,}6\ \mathrm{kV}}$$

With a reserve of 10% this results in:
U_c to 21.6 kV.

Therefore, chosen is a
POLIM-K with U_c = 22 kV

Control of the protection level

Required is

$U_{pl} \leq \mathrm{LIWV}/K_s$
With LIWV = 125 kV and K_s = 1.2, the maximum voltage at the electrical equipment results in 104.2 kV.
The POLIM-K 22 has a U_{pl} of 73.3 kV and meets the demands with a good additional safety margin.
According to the assumption, there is only low pollution to be taken into account, therefore the creepage distance is 16 mm/kV. This results in a minimum requirement of 384 mm creepage distance. With a silicon housing and a low pollution degree, the creepage distance can be reduced by 30 %. This ultimately results in a creepage distance of 269 mm.
The POLIM-K 22-04 has a creepage distance of 770 mm according to the datasheet and offers large reserves here as well.

The minimum necessary withstand values of the empty arrester housing are calculated according to IEC as:
Lightning voltage impulse 1.2/50 µs:
$1.3 \times U_{pl} = 1.3 \times 73.3$ kV = 95.3 kV
a.c. voltage test 1 min., wet:
$1.06 \times U_{ps} = U_{test}$, sw = 59.7 kV, sw.
This results in a withstand value of
59.7 kV / √2 = 42.2 kV, rms, 1 min, wet.
The proved withstand values according to the datasheet are:
Lightning discharge voltage 1.2/50 µs: 200 kV
a.c. voltage test:
54 kV, rms, 1 min wet.
Therefore, the housing of POLIM-K 22-04 has higher withstand values than are required according to IEC.
Taking into consideration the installation height of 3,600 m, it must be checked whether an extension of the arrester housing is necessary. The housing should be lengthened with 12% per 1,000 m above an installation height of 1,800 m, which means that a corresponding higher withstand voltage must be proved. Thus, at 3,600 m it must be corrected by 22%.
For the minimum required withstand voltage, this results in:
Lightning discharge voltage 1.2/50 µs:
95.3 kV. An increase of 22% results in
116.3 kV.
a.c. voltage tests 1 min., wet:
42.2 kV rms. An increase of 22% results in
51.5 kV rms.
Both calculated values according to the height correction lie below the proved withstand values. Therefore, it is not necessary to extend the housing.
The POLIM-K is tested with a short circuit current of 40 kA and easily meets the demands for a short circuit current of 20 kA.
The **POLIM-K 22-04** is the right arrester from all points of view for this application.

13.4 Economic considerations

To reach an appropriate overvoltage protection in medium voltage systems, it is necessary to find the best compromise between the costs and the benefits of the protection devices to be used. An optimized technical-economic balance is to be striven for.
The overvoltage protection, which is accurately applied, reduces:

- Outages of lines and substations
- Interruptions of critical manufacturing processes, which demand good voltage stability
- Costs due to interruptions in the energy supply
- Costs for the replacement and repair of electrical equipment
- Ageing of the insulation (e.g. cables)
- Maintenance work
- Etc.

The aim of overvoltage protection is to guarantee an uninterrupted supply of electrical energy with good voltage stability to the greatest degree possible.
In [27] and [28] is reported that according to extensive studies, breakdowns of medium voltage transformers in critical regions could be drastically reduced with an optimized use of surge arresters.
Therefore, the costs for a set of surge arresters are not the most important consideration, but the costs that may arise on a long-term basis if adequate overvoltage protection is not used.

14 | ASSEMBLY AND MAINTENANCE

Information about the assembly and installation, maintenance, transport, storage and disposal of MO arresters is to be found in the operating instructions (manual) for each surge arrester.
There are some points to be especially observed so that a MO arrester can fulfill correctly its function.

14.1 Connections

The national specifications and the requirements of the system user are in principle to be observed for the connections. However, the diameter of the connections must be chosen in such a way that at least the short circuit current for the respective arrester (for the given short circuit current duration) does not lead to the melting or the tearing off of the connections. This applies both to the overvoltage connections as well as the connections to the earth.
The connections must be installed as short and straight as possible. This is because inductive voltages appear at each conductor due to the self inductivity during the flowing of the impulse current. These induced voltages are considerable during high rate of changes di/dt, such as when lightning currents occur. The MO material itself reacts almost instantaneously even with very steep voltage and current impulses [29]. In view of the dimensions of the arrester itself and the connections, there are always inductive voltages and it is necessary to take them into account with a steep current impulse [4]. The specified residual voltages, which are to be found in the datasheets, are always the voltages between the arrester terminals only; for explanations see also Figure 39.

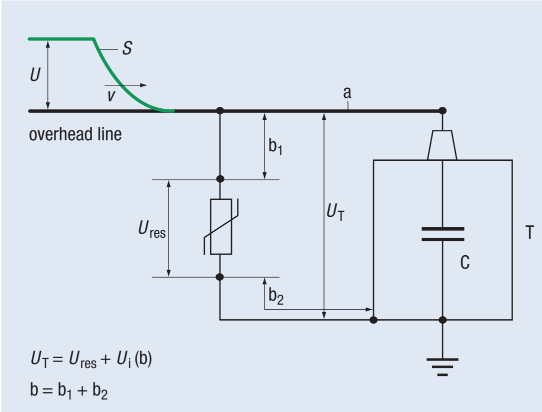


Figure 39: Typical arrangement of a transformer with a connected arrester. The inductive voltage U_i of the entire connection lengths is added to the residual voltage U_{res} of the arrester.

The additional inducted voltage is consequently calculated as:

$$U_i = L \times di/dt$$

An approximate inductive voltage of U_i = 1.2 kV per meter connection line results from an inductivity of L = 1 µH for a straight wire of 1 m length and a lightning current of 10 kA peak value of the wave shape 8/20 µs.
A voltage of U_i = 10 kV per meter connection line results from a steep current impulse with a rise time of 1 µs and 10 kA peak value. This means that the connections and the entire loop must be executed to the greatest degree possible without inductivity. It goes without saying that the arrester and the transformer must be connected at the same earthing point.

Earth resistances should be as small as possible. A value of $R_E \leq 10\ \Omega$ is considered to be sufficient. Earth resistances are measured mainly with d.c. current or 50 Hz a.c. current; however, in case of high frequency (or current impulse with high frequency content) the value may be much higher. That is why specially executed earthing installations are used in order to discharge the current impulse.

14.2 Maintenance

The MO arresters with direct sealed silicon housing do not have any parts that are subject to wear and are free of maintenance. Additionally, the pollution of the silicon housing does not have a negative influence on the insulation resistance of the housing. The arrester can be cleaned if the pollution is very strong. For the cleaning the use of abrasive cleaning materials or solvents are not recommended. The best way to clean silicon surfaces is with clear warm water and a soft cloth that does not make any fluff. This arrester should not be treated with silicon grease or oil after cleaning.

As part of a general control of the substation or installation a visual inspection of the arrester is sufficient. Included in such an inspection should be:

- the surge counter and the mA-meter, if installed,
- the housing, to see if it has any cracks or other damage,
- the connections, including disconnectors, if any.

14.3 Onsite measurements

Each MO resistor and each MO arrester are tested in the factory in the course of routine tests. On-site measurements of the arresters are not necessary before they are built into an installation.

If due to special reasons, such as after a failure (earth fault or short circuit) in the installation or as part of a routine control of all the electrical equipment, the verification of the correct functioning of the arrester is to be performed, then the arrester is to be disconnected from the system and brought to a specially equipped lab where it can be tested by trained specialists. In this situation, it is necessary to obtain from the manufacturer the information about the parameters to be proved and the equipment needed. The best solution is to send the arrester back to the factory and to have the routine tests repeated there.

On-site measurements with a “megger” or simple resistance measurements with an ohmmeter do not provide reliable and sufficient information about the condition of the arrester.

In this context, it is to be noted that when insulation measurements are being made in an installation or station, the arrester must be disconnected from the system. Otherwise, the measurement can be incorrect or lead to false conclusions. In such a situation it is also possible that the arrester may be destroyed.

15 | DISCONNECTORS

The disconnectors are used for automatically disconnecting a surge arrester that has been overstressed. The disconnectors are generally placed on the earth side directly under the arrester. In such cases, the arrester is installed on an insulating bracket; see also the example in Figure 32. The earth connection must be flexible and it is necessary to have sufficient distance beneath the arrester, so that the disconnected earth connection can hang freely and the applied operating voltage that occurs at the foot of the arrester does not lead to spark-over. Figure 40 shows an arrester that was overstressed and consequently disconnected.
The purpose of disconnectors is to prevent overstressed arresters from leading to a permanent short circuit resulting in the switching off of the system. It is thus possible to continue to supply consumers with electrical energy. This is surely an advantage in inaccessible areas or if the overstressed arrester cannot be quickly replaced. The disadvantage is that there is no overvoltage protection as long as the arrester is disconnected. That is why it is important to replace the arresters that are out of order and were disconnected from the system as quickly as possible.

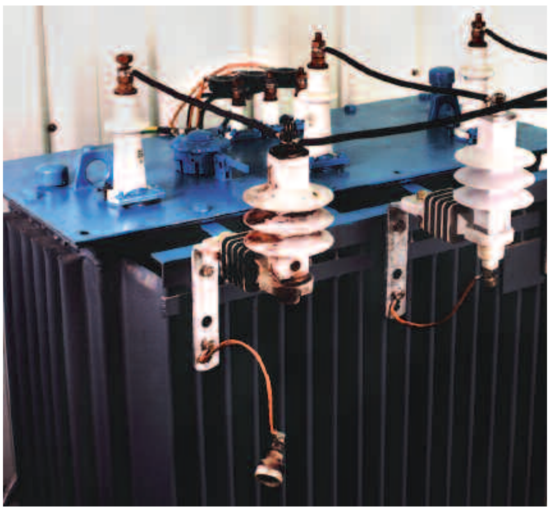


Bild 40: Overstressed MO arrester with disconnected earth connection.

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

16 | INDICATORS

Indicators are devices that clearly indicate an overstressed arrester, i.e. a short circuited arrester. Such devices are installed either on the overvoltage side or on the earth side directly at the arrester. In the event of an overstress, the short circuit is permanent and the system is switched off, but the damaged arrester can clearly be detected and in this way can be quickly replaced. Indicators are used in lines or stations with arresters that cannot easily be visually controlled.

17 | MONITORING OF MO ARRESTERS

An MO surge arrester behaves like an insulator, except in the event of very short discharges. The leakage current flowing under applied continuous operating voltage is very low. As it was depicted in Chapter 3.4.2 it is indispensable that the voltage-current characteristic does not change under the continuous applied voltage. Any rise of the leakage current is particularly inacceptable and in conjunction with this the rise of the power losses and the temperature of the active part.

Different methods of diagnosis and indicators were discussed and developed [5] for the condition monitoring of MO surge arresters. The disconnectors and the indicators mentioned above indicate the total destruction of an arrester.

Surge counters can be installed if there is interest in monitoring the occurrances of the discharges of an arrester in the system. These surge counters count all discharges above the threshold value of the surge counter. Modern surge counters can classify the discharge currents according the reached peak values as well as the moment of the discharge.

A mA-meter can be installed if the continuously flowing leakage current of an MO arrester is to be monitored. Newer devices offer both possibilities in a single device, partially with interfaces, which enables the reading out of stored data.

The arrester has to be installed insulated if surge counters or mA-meters are used.

In systems with a system voltage of 72.5 kV and higher, surge counters and mA-meters are frequently used for monitoring the arresters.

In medium voltage systems, on the other hand, the use of such monitoring devices is limited to a few special cases. On the one hand, this is due to the price of the monitoring devices, which can be more expensive than the MO arrester itself for the medium voltage system. On the other hand, the significance of the measured data tends to be low.

The number of discharges of an arrester does not provide any details concerning the condition or the function ability of the arrester. If the guaranteed energy and current values are not exceeded, no changes appear at the arrester that can be measured. If the guaranteed values are clearly exceeded, this leads to the destruction of the arrester. As a rule of thumb, there is no intermediate stage. The disadvantage of monitoring devices that analyze the harmonics of the leakage current, for example, or which filter and evaluate the 3rd harmonic, is, that the measured values from the system are difficult to interpret in the practice.

The measurement of the entire current is not important, because the leakage current at the continuous operating voltage is mainly capacitive, which means that possible changes occur in the very small ohmic component and therefore can hardly be registered. The leakage current in the range of the continuous operating voltage is dependent on the temperature; therefore, a correction must be made due to the actual temperature to correctly evaluate the measurement results.

The power losses give valuable information concerning the condition of the arrester. But the measurement of the power losses of the arrester in the system is not possible due to practical reasons, because it would be necessary to install a voltage divider near each arrester. Moreover, the power losses in the range of the continuous operating voltage are low and are strongly dependent on the temperature. It would be far too expensive to make exact and temperature compensated measurements.

The measurement of the temperature of the active part of the arrester is very complicated and it is not used with medium voltage arresters. Moreover, it would be necessary to register very small temperature changes. This means that the environmental temperature and the temperature changes due to the normal discharges have to be taken into consideration, i.e. they need to be compensated.

Some users employ thermo vision cameras to examine the electrical equipment or parts of the installation for increased temperature. This is a possible way to regularly control even the MO arresters as a part of a general control of the installation. The application is limited to high voltage arresters that have a surface large enough to be aimed at precisely.

If monitoring devices are used, for example, for measuring the continuous current that flows through an arrester it is important to watch the current tendency. The momentary values cannot provide enough information about the condition of an arrester. For this it is necessary to make the first measurement directly after the arrester installation and to record the conditions during the measurement (voltage, ambient temperature, pollution of the arrester housing, etc.)

Experience in recent decades has shown that modern MO arresters are very reliable. This is also shown by the low rate of arrester failures in the system. To achieve a reliable system operation without failures, it is enough to use high-quality and accurate dimensioned MO arresters in medium voltage systems. Additionally installed monitoring devices are not necessary in most of the situations.

The surge counters that are frequently used for MO arresters in high voltage systems, do not provide much information about the condition of the arrester itself, as previously discussed. However, they do provide valuable information about the activities in the system. Thus, they are intended more for the monitoring of the substation or the line and less for the arrester. Therefore, an arrester with surge counters can provide important data that can be used for analyses of occurrences in the system.

As a rule, monitoring devices for arresters in medium voltage systems are not recommended, in view of the above explanations. An exception to this are the disconnectors that should be used if the supply of electrical power without interruption is more important than the immediate replacement of an arrester that is out of order.

18 | OVERLOAD, FAILURE ANALYSIS, NECESSARY INFORMATION

The reliability of modern MO arresters is very high. The probability of the breaking down of high voltage arresters is almost zero. With medium voltage arresters it lies approximately at 0.1% throughout the world; however, there are considerable differences regionally.

The sealing system was the weak point in some older products with porcelain housings. Humidity was able to enter the housing after years of operation due to corrosion of the metal parts or due to deterioration of the sealing rings, which eventually led to the breaking down of the arrester.

For modern MO arresters direct-sealed with silicon, there are only a few reasons for an overstress. These include: extreme lightning strokes in the line directly at the arrester or unexpected high temporary overvoltages because of earth failures, ferromagnetic resonances or a short circuit between two systems with different system voltages.

Bild 41: MO arrester POLIM-K 36-08 after a short circuit test in the lab.

As a rule, the MO arrester builds a permanent earth or short circuit in case of an overstress. An overloaded arrester resulting from a type test in a test lab is shown in Figure 41.

If an arrester breaks down in the system, it is possible to determine the cause of the failure from the failure mode. However, the information received from overstressed arresters is rather vague, because it is generally not possible to differentiate between the cause of the failure and the secondary effects due to the arc.

If an overload case is to be examined, the following information should be available:

- All the lightning strikes that occurred close to the arrester before the breakdown and if possible also the height of the lightning current
- All the circuit breaker operations before the breaking down of the affected line
- The existing voltage at the arrester terminals before the breakdown, if possible a recording of the voltages
- Possible earth faults at other points in the affected system
- A line diagram of the line or the installation with the position of the arrester before the breakdown
- Counting data of the surge counter, if any
- Ambient conditions at the time of the breakdown.

If an arrester breaks down in a phase and it is replaced, the other two arresters in the other phases should be also replaced, or they should at least be examined to determine if they have also been damaged. It is thus recommended that all three arresters be sent to the manufacturer for examination.
It bears mentioning that an MO arrester fulfils its protection function even in a case of overloading. The voltage decreases towards zero due to the fact that an earth or short circuit is produced and in this way the devices connected in parallel to the arrester are protected against excessively high voltages.
The protection that takes place in an overload case, is deliberately used in some special cases as the last possibility to protect very important and expensive electrical equipment. If the aim is to overstress an MO arrester at a predetermined point – such as the exterior of a building – this arrester is dimensioned deliberately weaker, from the voltage point of view, than the other arresters in the installation. These so-called “victim” or “scarifying” arresters can be seen as an electrically predetermined breaking point in the system.

CONCLUSIONS

Modern MO arresters with direct silicon moulding are to be found in a large number of varieties, covering every necessity. In recent decades they have proved to be very reliable as protection elements in the system. They protect electrical equipment that is much more expensive than the arresters themselves and thereby guarantee high reliability and a good energy supply. They act as insurance against breakdowns in regard to high overvoltages. Integrated solutions are being used and corresponding installations, devices and concepts are being developed for systems that become more complicated.
At the same time, the available space decreases. This means that a single device has to perform several functions. For example, an arrester could perform, in addition to the function of overvoltage protection, the function of a support insulator as well. Therefore, it is necessary to continue developing and optimizing the MO arrester and all the other electrical equipment. At the same time, it is necessary to revise the standards and the application guidelines, because the requirements and the possible tests are also changing.
In the international committees of standardization, IEC and CENELEC, the existing standards are being contiuously revised and adapted to meet the latest developments. New standards are drawn up for new application cases, such as for renewable energy (e.g. photovoltaic and wind power).
Questions about lightning and overvoltage protection are dealt with in different working groups in Cigré and CIRED, and additional technical brochures and application guidelines are drawn up. New discoveries and methods bring about progress. In the Cigré "Surge Arresters" working group, there is an ongoing research program on the topic of "Energy Handling Capability of MO Resistors". The results of this study will bring a better and clearer definition of the term "energy handling capability" and will influence the tests and the decisive standards for these tests.

The actual state of our product portfolio and also the variety of typical applications for MO arresters are described in these application guidelines. The latest specification revisions are taken into account.
It is not possible within this brochure to list and to describe all occurrences, just as it is not possible to cover and to deepen all aspects of the basic principles and of special applications. We will be happy to provide additional information if further questions arise. Special new applications tend to require close cooperation between the manufacturer and the user to find a suitable solution. If there are any problems connected to overvoltage protection, we are ready to discuss possible solutions.

INDEX OF SYMBOLS AND ABBREVIATIONS USED

a	in m	Conductor length
α	-/-	Nonlinearity coefficient
ANSI		American National Standards Institute
b	in m	Conductor length
BIL	in kV	Basic lightning impulse insulation level (peak value). Similar to the LIWV according to IEC. The term BIL is used exclusively in US standards.
C	in F	Capacitance (mainly given in nF or µF)
CENELEC		European Committee for Electrotechnical Standardization
C_k	in F	Capacitance between phase conductor and earth
d	in m	Section length of an overhead line before the substation
f	in 1/s	Frequency, mainly given in Hz. Typical frequencies in power systems are f = 16.7 Hz, 50 Hz, 60 Hz.
i	in A	Peak value of a lightning current (primarily given in kA)
i_c	in A	Continuous current through the arrester under applied continuous operating voltage U_c. Sometimes also named leakage current (generally given in mA).
I_{Ce}	in A	Capacitive earth fault current, rms (given in A)
I_{hc}	in A	High current impulse with wave shape 4/10 µs peak value (generally given in kA)
I_k	in A	Earth fault short circuit current, rms (mainly given in A)
I_K	in A	50 Hz fault current (mainly given in kA, rms-value)
I_{ld}	in A	Long duration current impulse, mostly in connection with a line discharge class or test. Generally given in A, peak value and a time duration, such as 2.4 ms.
I_n	in A	Nominal discharge current of an arrester (mainly given in kA, peak value)
i_{ref}	in A	Reference current of an arrester (mainly given in mA, peak value)
I_{Rest}	in A	Earth fault residual current, in connection with Petersen coils (given in A, rms value)
I_{rw}	in A	Rectangular wave (or square wave). In principle, the same as I_{ld}, used here for rectangular waves with time duration of 2 ms.
I_s	in A	Rated short circuit current. The current, generally given in kA, rms value, with which the overload performance of a surge arrester is tested.
I_{sw}	in A	Switching current impulse with a wave shape of at least 30/60 µs (given in A, peak value)
$i(t)$	-/-	Time function of the lightning current
IEC		International Electrotechnical Commission
IEEE		Institute of Electrical and Electronics Engineers, Inc.
k	-/-	Earth fault factor, k × $U_s/\sqrt{3}$ is the maximum voltage between phase and earth in case of an earth fault.
k	-/-	Proportional factor
K	-/-	Corona damping constant
K_s	-/-	Safety factor
L	in H	Inductance
L	in m	Protection distance of an arrester
L_K	in m	Cable length
LIWV	in V	Standard rated lightning impulse withstand voltage of an equipment or insulation configuration (generally given in kV, peak value)
MCOV	in V	Maximum Continuous Operating Voltage (= U_c, mainly given in kV, rms-value). Defined and used in US standards.
P, P_v	in W	Power losses of the arrester in the case of U_c
p.u.	-/-	per unit, 1 p.u. = $\sqrt{2} \times U_s/\sqrt{3}$
Q	in W	Heat flow from the active part of an arrester to the external environment (cooling)
R_E	in Ω	Earthing resistance
$R_{E,M}$	in Ω	Earthing resistance of a pole or tower
$R_{E,S}$	in Ω	Earthing resistance of a substation
S	in V/s	Maximum steepness of voltage increase (mainly given in kV/µs)
SiC	-/-	Silicon carbide
S_K	in VAr	Three-phase reactive power of a capacitor battery

S_0	in V/s	Steepness of a lightning overvoltage at the point of the lightning stroke (generally given in kV/µs)
S(t)	in V/s	Steepness of a voltage increase in function of time (mainly given in kV/µs)
t	in s	Time
T	-/-	Resistance against temporary overvoltages, $U_{TOV} = T \times U_c$
T	in °C	Temperature
T	in s	Time duration of a long duration current (rectangular wave or square wave, given generally in ms)
T_k	in s	Time duration of earth fault (given generally in s, min and h)
t_s	in s	Time interval
$t_{90\%}$	in s	Virtual time duration of a long duration current impulse (rectangular wave or square wave). It is the time duration during which the current is equal or higher than 90 % of the maximum current (given in ms or µs).
U	in V	Peak value of the overvoltage of a traveling wave (mainly given in kV)
U_c	in V	Maximum continuous operating voltage (mainly given in in kV, rms)
$U_c{}^*$	in V	Increased continuous operating voltage (in kV, rms)
U_E	in V	Maximum overvoltage at the end of an open line (mainly given in kV, peak value)
U_i	in V	Induced voltage (in V or kV, rms value)
U_K	in V	Overvoltage at cable end (mainly given in kV, peak value)
U_L	in V	Charging voltage
U_{LE}	in V	Voltage between phase and earth (in kV, rms)
U_{LL}	in V	Voltage between phases (in kV, rms value)
U_m	in V	Maximum voltage for equipment (mainly given in kV, rms)
$U_{Mp\text{-}E}$	in V	Voltage between transformer neutral and earth (kV, rms)
U_{pl}	in V	Lightning impulse protective level of a surge arrester (kV, peak value)
U_{ps}	in V	Switching impulse protective level of a surge arrester (kV, peak value)
U_r	in V	Rated voltage (mainly given in kV, rms)

U_r^*	in V	Increased rated voltage (kV, rms)
U_{ref}	in V	Reference voltage (mainly given in kV, rms, or $U_{peak}/\sqrt{2}$)
U_{res}	in V	Residual voltage of the arrester (mainly given in kV, peak value)
U_s	in V	Maximum system voltage phase to phase (kV, rms)
u (t)	-/-	Time function of a lightning overvoltage
U_T	in V	Overvoltage at the transformer due to traveling waves (mainly given in kV, peak value)
U_{TOV}	in V	Power frequency overvoltage of a limited duration (mainly given in kV, rms)
U_{1mA}	in V	Voltage at the terminals of a surge arrester when a d.c. current of 1 mA is passing through the arrester. Sometimes required as reference voltage (generally given in kV).
v	in m/s	Speed of a traveling wave, v = 300 m/µs with overhead lines, v ≈ 150 m/µs in cables
W	in J	Energy absorbed by the arrester (mainly given in kJ or kJ/kV$_{U_c}$)
W'	in J/V	Specific energy, generally related to continuous operating voltage U_c (mainly given in kJ/kV$_{U_c}$)
W_c	in J	Discharged energy absorbed by the arrester (mainly given in kJ)
W'_{hc}	in J/V	Energy produced by a high current impulse, related to the continuous operating voltage (given in kJ/kV$_{U_c}$)
X_c	in Ω	Capacitive impedance
Z	in Ω	Surge impedance of an overhead line, Z ≈ 300 Ω…450 Ω
Z_K	in Ω	Surge impedance of a cable, ZK ≈ 20 Ω… 60 Ω
Z_L	in Ω	Surge impedance of a transmission line
δ_L	-/-	Load rejection factor of a generator
ω	in 1/s	v, $\omega = 2 \times \pi \times f$. At 50 Hz is $\omega = 314\ s^{-1}$

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